Research on Factors Relating to Density and Climate Change

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1201 15th St., NW
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Abt

Prepared by
Kimberly Burnett
Emily Holt
Lianne Fisman
Grace Chang
Abt Associates Inc.
55 Wheeler Street
Cambridge, MA 02138

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Executive Summary

The consensus of the scientific community is that human activity has contributed substantially to climate change through increased greenhouse gas (GHG) emissions. Given the potential impacts of a continuation of these trends, this conclusion suggests that significant action is warranted to reduce GHG emissions to avoid the worst possible consequences. One proposed course of action is to increase residential density, primarily on the grounds that it will reduce vehicle miles traveled, a measure that is closely related to the GHG emissions from driving.

Much of the vast volume of research conducted on the topic of residential density and its relationship to travel shows that there is a link between residential density and the number of vehicle miles traveled. However, the relationship is complex and characterized by inter-relationships that researchers are still in the process of disentangling. On the surface, there is a clear correlation between residential density and GHG emissions. Causation is far murkier, and this review of nearly 200 studies demonstrates that this relationship is affected by a complex set of interactions between density and at least a dozen factors, such as socioeconomic characteristics of residents, the availability of public transit, neighborhood accessibility to jobs and services, and the time and cost of various forms of transit. Although newly emerging research approaches are beginning to clarify the relationships, they are relatively untested.

This review of literature on residential density and its relationship to climate change—largely via its relationship to travel behavior—is intended to help inform this aspect of the debate on climate change by summarizing and synthesizing the literature in several key areas, discussed below.

Density is thought to influence travel behavior along several different pathways. The mode used for work travel – private auto, walking, biking, or public transit – is influenced by density at both home and work. People take non-work trips, which comprise the large majority of both trips and VMT, in order to engage in activities such as personal business, shopping, socializing, and recreation. Travel is an important part of the decision to engage in these activities, and density influences these decisions in at least three ways. Density affects the quality of the travel experience (particularly for walking), the distance required to access activities, and the price of travel, both in terms of time and money.

The research on the relationship between density and travel is virtually unanimous: after controlling for socioeconomic factors, density directly influences VMT and mode choice. However, the weight of the evidence suggests that the effect of density on travel behavior is modest (roughly 5 percent reductions in VMT and vehicle trips with a doubling of density). In comparison, large increases in regional accessibility (accessibility to regional centers), are found to have a much larger impact on travel behavior – roughly 20 percent reductions in VMT.

Based on the modest impacts on VMT of increasing density—and the difficulty of achieving that added density—several researchers suggest that it is not an effective policy tool. But some research suggests that doubling density *in combination with* other policies, including those that affect land-use diversity, neighborhood design, access to transit, and accessibility, could have more significant impacts on travel behavior – such as reductions in VMT on the order of 25 to 30 percent. It is

important to note, however, that VMT savings will be slow to develop because of the durability of the housing stock.

S*elf selection* is an important methodological issue that affects all studies of the relationship between travel behavior and the built environment. Researchers long assumed that characteristics of the built environment, such as density, the mix of land uses, transit availability, and neighborhood design, have a causal impact on travel behavior, the source of a significant share of the nation's GHG emissions. More recently, researchers have re-considered the direction of causality and acknowledge that land use patterns may facilitate travel behavior but not cause it, because household decisions about residential location—and all the characteristics of this location—are simultaneous with decisions about travel behavior. That is, people who dislike driving may self-select to live in walkable neighborhoods with convenient access to transit, while people who like driving may be more likely to select neighborhoods with good auto accessibility.

An important unresolved question then is the extent to which estimates of impacts on travel behavior are affected by self selection. The weight of the evidence suggests that self selection and the built environment both have independent effects on travel behavior, but there is little research on the magnitude of the effect of each factor. Regardless, studies that ignore the impact of self selection are likely to overestimate the impact of the built environment on travel behavior. One method for correcting for self selection is to include variables in models of travel behavior that capture people's predispositions to drive or take transit. Most studies that include these variables find that they explain a great deal of the variation in travel behavior, and suggest personality/attitudes toward driving and transit may be more important than characteristics of the built environment. However, research on this topic is in its infancy.

The size of the potential impact of changes in the built environment may depend in part on whether there is unmet demand for the high-density, walkable neighborhoods that are associated with lower auto ownership and VMT. If there is – perhaps because of local zoning restrictions that tend to encourage low density residential development – then neighborhood choices that better match consumers' preferences could indeed result in sizeable reductions in VMT. Given this, some researchers suggest that policy makers should allow for a wide range of neighborhood types.

In addition to research on the relationship between density and travel behavior, other studies included in this review of the literature examine the influence of New Urbanism-type street patterns, demographics and income, and transit availability. The literature demonstrates that several other factors also have important impacts on travel behavior. These include trends toward business decentralization, increases in the number of two-worker households, increases in travel for non-work purposes, and increases in commercial truck traffic.

Studies that consider New Urbanism-type street patterns generally find that they have only weak or no impact on auto use. They have more impact on walking and bicycling, as does pedestrian-oriented design.

Demographic and other characteristics such as income, race/ethnicity, and immigrant status affect the degree to which residential density influences travel behavior. Other aspects of the local context – such as the local economy and geography – also affect the relationship between residential density

and travel behavior. With so many factors influencing travel behavior it is clear that there is no one-size-fits-all strategy for changing travel behavior.

The general consensus of the literature is that transit availability has a negative—but marginal—impact on VMT. In general, cities with increases in transit use over the past few decades have higher population densities and are more centralized. This is consistent with findings that higher employment and population densities at trip destination increase the likelihood of using non-driving modes. Indeed, several researchers find that density at the destination is more important than at origin in predicting mode choice for work trips.

This suggests that densely developed monocentric cities with centralized employment are the best candidates for fixed rail transit. However, as discussed below, cities increasingly do not fit this description. Bus transit provides better flexibility in connecting jobs and workers than fixed-rail transit, but research consistently finds that it is more difficult to attract riders to buses than to rail transit. Given the small impacts of transit availability on travel behavior, most researchers conclude that massive investments in new rail lines would be required to substantially increase rail transit ridership and VMT.

There are at least three primary factors affecting the relationship between residential density and the climate (via travel behavior). One of these is the trend toward decentralization of employment from city centers. Less than a quarter of jobs are now located in the central business district, compared with nearly half located more than 10 miles from downtown. The trend, which started over half a century ago, indicates that the traditional view of the monocentric city is a poor approximation for the reality of most American cities. Importantly, it weakens the ability of public transit – particularly fixed rail systems – to meet travel needs, and reinforces the need for auto ownership and neighborhoods that accommodate autos.

A second factor is the increasing number of households with two workers who often commute to different locations. The literature is mixed on the implications of this trend, although there is consensus on one point: the research clearly demonstrates that households do not primarily select their residential location in order to minimize their commutes.

A third factor is the recent increase in non-work trips. Understanding trends in non-work trips is important because unlike work trips, non-work trips are often discretionary, and therefore may be more influenced by the built environment, pricing, and other factors designed to reduce auto trips and their associated greenhouse gas emissions. On the other hand, non-work trips may be less influenced by public transit options because they often involve multiple destinations and are thus less well suited to public transit than work trips.

Trends over the past decade also indicate that commercial truck traffic is increasing its share of total VMT, and that this trend is likely to continue in the next decade.

In addition to unresolved questions about the role of self selection, other important questions are left unanswered by the current research on the connection between residential density and the climate. Among others, how difficult would it be to achieve residential densities that are double their current levels across a metro area – that make Atlanta look more like Boston? Experience from Portland,

Oregon, an area known for its urban growth boundary, suggests that sizeable increases in density takes decades – at least 30 years. Given that the built environment is long lived, this result is not surprising.

Few studies include the impact of travel cost—either in terms of time or money—on travel behavior, but those that do conclude that pricing may play a more important role in explaining travel behavior than characteristics of the built environment. They conclude that changes in policies that affect the monetary or time cost of car ownership and use—such as increases in gas taxes or the price or availability of parking and the supply of roads—are more effective in changing travel behavior than any other policy. If policy makers find these types of economic incentives to be unpalatable, policies that lead to large-scale changes in land-use are a distant second-best alternative.

Introduction

Human contribution to global climate change through greenhouse gas (GHG) emissions is one of the most intensely debated policy issues of our time. Residential density is just one of the factors that affect GHGs, and yet a vast volume of research has been conducted on this topic. This review of the literature is intended to help inform this aspect of the debate by summarizing and synthesizing the literature—nearly 200 studies in total—in 12 key areas.

The report examines four groups of factors that influence the complex relationship between density, GHGs, and climate change: density and its relationship with travel behavior and energy use; how neighborhood characteristics affect travel behavior; transit efficiency compared with private autos; and demographics and other trends related to transportation and land use. The last section of this review identifies major conclusions and some areas for further research. More detailed reviews of the literature on each of these topics are provided in the Appendix.

1. Density's Relationship with Travel Behavior and Energy Use

Residential density affects travel behavior—which is related to greenhouse gas (GHG) emissions and thus climate impacts—in several ways.[1] First, residential density (both in terms of units of housing and population) is correlated with the number of vehicle miles traveled (VMT) by a person or household, the number of cars owned per household, the number of trips taken, and the mode choice of travel—walking, bicycling, driving, or taking public transit. In addition to its impacts on travel behavior, residential density also influences the climate through its effect on home energy use.

The Influence of Density on Travel Behavior

Density influences travel behavior along several different pathways. For work trips, density has a strong correlation with the mode choices available for travel. People take non-work trips, which comprise the large majority of both trips and VMT, in order to engage in activities such as personal business, shopping, socializing, and recreation. Travel is an important part of the decision to engage in these activities, and density influences these decisions in at least three ways. Density affects the quality of the travel experience (particularly for walking), the distance required to access activities, and the price of travel, both in terms of time and money.[2]

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[1] Travel behavior is frequently discussed in the literature and in this review in terms of vehicle miles traveled (VMT). VMT is only indirectly related to the impact of travel behavior on the climate, but far more easily measured than greenhouse gas emissions (GHGs), which vary depending on auto fuel efficiency, among other factors.

[2] Chatman, 2005

The Built Environment, Travel Behavior, and Self Selection

S*elf selection* is an important methodological issue that affects all studies of the relationship between travel behavior and the built environment. That is, many studies observe correlations between characteristics of the built environment and travel behavior, and assume that these characteristics *cause* the travel behavior. More recently, researchers have recognized that the relationship is more complex, because household decisions about residential location—and all the characteristics of this location—are simultaneous with decisions about travel behavior. That is, people who dislike driving may self select to live in walkable neighborhoods with convenient access to transit, while people who like driving may be more likely to select neighborhoods with good auto accessibility.

Research indicates that studies that ignore the impact of self selection are likely to overestimate the influence of characteristics of the built environment on travel behavior, although the question about the magnitude of this effect is not settled. At least nine different methods have been used to correct for self selection. One method is to use instrumental variables to first predict residential location of individuals before modeling the impact of the built environment on travel choices. Studies using this method have somewhat inconsistent findings—the effect of the built environment is weak in some studies and strong in others. A second method is to directly include variables that capture people's predispositions to drive or take transit. Most that include these variables find that they explain a great deal of the variation in travel behavior, and suggest personality/attitudes toward driving and transit may be more important than characteristics of the built environment.[3] Other methods include longitudinal analysis, propensity score stratification, and direct questioning.[4]

Researchers' findings about the impact of self selection vary based on the methodology used. For example, one study finds no impact of the built environment on auto ownership when personality/attitudes are included in the analysis, but finds an impact using a quasi-panel model that controls for self-selection by asking respondents to report changes in travel behavior following a move to a different residential area.[5] The best method is considered to be a longitudinal analysis, which observes the behavior of a group of individuals over time, typically with a series of surveys administered periodically. This approach allows researchers to observe how individuals respond to changes in their environment, but these are expensive and difficult to administer, and therefore rare. Among the remaining methods, it is not clear which are most reliable.

Regardless, virtually all studies that account for the impact of self selection show that the built environment does affect travel behavior. However, the weight of the evidence indicates that the measured influence of the built environment is diminished once the impact of self-selection is taken into account.[6]

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[3] See for example Bagley and Mokhtarian, 2002; Cao, *et al.*, 2007b; Van Acker, *et al.*, 2007; and Kitamura *et al.*, 1997.

[4] For a thorough discussion of the methods used to correct self-selection bias, see Cao, *et al.*, 2008.

[5] Cao, *et al.*, 2007b

[6] Cao, *et al.*, 2009a

To assess the potential impact of policies that support alternative (high-density, walkable) developments, it is important to understand the demand for them. If there is unmet demand for alternative developments, then increasing their supply – for example by removing local zoning restrictions that tend to discourage high-density residential development – may enable people living in low-density areas to move to neighborhoods that better match their preferences. That is, it allows them to self select into a new environment that enables them to act on their preferences to walk more and drive less. For this group of people, policies that support high-density development may meet or even exceed expectations.[7] Other research suggests that preferences can change over time, and that some people who live in high-density neighborhoods because of an initial lack of alternatives may eventually come to prefer these environments, reinforcing travel behavior suitable to these neighborhoods.[8]

Density and VMT

The research on the relationship between density and travel is virtually unanimous: after controlling for socioeconomic factors, density directly influences VMT and mode choice. The weight of the evidence suggests that the effect of density on travel behavior is modest.[9] Several studies, including one meta-analysis, find that a doubling of density is associated with a 5 to 7 percent decrease in VMT per household per year.[10] Some researchers find larger impacts, although these studies generally do not account for the impact of self selection. For example, one study – which uses aggregate data and thus is particularly subject to self-selection bias – finds that doubling population density is correlated with a 30 percent decrease in driving.[11]

Of some importance, one study finds that the impacts of increasing density on VMT are found to be larger in urban areas than suburban ones, so efforts to increase density in these areas may be more effective in reducing VMT than efforts to increase density elsewhere.[12]

Based on the modest impacts on VMT of increasing density—and the difficulty of doing so—several researchers suggest that it is not an effective policy tool.[13] In the recent past, average densities have been declining, and reversing this trend will certainly require effort. However, cities such as Portland that have made a concerted effort – including strong regional government, large transit investments, and state laws requiring the establishment of urban growth boundaries – have had an increase in density over the last several decades.[14]

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7 Bailey, 2008; Chatman, 2009; Levine, 2006; Stone, *et al.*, 2007; and Cao, *et al.*, 2009a

8 Transportation Research Board, 2009

9 Schimek, 1996; Brownstone and Golob 2009; Ewing and Cervero, 2001

10 Schimek, 1996; Ewing and Cervero, 2001

11 Newman and Kenworthy, 1989

12 Van de Coevering and Schwanen, 2006

13 Brownstone, 2008; Brownstone and Golob, 2009; Schimek, 2006

14 Transportation Research Board, 2009

Others argue that increased density in combination with other policies that affect land-use diversity, neighborhood design, access to transit, and regional accessibility can have significant impacts on travel behavior (such as reductions in VMT of 25-30 percent).[15] In any case, it is important to note that VMT savings will be slow to develop because of the longevity of the housing stock.[16]

Density and Mode Choice

There is also consensus in the literature that residential density is associated with greater transit use, although some studies suggest that the magnitude of the relationship is small.[17] Research suggests that the relationship between density and transit use is non-linear. For example, one study finds a sharp rise in the use of transit when residential density increases from seven to 16 dwelling units per acre.[18]

In addition to residential and population density, travel behavior—particularly mode choice—is also affected by employment density and the centrality of the central business district. Higher employment and population densities at trip destination are generally found to increase the likelihood of non-driving modes. Most studies conclude that, for work trips in particular, density at the destination is more important than at origin in predicting mode choice.[19]

Conclusions: Residential density has a modest effect on VMT. It also has a small impact on transit use, but densities at trip destinations may have a larger impact. Increases in density that are combined with other policies that affect land-use diversity, neighborhood design, access to transit, and accessibility are estimated to have larger impacts on travel behavior than an increase in density.

Residential and Employment Density Required to Support Public Transit

Public transit requires a minimum level of residential density to produce enough users to financially support the system. While researchers acknowledge that higher densities provide a larger ridership base to support public transportation, the exact threshold varies by area, transit type, and service level. One widely cited source is from the Institute of Transportation Engineers, shown in the exhibit below.

In general, a minimum residential density threshold of seven dwelling units per acre is needed to support basic local bus service. Given their higher expense and energy use, the minimum threshold is higher for more frequent bus service and for light rail and rapid rail transit. The residential density required for commuter rail is lower, but this mode does require a heavily populated transportation corridor.

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15 Ewing and Cervero, 2001; Ewing, *et al.*, 2008; Bento, *et al.*, 2005

16 Transportation Research Board, 2009

17 Ewing and Cervero, 2001; Frank and Pivo, 1994; Kockelman, 1996; Cervero, 2002

18 Smith, 1984; see also Seskin, *et al.*, 1996

19 Ewing and Cervero, 2001; Frank and Pivo, 1994; Zhang, 2004; Chen, *et al.*, 2008

Type of Transit Service	Residential Density Threshold (Dwelling Unit/Acre)
Local bus (1 bus per hour)	4-5
Intermediate bus (1 bus every 30 minutes)	7
Frequent level bus (1 bus every 10 minutes)	15
Light rail (5-min headways or better during peak hour)	9
Rapid transit (5-min headways or better during peak hour)	12
Commuter rail (20 trains a day)	1-2

Source: Institute of Transportation Engineers 1989.

The minimum residential density required to support transit is also influenced by other factors. For example, higher employment density increases transit ridership.[20] Other factors such as income, parking availability, attitudes toward transit, and neighborhood design also affect the likelihood of taking transit, and therefore the minimum density required to support transit.[21] Transit service levels (frequency and quality) also affect ridership, so that the demand for transit is also a function of the supply of transit.[22]

The Effect of Density on Home Energy Use

The impact of urban form on transportation energy use has been studied extensively, but its impact on residential energy use is a relatively new area of exploration. The limited research done to date generally concludes that higher density is associated with lower GHG emissions on a per-capita basis.

Smaller houses and multifamily housing, both more common in dense neighborhoods, use less energy than larger detached housing units. One analysis concludes that an average household living in a compact county would be expected to consume about 20 percent fewer BTUs of energy annually than one living in a sprawling county,[23] primarily because of larger, detached homes in sprawling counties.[24]

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[20] Cervero, 1993; Frank and Pivo, 1994; Zhang, 2004; Chen, *et al.*, 2008

[21] Cervero, *et al.*, 2004; Cervero, 1994; Messenger and Ewing, 1996; Newman and Kenworthy, 2006; Bagley and Mokhtarian, 2002; Cao, *et al.*, 2009a

[22] Taylor, *et al.*, 2009

[23] A compact county has a value that is one standard deviation above the mean of the county sprawl index employed in this study. A sprawling county is one that falls one standard deviation below the mean value in this index.

[24] Ewing and Rong, 2008

However, the most densely populated housing type—high-rise apartments—were found in one study to produce higher per capita GHG emissions than mid-rise, low-rise or detached housing. The most efficient housing types are townhouses and villas (two or more detached dwellings with common or shared facilities). The inefficiency of high-rise buildings is a result of the huge energy draw from heating and cooling common areas and maintaining amenities, such as gyms and swimming pools.[25]

A second estimate comparing GHG emissions of high- and low-density residential developments uses a life-cycle analysis that considers three major elements of urban development: construction materials for buildings and infrastructure (including residential dwellings, utilities and roads); building operations; and transportation (private automobiles and public transit). This analysis finds that low-density suburban development produces one and a half times more GHG emissions than high-density residential development. But this difference is almost entirely due to higher emissions from transportation, with little difference between the per-unit emissions from building operations in the two settings (e.g., heating, cooling, and lighting).[26]

Another study considers the CO_2 absorption from plants (sequestration), which offsets some of the human-produced GHG emissions in lower-density areas. The study suggests that because of this, the relationship between density and CO_2 emissions is not linear—that is, higher density does not always translate to lower CO_2 emissions. In very low density areas, carbon sequestration from preserved forestlands outweighs GHG emissions from human activity. On a per-capita basis, post-war suburbs have the highest GHG emissions. The densest cities have the smallest per-capita emissions, because of smaller, multi-family housing units, walkable streets and access to public transit.[27]

2. Neighborhood Characteristics Influencing Travel Behavior

A number of characteristics of the built environment are shown to influence travel behavior. These include neighborhood design, mixed-use development, and transit availability. As in studies of the relationship between residential density and travel behavior, self-selection also affects studies of the relationship between travel behavior and neighborhood design, the mix of uses, and transit availability. Generally, researchers who correct for the influence of self selection find that the impact of the built environment variables is weakened.

The Influence of Neighborhood Design on Travel Behavior

Neighborhoods have a number of characteristics that are shown to influence travel behavior, including pedestrian-oriented design, such as features designed to encourage walking and bicycling like bike paths and sidewalks; street patterns such as small block sizes, the absence of cul-de-sacs,

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[25] Myors, *et al.*, 2005

[26] Norman, *et al.*, 2006

[27] Andrews, 2008

and grid-like street patterns, which both discourage driving and encourage walking and bicycling; and neighborhood accessibility to centers of activity such as employment, retail, and recreation.

Studies often include more than one characteristic of neighborhood design, and sometimes summarize groups of characteristics by describing them as either having traditional neighborhood design or suburban neighborhood design. Suburban neighborhoods are associated with large lot sizes, limited diversity of land use, and an auto-oriented design; traditional neighborhoods are associated with higher density, mixed uses, and street patterns that encourage walking and bicycling and discourage driving.

Overall, most studies find that *New Urbanism-type street patterns* have only weak or no impact on auto use.[28] They have more impact on walking and bicycling, as does p*edestrian-oriented design.*[29] The research is mixed on whether these non-motorized trips substitute for motorized travel: one study finds evidence that this travel complements rather than substitutes for motorized trips; another study finds evidence of substitution.[30]

Findings of studies on *destination accessibility* (accessibility to specific destinations)—most of which do not consider the impact of self selection—generally find that it reduces VMT.[31] Increases in access to regional centers (called *regional accessibility*) are also found to reduce VMT, and in fact to have a larger influence on VMT than density.[32] Some researchers note that environments designed to be more accessible tend to lower the costs associated with travel. This, in turn, leads to shorter but more frequent trips, although overall VMT remains lower than in less accessible environments.[33]

Considering the influence of *neighborhood type*, researchers find that differences in travel behavior between residents of suburban and traditional neighborhoods are largely explained by differences in attitudes. The built environment does have an effect on travel behavior and auto ownership, however, even after the impact of self selection is considered. The influence of the built environment appears to be stronger for walking than for driving. Residents in traditional neighborhoods also tend to choose public transit to get to work more often than residents of suburban neighborhoods.[34]

Conclusions: New-Urbanism-type street patterns and pedestrian-oriented design have little impact on auto use, but have more impact on walking and bicycling. Greater accessibility to destinations has a larger impact on reducing driving than density. Residents of traditional neighborhoods tend to

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28 Boarnet and Sarmiento, 1998; Zhang, 2004; Hess and Ong, 2002; Holtzclaw, 2002; Bhat, *et al.*, 2009; Cervero and Kockelman, 1997; Guo, *et al.*, 2007

29 Chatman, 2009; Guo, *et al.*, 2007; Kitamura, *et al.*, 1997; Cao *et al.*, 2007b; Cao *et al*., 2009a

30 Guo, *et al.*, 2007

31 Cao *et al.*, 2007b; Kockelman, 1996; Krizek, 2003

32 Ewing and Cervero, 2001; Badoe and Miller, 2000; Kockelman, 1996; Chen, 2008

33 Zhang, 2005b; Shay and Khattak, 2007

34 Handy, *et al.*, 2005; Cao, *et al.*, 2009a; Cao, *et al.*, 2007a; Cao, 2009; Khattak and Rodriguez, 2005; Schwanen and Mokhtarian, 2005

walk more and choose public transit to get to work more often than residents of suburban neighborhoods.

The Influence of Mixed-Use Development on Travel Behavior

The research on the relationship between mixed-used development and travel behavior is difficult to assess, because studies use a wide range of variables to measure "mixed use." Variables used to represent mixed use include employment accessibility, service diversity, land-use diversity, retail diversity, and commercial diversity, all measured differently across studies.

The research generally demonstrates that mixed-use development does influence travel behavior.[35] However, findings vary somewhat depending on model type, measures used to characterize mixed-use development, and the type of trip or travel mode.

There is no clear consensus in the literature on the impact of mixed-use development on trip frequency. The limited research available indicates that it reduces discretionary trips and increases maintenance (e.g., those for personal business).[36] It is more clear from the literature that households living in mixed-use neighborhoods own fewer cars.[37]

The weight of the evidence suggests that mixed-use development reduces VMT, although findings vary somewhat with trip purpose and with how land use mix is measured, and the magnitude of the impact is small.[38] Mixed-use development increases the likelihood of using non-motorized modes of transportation (walking and biking).[39] Researchers also generally find that mixed-use development increases the likelihood of commuting via public transit; however, some studies find that the effect of mixed-use development is stronger when measured at the workplace than when measured at home.[40]

In terms of the relative importance of mixed-use compared with other factors, one study finds that the effect of mixed-use development is much weaker than the influence of neighborhood density, others find that the two have roughly similar effects on travel behavior.[41]

Several researchers attempt to correct for the effect of self-selection into mixed-use areas of residents who prefer not to drive. One study, of Southern California, finds a true impact of mixed use on travel behavior in a model of travel behavior at the zip code level, but not for smaller geographies. A

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35 Ewing and Cervero, 2001; Cervero and Duncan, 2006; Cervero and Kockelman, 1997; Kockelman, 1996; Guo, et al., 2007; Dargay and Hanley, 2004

36 Cervero and Kockelman, 1997 and Guo, *et al.*, 2007

37 Cervero, 1996; Dargay and Hanley, 2004; Kockelman, 1996

38 Cervero and Duncan, 2006; Kockelman, 1996; Bailey, *et al.*, 2008; Cervero and Kockelman, 1997

39 Cao, *et al*., 2009a; Cervero, 1996; Cervero and Duncan, 2003; Kockelman, 1996; Rajamani, *et al.*, 2003

40 Cervero, 2002

41 Cervero, 1996; Ewing and Cervero, 2001

second study, of Northern California, finds a true impact of mixed land uses in discouraging auto travel and facilitating use of transit, walking, and biking. A third study, of Germany, finds no impact of mixed land use on travel behavior.[42]

Conclusions: Households living in mixed-use neighborhoods own fewer cars and drive less than other households, although the impact of mixed-use development is fairly small. These households are also more likely to walk and bike, and to commute via public transit.

The Influence of Transit Availability on Travel Behavior

The relationship between improved transit availability and travel behavior is a complex one. The demand for transit depends in part on its supply—the frequency and quality of service—while transit supply is dictated more by residential or employment density than any other measure of demand.[43] Given the correlation between transit availability and density, as well as the inter-relationship between the supply of and demand for transit, it is difficult to separate the effects of access to transit from other land-use variables.

The general consensus of the literature is that transit availability has a negative—but marginal—impact on VMT.[44] Only two of the studies reviewed account for the possibility of self selection. Both of them find an impact of transit availability on the decision to use transit, but that the impact is small.[45]

The impact of transit availability on travel behavior depends on a number of factors. In general, cities with increases in transit use over the past few decades have higher population densities and are more centralized.[46] This result is not surprising given the consistent findings that transit use is more closely related to density at the destination of the trip than at the origin.[47] That is, densely developed monocentric cities with centralized employment are the best candidates for fixed rail transit. As discussed below, cities increasingly do not fit this description. Bus transit provides better flexibility in connecting jobs and workers, but research consistently finds that it is more difficult to attract riders to buses than to rail transit.

Conclusions: Given the small impacts of current transit availability on travel behavior, most researchers conclude that massive investments in new rail lines would be required to substantially increase availability and thus increase rail transit ridership and decrease VMT.[48]

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42 Cao, *et al.*, 2009b; Vance and Hedel, 2007; Boarnet and Sarmiento, 1998

43 Badoe and Miller, 2000

44 Buehler, 2009; Vance and Hedel, 2007

45 Vance and Hedel, 2007; Bento, *et al.*, 2005

46 Baum-Snow and Kahn, 2005

47 Pushkarev and Zupan, 1977; Cervero, 1993; Frank and Pivo, 1994

48 Baum-Snow and Kahn, 2005; Bento, *et al.*, 2005

3. Transit Efficiency from a Greenhouse Gas Perspective

It is clear from the literature that on average, rail transit (subway and light rail) is more efficient from a GHG perspective than automobile use. On the other hand, bus transit is less efficient on average. Several important factors determine the relative efficiency of public transit and automobile use. These include average levels of occupancy, the source of fuel, and whether or not secondary benefits of public transit are counted. The most accurate comparisons of public transit and auto energy use and GHG emissions is a life-cycle analysis that includes direct (tailpipe) emissions as well as the emissions related to manufacture of vehicles, construction of transportation infrastructure, and disposal of vehicles and infrastructure at the end of their useful life.

A critical factor in comparing the efficiency of transit to automobile travel is the energy intensity of the sometimes massive construction efforts involved in transit systems. Construction techniques (such as less use of concrete) and energy efficiency technologies have a major impact on energy intensity of both construction and operation of rail systems. Life-cycle GHG emissions for rail and bus modes of transit can be considerably higher than those based only on tailpipe GHG emissions; however, public transit is still more efficient than auto use on average.

For example, in a comparison of the life-cycle GHG emissions of several different vehicles, one study found that off-peak (with low ridership) urban diesel buses have the highest GHG emissions per passenger kilometer traveled (PKT), followed by a conventional gasoline pickup and then a conventional gasoline SUV. But an urban diesel bus at peak travel times (with higher ridership) had the lowest GHG emissions per PKT, followed by light rail (Boston's Green Line).

The relative rankings of urban diesel buses—which had either highest or lowest GHG emissions depending on occupancy—underscore the importance of levels of ridership in the relative efficiency of transit modes.[49] Under current average levels of occupancy, rail transit is more efficient than auto use, but diesel buses—currently the most common bus fuel—are less efficient. Eleven passengers per vehicle are needed to make an average bus ride equivalent to automobile travel, but they currently average only nine passengers per vehicle, which is too low to provide GHG benefits.[50] Average vehicle occupancies vary by location, route, and time of day, so in some places diesel buses are likely to be far more efficient than automobile travel and in other places far less. On average, rail transit has sufficiently high vehicle occupancies to be more efficient than auto use, but rail occupancies also vary.[51]

The GHG emissions of any transit mode are also dependent on its fuel source. Transit systems that are more heavily reliant on fossil fuels for electricity emit more greenhouse gases than those using

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[49] Chester, 2008; Chester and Horvath, 2009

[50] Kockelman, *et al.*, 2009; and Davis and Diegel, 2007

[51] Chester and Horvath, 2009

fuel sources such as hydropower. For example, San Francisco's Muni Metro uses electricity that is 49 percent fossil fuel-based, and Boston's Green Line's is 82 percent. As a result, the Green Line uses less energy than the Muni Metro but has greater GHG emissions.[52] The availability of fuel sources other than fossil fuels varies by geographic region and may change over time with the emergence of new technologies.[53]

Even setting aside these factors, the influence of public transit on GHG emissions is complex. Some studies measure the impact of transit on the environment broadly, counting the benefit of transit as direct reductions in auto trips for each transit rider as well as secondary benefits.[54] Secondary benefits counted include reduced congestion for non-riders (and thus reduced emissions) as well as influences on land-use patterns that reduce driving, although the magnitude of these secondary benefits—and their existence—is debated. Some researchers argue that the costs of public transit outweigh any reductions in congestion.[55]

Given the lower GHG emissions from public transit, several researchers argue that expanding the capacity and ridership of public transit is a viable strategy for reducing GHG emissions. Other researchers conclude, however, that massive investments in public transit would be required to attract new riders to transit in large numbers, particularly to buses.[56]

Conclusions: An average, rail transit (subway and light rail) is more efficient from a GHG perspective than automobile use, and bus transit is less efficient. The GHG benefits of transit are dependent on levels of ridership, fuel sources, and whether new transit investments reduce congestion.

4. Income and Demographic Influences and Other Trends that Influence the Relationship between Residential Density and Climate Change

A number of trends in demographics and patterns of urban development over recent decades have had significant impacts on travel behavior. Trends in employment decentralization suggest that our traditional understanding of cities and how they function—the monocentric city model—no longer applies to many places, a development that has important implications particularly for the ability of fixed-rail transit systems to meet travel needs.

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52 Chester and Horvath, 2009

53 Chester and Horvath, 2009; Chauhan and Singh, 2009; Kockelman, *et al.*, 2009

54 Bailey, 2007

55 Winston and Maheshri, 2007

56 Litman, 2009; Baum-Snow and Kahn, 2000

Increases in the share of trips and the number of miles traveled for non-work purposes also have important implications. The built environment appears to affect work and non-work trips differently, in part because non-work travel is more complex, involves more stops, and is therefore less well served by public transit than work trips.

Trends over the past decade indicate that commercial truck traffic is increasing its share of total vehicle miles traveled (VMT), and that this trend is likely to continue in the next decade.

Significant increases in the number of workers per household and labor force participation of married women also has important ramifications for households' decisions about residential location in relation to employment location. Decentralizing job locations in combination with the need to accommodate the commutes of two workers means that most households do not choose their residential locations to minimize commutes into the central business district.

The demographics and income of neighborhood residents (including the role of personality and attitudes) also influence travel behavior – and thus GHG emissions and the climate.

Employment Decentralization Trends

The dispersion of jobs from central cities in recent decades is well documented.[57] The spread of jobs within market areas, away from the central business district, is referred to as *decentralization*. Although it is less well documented, jobs have also spread from more dense Metropolitan Statistical Areas (MSAs) to less dense MSAs, a process referred to as *deconcentration*.

As a result of decentralization, jobs are increasingly located further away from the city center rather than closer. Less than a quarter of jobs (21 percent) are now located in the central business district. In comparison, almost half (45 percent) are located farther than 10 miles from the downtown area of the city.[58] This trend has been occurring since at least the 1950s, and is continuing into the present decade.[59] Further, the trend toward decentralization of employment is occurring in virtually every industry.[60]

Although almost every major metropolitan area has experienced job decentralization over recent decades, there are differences in the degree by region. The Midwest is the most decentralized, while the West and Northeast are the most centralized regions.[61] This decentralization has resulted in important changes in commuting patterns. In 2000, 46 percent of all metropolitan area commutes were from suburb to suburb compared with 19 percent of commutes from a suburb to the central city.[62]

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[57] Giuliano, *et al.*, 2008; Glaeser and Kahn, 2001; Kneebone, 2009; Lee, 2006

[58] Kneebone, 2009

[59] Carlino and Chatterjee, 2002

[60] Kneebone, 2009

[61] Glaeser and Kahn, 2001; Kneebone 2009

[62] Pisarski, 2006

As an indication of deconcentration, the share of all employment in the most job-dense MSAs declined between 1951 and 1996. Specifically, the 30 most dense cities accounted for over half of total employment in 1951 (54 percent) but only 40 percent of total employment in 1996.[63]

Conclusions: The continuing trend of employment decentralization indicates that the traditional view of the monocentric city is a poor approximation for the reality of most American cities. There is much debate as to what form, if any, cities are following in their evolution. Some observers posit that cities are following a polycentric form; others argue that in some cities, jobs are dispersed without any centering.[64]

Trends in Work versus Non-work Trips

During the 1970s, 1980s, and 1990s, the proportion of travel dedicated to trips to and from work fell sharply. Work travel decreased from 26 percent of all trips in 1969 to 16 percent in 2001, and decreased from 34 percent of VMT to 27 percent in 2001, with corresponding increases in the share of non-work travel.[65] Some researchers identify a household "travel budget," implying that overall household travel time is fixed but that the purpose of the travel varies. As evidence of this, studies show that commute length is a determinant of non-work travel: a longer commute (time) decreases the number of non-work trips one takes and vice versa.[66]

Understanding trends in non-work trips is important because unlike work trips, non-work trips are often discretionary, and therefore may be more influenced by the built environment, pricing, and other factors designed to reduce auto trips and their associated greenhouse gas emissions. On the other hand, non-work trips may be less influenced by public transit options given that non-work trip destinations generally vary more than work trips.

Research indicates that the built environment can affect non-work travel behavior in several ways. For some types of non-work trips, the accessibility of the destination increases the number of trips taken to the destination and so also increases the time spent traveling.[67] In addition, suburban growth has facilitated firms and households to locate near each other, thus shortening commutes and freeing up more time for leisure travel.[68] Finally, more varied and more convenient shopping and recreational opportunities may also be responsible for the increase in non-work travel.[69]

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63 Carlino and Chatterjee, 2002

64 Giuliano, *et al.*, 2008; Glaeser and Kahn, 2001; Lee, 2006

65 McGuckin and Srinivasan, 2005

66 Purvis, *et al.*, 1996

67 Nelson and Niles, 2000

68 Gordon, *et al.*, 1988

69 Zhang, 2005b

Conclusions: Travel for non-work purposes has increased sharply over the last decades, diminishing the share of travel for work. Non-work trips are often more complex than work trips, and therefore less likely to be well served by public transit options.

Trends in Personal Vehicle versus Freight and Commercial Truck Traffic

Although personal vehicles, which include automobiles and light trucks, make up the majority (57 percent) of total carbon emissions from the transportation sector, commercial truck traffic is also a significant source. This category, which includes light duty commercial trucks as well as heavy trucks, accounts for another 20 percent of emissions, with this percentage expected to increase in the next decades.[70] However, very little is known about the relationship between land-use patterns and commercial truck VMT.[71]

Over the 10-year period ending in 2006, VMT for passenger vehicles increased about 23 percent, compared with much larger increases of 39 to 42 percent for truck traffic, depending on the type of truck. In the future, overall total freight tonnage is forecasted to double between 2002 and 2035.[72] Of the five freight modes (air, water, pipeline, truck, and railroad), trends indicate that truck's share of this freight is increasing because of its scheduling and routing flexibility. Researchers estimate that over the last 15 to 20 years, truck's share of all freight ton-miles (one ton of freight shipped one mile) has increased from 26 percent to 32 percent. At the same time, truck energy efficiency (ton-miles per pound of CO_2) has fallen 10 percent, perhaps due to decreases in operational efficiency (e.g., more miles where trucks are traveling empty) since truck fuel economy has remained constant or increased over the same time period.[73]

Very little research has been conducted on the relationship between land use, urban form, and freight and commercial VMT, although higher population density is correlated with lower freight and commercial VMT.

Conclusions: The share of total transportation sector GHG emissions from commercial truck traffic is increasing and expected to continue to do so. Little is known, however, about how land use and urban form affect freight and commercial VMT.

Trends in Two-Worker Households

The increase in number of women in the workforce over the last four decades is one of the most significant social developments of the 20th century, and the most important factor in the increasing share of households with two or more workers.

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70 Southworth, *et al.*, 2008

71 Bronzini, 2008

72 Kockelman, *et al.*, 2009

73 Kockelman, *et al.*, 2009

Although the labor force participation of people of retirement age has also risen, this increase is largely a result of dramatic growth in the labor force participation of married women. In 1968, 55 percent of 25-54 year-old married women with no children living at home were working or looking for work. By 1993 labor force participation among this group peaked at about 79 percent, and has stayed roughly constant since then. Among married women with children living at home, labor force participation nearly doubled from 38 percent in the late 1960s to 72 percent by 2000.[74]

The literature is mixed on the implications of this increase in two-worker households, although there is consensus on one point: the research clearly demonstrates that households do not primarily select their residential location in order to minimize their commutes. Research identifies the increasing prevalence of two-worker households as a key reason for "excess commuting," which is the difference between the average actual commute and the smallest possible average commute.[75] Other studies blame the lack of affordable housing near job locations as a primary reason for lengthy commutes among both single-earner and dual-earner households.[76]

The literature also suggests that the presence of children in the household affects residential location and therefore work-related travel behavior. When children are present, families with two earners tend to live further away from their work, perhaps because of access to childcare amenities and better schools. In contrast, childless couples tend to live closer to where they work.[77]

In addition to differences in residential location, some research finds that the travel behavior of dual-earner families differs from that of single-earner families in other ways. One study found that residential density was significant in predicting auto use among single-earner families, but not among dual-earner families. The auto use of all commuters was affected by density at the work location, but effects were stronger for dual-worker families than for single-earner families.[78]

Conclusions: The increase in two-worker households over the last several decades has affected household location decisions in important ways. Households do not primarily select their residential location in order to minimize their commutes. Housing affordability and accessibility to other amenities are also factors in the residential location decision.

The Influence of Income and Demographic Characteristics on Travel Behavior

A number of socioeconomic characteristics are shown to influence travel behavior, including income, age, gender, race/ethnicity, immigrant status, and household structure. The characteristics of

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[74] Fischer and Hout, 2006

[75] Ma and Banister, 2006; Deding, *et al*., 2009

[76] Sultana, 2005

[77] Mok, 2007

[78] Maat and Timmermans, 2009

neighborhood residents may influence the degree to which changes in the built environment – such as increases in residential density – affect travel behavior. In other words, the same policy may be less effective in one location than in another because of differences in the characteristics of neighborhood residents.

There is a clear consensus in the literature that both characteristics of the built environment *and* socioeconomic characteristics of households affect travel behavior. There is not a consensus, however, on which of the two is more important. The literature is also not clear on which of the socioeconomic characteristics are most important in explaining travel behavior.

Findings about the influence of any one income/demographic characteristic taken in isolation are mixed. It is the combination of several factors that drives travel behavior to a much greater extent than any one characteristic. A few generalizations can be made, however:

- Mobility increases with income, evidenced by an increase in the number of trips taken and higher levels of auto ownership among high-income households.[79] While low-income households are more likely to use transit, this behavior is more closely correlated with car ownership than with income level, and is simultaneously influenced by race/ethnicity.[80]
- Mobility decreases as people age, both in terms of commute time [81] and the number of trips taken.[82] The research is mixed on the impact of age on driving and transit use.[83]
- Overall, men travel further and longer than women, especially when commuting to work.[84] Women make more daily trips than men but the research is mixed on the relationship between gender and mode choice.[85] The effect of gender is complicated by the effects of other characteristics such as race and ethnicity, household responsibilities, and residential location.[86]
- Minorities travel shorter distances, have longer commutes, use transit more, and have lower rates of car ownership than non-minorities.[87]

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79 Giuliano, 2003; Van Acker, *et al.*, 2007

80 Giuliano, *et al.*, 2001

81 Giuliano, 2003; Doyle and Taylor, 2000

82 Pucher and Renne 2003; Collia, *et al.* 2003

83 Cao, *et al.*, 2009a; Chatman, 2003; Chen, *et al.*, 2008; Cervero and Kockelman, 1997; Doyle and Taylor 2000; Giuliano, *et al.*, 2001; Kim and Ulfarsson, 2004; Polzin, *et al.* 1999; Rajamani, *et al.* 2003; Schimek 1996; Handy and Tal, 2005

84 Giuliano, 2003; Crane, 2007

85 Boarnet and Crane, 2001; Boarnet and Sarmiento, 1998; Doyle and Taylor, 2000; Guo, *et al.* 2007

86 Crane and Takahashi, 2009; Doyle and Taylor, 2000; Rosenbloom, 2006

87 Crane, 2007; Doyle and Taylor, 2000; Giuliano, 2003; Guo, *et al.* 2007; Pucher and Renne, 2003; Taylor and Ong, 1995

- Foreign-born residents are less likely to drive than U.S.-born residents,[88] but their likelihood of driving increases the longer they live in the U.S.[89]
- Household structure impacts travel behavior but the findings vary with the number of people and the age of children in the household. In general, households with more children take more household trips and drive more.[90]

5. Summary and Areas for Further Research

The relationship between residential density and the climate is complex and characterized by inter-relationships that researchers are still in the process of disentangling. On the surface, there is a clear correlation between residential density and GHG emissions. But whether lower residential density itself is causing higher GHG emissions is far murkier. This review of nearly 200 studies demonstrates that this relationship is affected by at least a dozen factors. Although newly emerging research approaches are beginning to clarify the relationship, more studies using these approaches are necessary.

Researchers long assumed that characteristics of the built environment, such as density, the mix of land uses, transit availability, and neighborhood design have a causal impact on travel behavior, the source of a significant share of the nation's GHG emissions. More recently, researchers have re-considered the direction of causality and acknowledge that land use patterns may facilitate travel behavior but not cause it. More specifically, personal attitudes and preferences for travel may be a more important predictor of travel behavior than the built environment. The implication is that studies that ignore the impact of self selection are likely to overestimate the influence of characteristics of the built environment on travel behavior, although the question about the magnitude of this effect is not settled, and more research about the appropriate methods for correcting this bias is needed.

More research is also needed on the magnitude of the impacts of the built environment on travel behavior. More recent research suggests that the impacts of the built environment on travel behavior are modest. Some estimates are in the range of 5 percent reductions in VMT for large changes in particular changes in the built environment (such as doubling residential density or making large investments in rail transit) are typical. However, some researchers point out that in combination, mixed-use development, increasing density, improved transit availability, and changes in neighborhood design such as improved accessibility could reduce VMT by 25 to 30 percent. Others argue that such significant changes in the built environment are hard to achieve, making them poor levers for influencing travel behavior.

Few studies include the impact of travel cost—either in terms of time or money—on travel behavior, but those that do conclude that pricing may play a more important role in explaining travel behavior

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88 Chatman and Klein, 2009

89 Handy and Tal, 2005

90 Shay and Khattak, 2007; Chen, *et al.*, 2008

than characteristics of the built environment. They conclude that changes in policies that affect the monetary or time cost of car ownership and use—such as increases in gas taxes or the price or availability of parking and the supply of roads—are more effective in changing travel behavior than any other policy. If policy makers find these types of economic incentives to be unpalatable, they suggest that increasing the supply of transit or implementing policies that change land-use patterns are a distant second-best alternative.

The research is clear on an important methodological issue: few studies are sufficiently comprehensive to explain travel behavior. To be complete, analysis of travel behavior should include not just characteristics of the built environment, but also income and demographic characteristics of households, variables related to the cost of travel, individual attitudes that affect people's predisposition for certain travel behaviors, and the availability of transit.

Appendix. Research on Factors Relating to Density and Climate Change

Appendix Table of Contents

Introduction

Concerns over the possible consequences of climate change have resulted in vigorous debate over virtually all aspects of human activity, from the way we eat, work, and travel, to the way we house ourselves. Noticing a link between housing patterns and travel behavior—and between travel behavior and greenhouse gas emissions—many state and local officials have encouraged or required higher-density residential development in well-intended efforts to slow climate change.

A link between higher-density housing and the number of miles traveled by residents of the housing is intuitively appealing. Much of the vast volume of research conducted on the topic of residential density and its relationship to travel shows that there is such a link. However, the relationship between residential development patterns and climate change is not as simple or as causal as "higher-density development equals lower greenhouse gas emissions." Rather, it is a complex set of interactions between density and other factors that affect the number of vehicle miles traveled (VMT), such as socioeconomic characteristics of residents, the availability of public transit, neighborhood accessibility to jobs and services, the time and cost associated with various forms of transit, and many other factors.

Indeed, the decision to encourage or require higher-density residential development is more complex still, because an effort to reduce greenhouse gas emissions is only one reason for favoring a particular development pattern. Other important features of residential development include the affordability of the homes, their appeal, the cost of production, the privacy they provide, and the comfort and protection they offer to the residents of the housing.

This review of literature on residential density and its relationship to climate change—largely via its relationship to travel behavior—is intended to help inform this aspect of the debate on climate change by summarizing and synthesizing the literature in 12 key areas.

The report begins in Section 1 with a discussion on the relationship between density and travel behavior and home energy use. In Section 2, literature on three characteristics of neighborhoods that influence the relationship between density and travel behavior are reviewed. These are neighborhood design, mixed use development, and transit availability. In Section 3, transit efficiency from a greenhouse gas perspective is reviewed to provide some context on the relative energy use of public transit and private auto travel.

Then several topics related to transportation and land-use trends are reviewed in Section 4. These include employment decentralization trends; trends in work versus non-work trips; trends in personal vehicle versus commercial truck traffic; trends in two-worker households; and the demographics and income of neighborhood residents (including the role of personality and attitudes). The last section of this review identifies major conclusions and some areas for further research.

1. Density's Relationship with Travel Behavior and Energy Use

This chapter reviews the literature to address three ways in which density and energy use are related. First, the influence of density on travel behavior is considered. Density influences travel behavior along several different pathways. People take non-work trips, which comprise the large majority of both trips and VMT, in order to engage in activities such as personal business, shopping, socializing, and recreation. Travel is an important part of the decision to engage in these activities, and density influences these decisions in at least three ways. Density affects the quality of the travel experience (particularly for walking), the distance required to access activities, and the price of travel, both in terms of time and money.

S*elf selection* is an important methodological issue that affects all studies of the relationship between travel behavior and the built environment. That is, many studies observe correlations between characteristics of the built environment and travel behavior, and assume that these characteristics *cause* the travel behavior. More recently, researchers have recognized that people who dislike driving may self select to live in walkable neighborhoods with convenient access to transit, while people who like driving may be more likely to select neighborhoods with good auto accessibility. Research indicates that studies that ignore the impact of self selection are likely to overestimate the influence of characteristics of the built environment on travel behavior, although the question about the magnitude of this effect is not settled.

After the review of the literature on the relationship between density and travel behavior, a profile of the density required to support different types of transit is provided. This shows that rail transit requires very high density and that buses are feasible with lower density but are not as highly preferred by transit users. Further, density at both trip origins (generally residential locations) and destinations (typically employment centers) are important. Last, the review of literature on how density affects home energy use indicates that even without influencing travel patterns, residential density may influence climate change.

1.1. The Influence of Density on Travel Behavior

As a starting point for understanding the *factors* that influence the relationship between residential density and travel behavior, it is useful to recall that the demand for travel is mostly derived from the demand for other goods and services. Although some people travel simply to enjoy the experience of traveling,[91] the large majority of traveling is done to engage in activities outside the home. The decision to engage in non-work activities in particular is importantly affected by the time and costs associated with travel. According to Chatman (2005), density influences the quality of the travel experience (particularly for walking trips); the distance required to access activities; and the price of travel in both time and money.

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[91] See, for example, Mokhtarian and Salomon, 2001.

Although much of the literature has a focus on residential density, other measures of density also have a significant impact on travel decisions. Many studies use measures of density both at the household's residential location and at the destination of the trip to predict travel behavior. These measures include employment density (e.g., number of jobs per acre), residential density (e.g., number of households per acre), and population density (e.g., number of people per acre), or the very generic "development density" (e.g., residents or employees per acre), all of which are considered in this section.

There are unresolved issues, but the current consensus of the literature is that residential density does have an influence on travel behavior, but that the magnitude of the influence is small. The findings of Ewing and Cervero (2001) are not unusual. They find that doubling neighborhood density (a 100 percent change) is expected to result in approximately a 5 percent reduction in both vehicle trips and VMT, all else equal. With other built environment changes, however, the combined impact might be much larger.

An important question then, is how difficult would it be to achieve residential densities double their current levels? In areas with low densities, this could be a simple matter of adding a small apartment building. In areas with higher densities, this could be quite difficult. Although it is beyond the scope of this literature review to answer this question, a few statistics from Portland, Oregon, an area known for its urban growth boundary, are informative. Between 1970 and 2000, the central county in the metropolitan area increased in density by about 19 percent. The suburban county more than doubled in density over this period, with an increase in population per square mile of 119 percent (McGuckin and Srinivasan, 2003). It appears that even with a concerted effort to increase densities in the center of a metro area, it is very difficult to double density. Doubling suburban densities is far more achievable, given the relatively small increase in population required.

The literature reviewed in this section highlights the fact that the methodology used to estimate the relationship between residential density and travel behavior matters a great deal. In particular, a complete set of controls for other factors that influence travel behavior is essential, including sociodemographic characteristics of travelers, transit availability, the price of travel (e.g., congestion and the availability of parking) and accessibility to destinations such as jobs, services, and recreation.

The levels of geography over which density and other land-use characteristics are measured also appear to be important, as well as the precise measure of density. For example, population density measured at the zip code level may mask important variations in density over the area. In addition, *net* residential density (which excludes land area devoted to industrial and other non-residential uses) is a more precise measure of residential density than *gross* residential density, although the latter is more common.

Last, much of the research on the relationship between the built environment and travel behavior acknowledges that self-selection may be confounding the influence of land use. That is, people choose to live in walkable, transit-oriented neighborhoods because they prefer not to drive, and that preference motivates their travel behavior rather than the built environment itself. Regardless, many studies do not properly account for the choice of neighborhood—such as through the appropriate variables, data, or statistical techniques—to correct for self-selection bias. Therefore, features of the built environment may appear to influence travel behavior more than they actually do (Handy, 2006).

A few studies find that some measure of density is the single most important factor influencing travel. More often, however, studies that carefully control for a variety of factors that accompany density find the influence of density is diminished. According to Handy (1996), "Many studies focus on density, but is it density that matters? No, probably not. Probably what matters is what goes along with density: shorter distances to activities, better transit service, and other sorts of characteristics."

Is it important whether it is density that matters, as long as density correlates with characteristics that do matter? According to Chatman (2008), the distinction has important policy implications. He points out that for historical reasons, road capacity, development density, accessibility, and pedestrian or transit-oriented design are highly correlated across urban areas. However, these characteristics are *not* always correlated in new development. Chatman concludes: "Research failing to control for each [characteristic] may erroneously conclude that high-density developments will reduce auto use, when whether this will happen is clearly dependent on the particular details and context of development." Importantly, compact or smart growth developments that supply higher levels of road capacity than, for example, central city neighborhoods, are likely to produce disappointingly small impacts on VMT.

In addition, much of the research finds that density at the destination is more important than at the origin of the trip in influencing travel decisions. Ewing and Cervero (2001) go so far as to say, "… for both transit and walk modes, employment densities at destinations are as important, possibly more important, than population densities at origins. In this sense, the preoccupation of the transit-oriented design literature with residential density and neighborhood design may be misguided."

This review of the literature is organized according to the type of behavior studied. Studies analyzing density's influence on VMT and number of auto trips are discussed first, followed by studies of mode choice, and then other behaviors affected by density including car ownership decisions (number and type of vehicles) as well as trip chaining.

Key Findings

- A variety of measures of density are used in analyses of travel behavior. In addition to residential density (often measured as households per geographic area), other measures of density include employment density (e.g., number of jobs per area), and population density (e.g., number of people per area). Several different levels of geography are used to measure these types of density: census block groups, census tracts, zip codes, acre, square mile, and even metropolitan area.
- The weight of the evidence suggests that residential or population density has an impact on VMT, vehicle ownership, and mode choice, but that the impact is quite small. For example, a meta-analysis of 14 studies finds that doubling neighborhood density is expected to result in approximately a 5 percent reduction in both vehicle trips and VMT, all else equal.
- Although the impact of density in isolation is small, the combination of higher density with other changes in neighborhood and regional characteristics, such as improved

accessibility, increased land-use mix, and more pedestrian- and bike-friendly neighborhood design characteristics have a larger impact on travel behavior.

- Socioeconomic factors are generally more important predictors of travel behavior than density.
- Employment density at work is more important for reducing the share of commutes made by single occupant vehicle than residential density.
- Network load density—a type of density that is relatively unstudied—may have important impacts on auto trips through its effect on the price of auto travel: higher network load density results in reduced auto speeds, raising the costs of auto travel in terms of time spent traveling.
- The context of residential density is important: islands of residential density in a sea of low density development have less impact on travel behavior than high-density development that is closer to the CBD and is surrounded by relatively dense development.

The Built Environment, Travel Behavior, and Self Selection

S*elf selection* is an important methodological issue that affects all studies of the relationship between travel behavior and the built environment. That is, many studies observe correlations between characteristics of the built environment and travel behavior, and assume that these characteristics *cause* the travel behavior. More recently, researchers have recognized that the relationship is more complex, because household decisions about residential location—and all the characteristics of this location—are simultaneous with decisions about travel behavior. That is, people who dislike driving may self select to live in walkable neighborhoods with convenient access to transit, while people who like driving may be more likely to select neighborhoods with good auto accessibility.

Research indicates that studies that ignore the impact of self selection are likely to overestimate the influence of characteristics of the built environment on travel behavior, although the question about the magnitude of this effect is not settled. At least nine different methods have been used to correct for self selection. One method is to use instrumental variables to first predict residential location of individuals before modeling the impact of the built environment on travel choices. Studies using this method have somewhat inconsistent findings—the effect of the built environment is weak in some studies and strong in others. A second method is to directly include variables that capture people's predispositions to drive or take transit. Most that include these variables find that they explain a great deal of the variation in travel behavior, and suggest personality/attitudes toward driving and transit may be more important than characteristics of the built environment.[92] Other methods include longitudinal analysis, propensity score stratification, and direct questioning.[93]

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[92] See for example Bagley and Mokhtarian, 2002; Cao, *et al.*, 2007b; Van Acker, *et al.*, 2007; and Kitamura *et al.*, 1997.

[93] For a thorough discussion of the methods used to correct self-selection bias, see Cao, *et al.*, 2008

Researchers' findings about the impact of self selection vary based on the methodology used. For example, one study finds no impact of the built environment on auto ownership when personality/attitudes are included in the analysis, but finds an impact using a quasi-panel model that controls for self-selection by asking respondents to report changes in travel behavior following a move to a different residential area.[94] The best method is considered to be a longitudinal analysis to observe how individuals respond to changes in their environment, but these are expensive and difficult to administer, and therefore rare. Among the remaining methods, it is not clear which are most reliable.

Regardless, virtually all studies that account for the impact of self selection show that there is an independent effect of the built environment on travel behavior. However, the weight of the evidence indicates that the measured influence of the built environment is diminished once the impact of self-selection is taken into account.[95]

The size of the potential impact of changes in the built environment may depend in part on whether there is unmet demand for the high-density, walkable neighborhoods that are associated with lower auto ownership and VMT. If there is – perhaps because of local zoning restrictions that tend to encourage low density residential development – then neighborhood choices that better match consumers' preferences could indeed result in sizeable reductions in VMT.[96] Other research suggests that preferences can change over time, and that some people who live in high-density neighborhoods because of an initial lack of alternatives may eventually adopt attitudes that are more consonant with the environment, reinforcing travel behavior suitable to these neighborhoods.[97]

Density's Influence on VMT and Auto Trips

Newman and Kenworthy (1989) launched the debate on the influence of density on travel behavior with their international study that demonstrated a correlation at the metropolitan area level between higher densities and lower gasoline consumption. Their data suggest that doubling density reduces driving by 30 percent. A number of criticisms have been made about their study—including the fact that they compare whole metro areas rather than smaller geographies—and dozens of studies have sought to improve on it (such as Kenworthy, *et al.*, 1999), including those discussed below.

Aggregate travel studies—those that use region-level behavior and socioeconomic controls rather than household-level data are discussed first. Meta-analyses, which synthesize the results of many studies, are reviewed next. These are followed by simulation studies and then disaggregate travel studies. The studies are unanimous in concluding that density has a statistically significant effect on travel behavior, even controlling for socioeconomic and other factors. The findings of the aggregate travel studies are mixed with regard to the magnitude of the effect, but the disaggregate travel studies agree that the magnitude of the impact of density on VMT and auto trips is small.

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94 Cao, *et al.*, 2007b

95 Cao, *et al.*, 2009.

96 Bailey, 2008; Chatman, 2009; Levine, 2006; Stone, *et al.*, 2007; and Cao, *et al.*, 2009

97 Transportation Research Board, 2009

Aggregate Travel Studies

Aggregate travel studies, as a group, suffer from some common problems. The most important of these is that the reliance on MSAs as the unit of analysis limits their ability to explain the causes of the observed correlations, because the aggregate data masks a great deal of variation within MSAs and at the household level. It is also not entirely clear what the policy implications of aggregate travel studies are. If travel behavior is largely determined by socioeconomic characteristics, for example, the role for transportation policy is quite limited. In general, aggregate travel studies are considered to be less convincing than disaggregate travel studies because of the latter's superior ability to explain the relationship between individual behavior and the built environment.

Like Newman and Kenworthy, some studies identify residential density as one of the most important factors explaining travel behavior. Holtzclaw, *et al.*, (2002) identify neighborhood[98] residential density (households per residential acre), average per capita income, average family size, and the availability of public transit as the most important factors explaining auto ownership and VMT. They use data from Chicago, Los Angeles, and San Francisco, and find magnitudes of the impact of density that are roughly on the order of those identified by Newman and Kenworthy.

Their findings are weakened by the extremely limited aggregate socioeconomic controls, which include only per capita income and average persons per household. Other researchers have found household income, gender, number of workers per household, and age to be important predictors of various aspects of travel behavior. As a result, the estimated influence of density on travel behavior may be attributable to the omitted household-level socioeconomic variables rather than density to the extent these omitted factors may be correlated with density.

Van de Coevering and Schwanen (2006) directly build on work by Newman, Kenworthy, and their co-authors, in an international study comparing density and travel behavior in 31 cities in the U.S., Canada, and Europe. Among other aims, they seek to improve on Newman and Kenworthy and other related work by taking into account the fact that travel patterns in a city are the outcome as well as a context for individuals' housing, employment, and leisure. They compare travel behavior in the cities, controlling for population and employment density, population and employment centrality (a measure of the strength of the CBD), transport service level, housing (tenure and dwelling size), urban development history (proportion of buildings built before 1945, from 1945-1970, and since 1971), and sociodemographic factors.

They find that the urban form variables are relevant to travel behavior—distance traveled by private car and by public transit, commuting distance, commuting time, and commuting mode choice—although socioeconomic variables are typically more important. Residents of cities with higher population densities in the CBD travel fewer miles by private car, higher employment densities in the CBD are associated with more miles traveled by public transit, and a higher percentage of jobs in the CBD lead to shorter average commutes in terms of distance but longer average commute times. Last, a higher population density is associated with a smaller share of car trips and more walking/bicycling trips.

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[98] Land-use variables are measured for travel analysis zones, which are typically small area neighborhoods or communities that serve as the smallest geographic basis for travel demand forecasting.

More interesting, however, is their finding that land-use characteristics of the central city—the part built before World War II—may be more directly associated with travel patterns than metropolitan population density. Based on this, they conclude that historical development conditions matter to travel patterns. Further, they find large regional differences in the effects of explanatory variables. According to the limited set of cities in their data, they find for example that population density has little effect on VMT in the U.S. but a larger impact (by an order of magnitude) on VMT in Canadian and European cities. Similarly, the influence of employment density in Canadian and European cities is more than twice as large as its influence in U.S. cities. They speculate that this may be true because of the much lower densities in the U.S. than in Europe: the average metropolitan population density is more than three times lower and the proportion of the metropolitan population residing in the inner area is 1.6 times lower in the U.S. than in Europe. Along with these existing low levels of density is higher reliance on cars and a greater predisposition to use cars. Although Van de Coevering and Schwanen do not consider price factors, it may also be the case that the relative price of travel options—such as differences in gas taxes—also plays an important role.

Van de Coevering and Schwanen conclude that these regional variations suggest that it may be inappropriate to apply a single model of the future sustainable city everywhere. Instead, they suggest taking that a strong focus on the traditional urban core, high densities, and development along rail corridors may be more appropriate in Europe than in the U.S., where in many cities an emphasis on providing sufficient and affordable housing in mixed-use, medium-density neighborhoods with good road access to suburban employment may be more successful.

Ewing, *et al.*, (2002) examine density indirectly, as one input into an index measuring the degree of sprawl in 83 of the largest urban areas in the United States. The other factors used to define sprawl include the neighborhood mix of homes, jobs, and services; the strength of centers (measured by the density at the center of the metro area); and accessibility via street networks. The density factor itself is a weighted combination of seven variables including gross population density, net population density (which excludes industrial and other non-residential uses), and weighted average lot size for single-family dwellings.

They regress each of several possible outcomes of sprawl on the sprawl index and a set of control variables. The outcomes include the percentage of commuters using public transportation, the percentage of commuters walking to work, the mean journey-to-work time in minutes, annual hours of delay per capita, daily VMT per capita, annual fatal highway accidents per 100,000 persons, and a measure of air quality. The control variables include per capita income, metropolitan area population, average household size for the metro area, percentage of population of working age in the metro area.

Doing this, they find that sprawling places have higher rates of driving and vehicle ownership, a lower share of commute trips via public transportation, and fewer walking trips than more compact places. Examining each factor included in the sprawl index separately, they also find that the density factor has a significant inverse relationship with average vehicle ownership, VMT per capita, traffic fatality rate, and maximum ozone level. It also has a significant direct relationship to transit and walk shares of commute trips. They find no significant differences in congestion delays between more and less sprawling places. In terms of its relationship to the other factors, the authors find that density

alone is associated with a nearly one-half vehicle difference per household between high- and low-density areas.

Meta Analyses

Leck (2006) conducts a meta-analysis of the impact of urban form on travel behavior that includes 17 primary studies in total. Not surprisingly, one of the difficulties of meta-analysis is the variety of measures of travel behavior used in various studies in addition to different measures of density (gross residential/population and gross employment). As a result, a small subset of the 17 studies is relevant to each dependent variable. The meta-analysis finds that residential/population density is a significant built environment element influencing VMT (3 studies), vehicle hours traveled (2 studies), and vehicle trips (2 studies), and commute mode choice (up to 6 studies). He also finds that employment density is also important in predicting VMT (2 studies), vehicle trips (2 studies), and commute mode choice (2 studies). The study does not attempt to estimate the magnitude of the impact of the built environment on travel behavior.

Two meta studies by Ewing, Cervero, and their colleagues, however, do focus on assessing the magnitude of the impact of neighborhood characteristics (including density) on travel behavior. The first, by Ewing and Cervero (2001), synthesizes 14 travel studies by computing elasticities—or responsiveness—of VMT and vehicle trips with respect to density (a variety of measures including gross population density and employment density), diversity (e.g., jobs/population balance), design (sidewalk completeness, route directness, and street network density), and destination accessibility (distance from specific destinations).

Exhibit 1.1-1 shows these elasticities, which are the expected percentage change in the travel behavior measure associated with a 1 percent change in the built environment variable. For example, doubling neighborhood density (a 100 percent change) is expected to result in approximately a 5 percent reduction in both vehicle trips and VMT, all else equal. The elasticity of VMT with respect to regional accessibility (e.g., access to particular regional centers) is by far the largest, on the order of four times larger than the elasticities of density, land-use mix, and design on VMT. The latter are all quite small, but positive.

Exhibit 1.1-1. Typical Elasticities of Travel

	Vehicle Trips	Vehicle-Miles Traveled (VMT)
Local density	0.05	0.05
Local diversity (mix)	0.03	0.05
Local design	0.05	0.03
Regional accessibility	–	0.20

Source: Ewing and Cervero, 2001

Ewing and Cervero emphasize that these elasticities are additive. That is, doubling all four characteristics of the built environment would be expected to reduce VMT by about a third.

Ewing, *et al.*, (2008) review a variety of planning literatures and conclude that compact development—a combination of increases in density, infill development, mixed land uses, and transportation investments coordinated with land uses—could lead to a 20 to 40 percent reduction in VMT compared to sprawl. About 5 percent of this comes from doubling density; the remainder of reduction comes with combining this with changes in land use diversity, neighborhood design, and destination accessibility. The literature also suggests that the reduction in VMT from compact development could result in a 7 to 10 percent reduction in total U.S. transportation carbon dioxide emissions by the year 2050. The authors conclude that, given these and other benefits of compact development—such as improved quality of life and other economic and environmental benefits—the reduction in CO_2 emissions that can be achieved through land-use planning is worth the effort.

Ewing is also the lead author of *Growing Cooler* (Ewing, *et al.*, 2007), which uses the results of aggregate analysis, disaggregate analysis, and regional simulation studies to estimate the impact of compact development on CO_2 emissions by 2050. Their result is essentially identical to Ewing, *et al.*, (2008): a combination of increases in density, infill development, mixed land uses, and transportation investments coordinated with land uses—could lead to a 20 to 40 percent reduction in VMT compared to sprawl, and this could reduce total transportation-related CO_2 emissions from current trends by 7 to 10 percent in 2050. In comparison, a doubling of the price of fuel would reduce CO_2 emissions by 8 to 11 percent.

Moving Cooler, a study by Cambridge Systematics (2009), takes a broader look at the potential magnitude of the impact of a variety of strategies to reduce greenhouse gas emissions. It also finds that the impacts of changes in neighborhood design are modest and benefits are slow to materialize because the built environment is long lasting. For the same reason, the benefits are also long lasting.

The land use and smart growth strategies assessed include adopting growth boundaries around urban areas; minimum targets for the share of new development in high-density areas that include mixed-use development as well as pedestrian-, bicycle-, and transit-friendly features; zoning and planning standards that support such high-density areas; and incentives for agencies (such as planning and implementation grants) to help achieve these types of objectives.

In addition to land use and smart growth strategies, other strategies analyzed include pricing and taxes; nonmotorized transport; public transportation improvements; ride-sharing, car-sharing, and other commuting strategies; regulatory strategies; operational and intelligent transportation system strategies; capacity expansion and bottleneck relief; and multimodal freight sector strategies.

The authors project that at "maximum effort deployment" (at least 90 percent of new development in compact, pedestrian- and bicycle-friendly neighborhoods with high-quality transit), land use and smart growth strategies could achieve annual GHG reductions of 4.4 percent from the baseline by 2050. At aggressive deployment (at least 64 percent of new development in such neighborhoods), they project that the combined land-use strategies could achieve GHG reductions of 2.7 percent from the baseline.

However, the authors project that combining most of the strategies assessed for the study could achieve annual GHG emission reductions of up to 24 percent less than projected baseline levels in 2050 (under a maximum effort deployment scenario).

Moving Cooler is different from some of the other meta-analyses in this section. Although it combines results from several different studies, GHG emissions reductions related to land-use strategies are largely from one source, which is Polzin *et al.*'s (2007) VMT forecasting model that predicts the relationship between neighborhood density and VMT (high density is a proxy for smart growth development).

In comparison with Moving Cooler's findings that annual GHG emission reductions of up to 24 percent could be achieved by 2050, a scenario developed by the Transportation Research Board (2009) in its study *Driving and the Built Environment* suggests that a combination of policies would have more modest impacts – in the range of 1 to 11 percent reductions in fuel use and CO_2 emissions by 2050. They assume that compact development is focused on new and replacement housing because of the difficulty in increasing the density of existing housing. They base their projections on the number of new and replacement housing units needed to accommodate the population, the percentage of new housing developments that will be built compactly (at double the current density of new residential development), and how much less residents of more compact developments will drive.

The upper-bound scenario, which assumes that 75 percent of new and replacement housing units will be in compact developments and that residents of compact communities will drive 25 percent less, results in annual 8 to 11 percent reductions in fuel use and CO_2 emissions by 2050. A moderate scenario that assumes that 25 percent of new and replacement housing units will be in compact developments and that residents of these new communities will drive 25 percent less results in reductions in fuel use and CO_2 emissions of about 1.3-1.7 percent by 2050. One critique of this scenario is that it considers only increases in the density of residential housing, and not commercial development, which could have an important impact on VMT, fuel use, and CO_2 emissions (Ewing, 2009).

Disaggregate Travel Studies

The disaggregate travel studies generally find that density matters, but not very much. For example, Schimek (1996) uses national data and finds that income is about twice as important as residential density in predicting VMT. Specifically, each 10 percent increase in density is associated with a 0.7 percent decrease in VMT per household per year. His study includes controls for income and demographics as well as transit availability, all of which are correlated with density. Schimek deals with the simultaneity of the decision between residential location and travel by using a regression including city size, an indicator for a nonwhite household head, an indicator for a Hispanic household head, and an indicator that a household is located in the New York City SMSA as an instrument for population density.

Importantly, Schimek finds that the effect of density on vehicle ownership (the indirect effect) is larger than its effect on distance traveled (the direct effect). In fact, the direct effect is only half as great as the indirect effect. This finding underscores the importance of vehicle ownership as a mechanism for the effect of the independent variables on vehicle use (e.g., VMT).

Using data from California, Brownstone and Golob (2009) also find that density directly influences vehicle usage, and that the effect is small. Comparing two households that are similar in all respects

except residential density, they find that a household located in a neighborhood at a lower density (roughly 40 percent of the sample average) would drive almost 1,200 more miles per year and use about 65 more gallons of gas than a household at the average density (measured in housing units per square mile). They find that the effect of lower density on fuel usage results from both increased mileage (which accounts for 45 gallons of fuel) and lower fleet fuel economy (which accounts for the remaining 20 gallons). The lower fleet fuel economy is attributable to vehicle choice including the greater number of SUVs, vans, and pick-up trucks in lower-density areas. Given the difficulty of increasing population density by 40 percent and the size of the impacts, the authors conclude that increasing density is not an effective policy tool.

Like Van de Coevering and Schwanen (2006), Buehler (2009) compares travel behavior between countries. He investigates the role of socioeconomic and demographic factors, spatial development patterns, and transportation policies in explaining differences in travel behavior between Germany and the U.S.—both of which have high rates of auto ownership. Socioeconomic and demographic factors, as a group, are more important than spatial development patterns and transportation policies in explaining travel behavior. However, population density and automobile operating costs both play a role in travel behavior after controlling for socioeconomic factors.

In terms of the magnitude of the impact of density, he finds that doubling population density is predicted to reduce daily car travel distance by 2.7 km in U.S. In comparison, a one cent increase in the operating cost of car use (from 4.2 cents per km to 5.2 cents per km, about a 24 percent increase) reduces daily car travel distance by 2.4 km. These findings suggest that car travel in the United States is more responsive to changes in the price of travel than to changes in density.

Density's Influence on Mode Choice

The consensus of the literature is that density is significantly positively related to non-driving mode choices (transit and walking), but there is disagreement about the magnitude of the effect. There is also some evidence that employment density at the trip destination matters more for mode choice in work trips than other measures of density (such as population density at the trip origin), and that the relationship between density and mode choices may be non-linear.

Frank and Pivo (1994) use data from Puget Sound in Washington and find that population and employment density (measured at the census tract level) and land-use mix are both related to mode choice for work and shopping trips. As density and land-use mix increase, transit use and walking increase and single-occupant vehicle use decreases. Walking trips were more sensitive than the other two mode types to increases in population density, and single-occupant vehicle travel was more significantly associated with employment density than population density.

Interestingly, they find that the relationship between mode choice and employment density is nonlinear. They identify two thresholds of employment density: significant mode shifts occur from single-occupant vehicle to transit and walking with employment densities between 20 and 75 employees per acre, and again with more than 125 employees per acre. They also found a nonlinear relationship between mode choice and population density for shopping trips. The authors suggest that these findings indicate that policies that encourage employment densities to increase from 75 to 125 employees per acre will have little effect on mode choice.

Although Kockelman (1997) also found that density was significantly related to mode choice, she found that its impact was negligible after controlling for accessibility. This suggests that much of the influence of density observed in other studies may be attributable to its role as a proxy for other neighborhood characteristics. Based on data from the San Francisco Bay Area, Kockelman finds that accessibility, land-use mixing, and land-use balance (all measured using hectare-level data) are highly statistically significant and more influential in their impact on mode choice than density (per acre). Her findings suggest that local characteristics of the built environment are more important for auto ownership, but that VMT and vehicle trip distances are influenced by characteristics of the community and region. Therefore, she suggests including both local and regional variables in models of travel behavior.

Unlike other studies, Kockelman finds that population density is more useful than jobs density in determining mode choice.[99] However, in the personal vehicle mode choice model, job density was significantly, inversely related to the decision to choose the personal vehicle mode (although the impact was marginal). In terms of magnitude, Kockelman estimates that a 10 percent increase in population density will decrease auto ownership by 0.7 percent, and decrease the personal vehicle mode choice by about 0.1 percent.

Studying Montgomery County, MD, an area just outside of Washington, D.C. that has extensive public transit options, Cervero (2002) finds that density[100] encourages transit use. Further, density at the trip destination is more important than density at origin in predicting the choice to select the "drive alone" mode for work trips. Estimated elasticities, or the percentage change in the probability of selecting a mode with a change in density, suggest that increasing density by 10 percent at trip destinations would reduce the probability of choosing to drive alone by about 2.6 percent.

Dargay and Hanly (2004) also find that population density plays a significant role in car ownership and mode use, within limits. Using data from Great Britain, they find that the share of trips taken by public transit is higher in the highest density areas (the highest quartile, which is 40 or more persons per hectare) than in lower-density areas, but there is no statistically significant difference in public transit shares between the remaining areas. However, the generalizability of their results to the U.S. may be limited because their data are from Great Britain. Research by Van de Coevering and Schwanen (2006) discussed above suggests that there are regional variations in the responsiveness of travel behavior to land-use characteristics, and that U.S. cities have lower responsiveness than cities in other parts of the world.

Zhang (2004) studies the impact of land-use patterns—including both population density and employment density at the origin of the trip and at its destination—on travel patterns in Boston. He finds that higher *population* density at trip origin and destination is associated with higher likelihood of using transit or non-motorized modes of travel for work trips, but is not significant for non-work

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[99] Mode choice models are based on binary dependent variables with logit model assumptions. The transit mode choice was not modeled separately.

[100] Density is defined as the total of population and employment divided by total square miles of the travel analysis zone.

travel. Higher *employment* densities at the trip destination (but not trip origin, which was not significant) increased the likelihood of non-driving modes for work trips. Again, the magnitude of the impact is small: the elasticity between driving probability and population density indicates that doubling Boston's current net population density would decrease driving probability by about 4 percent, all other factors being held constant.

Chatman's (2007) study focuses on transit-oriented developments in California (in the San Diego and San Francisco-Oakland-San Jose metro areas). He conducted a survey of people living and working near train stations, and found that the presence of transit was associated with more transit use. Overall, those living within a quarter mile of a rail station were three times more likely to commute via rail than those living farther away. Built form density (total workers and residents per developed acre) did not have a statistically significant impact on the number of trips by any mode made for non-work purposes. However, this measure had a strong negative association with VMT for non-work trips.

Importantly, Chatman also found that "population network load density," a measure of potential congestion, is the most important predictor of travel behavior. (See also Chatman, 2008.) It was significantly associated with slower auto speed, fewer non-work auto trips, and a lower share of auto commuting, even when controlling for transit accessibility, accessibility to downtown, socioeconomic characteristics, other built environment characteristics, and residential self selection based on self-reported attitudes towards travel. The finding is striking because network load density is not often included in studies of travel behavior, and suggests that previous research may suffer from omitted variable bias. The evidence here suggests that omitting this variable may result in overestimates of the impact of density on travel behavior.

Using data from the New York metropolitan region, Chen, *et al.*, (2008) assess the role of density in affecting mode choice decisions in home-based work tours and find that employment density at work is more important than residential density at the household location. They use four measures of density: population density at home and at work and employment density at home and at work. To control for residential self-selection bias, they use a multiple-endogenous variable equation system. Of the density variables, only employment density at work is found to be significantly inversely related to choosing to drive. They find that job accessibility at work via transit has a larger impact on deterring auto use than any measure of density, and both are more important than access to transit. They find that travel time and cost also matter, but are not as important as density in influencing mode choice. They conclude that simply increasing density will not change travel behavior, but can be effective if used in combination with job accessibility and access to transit.

Density's Influence on Other Behaviors

A great deal of research shows that travel behavior is complex. As will be discussed throughout this literature review, multiple factors affect travel behavior, including the built environment, the availability of transit, personal preferences and attitudes, and socioeconomic characteristics of travelers, among others. The large majority of studies, however, categorize travel behavior in fairly simple ways, measuring the choice to drive or take transit for a given trip, for example. Two additional complexities that are overlooked by these studies is the tendency of drivers to engage in trip chaining or to make different vehicle type choices in response to their environments.

Trip chains are travel tours that involve multiple destinations in one outing. They can be as simple as a stop for coffee on the way to work to much more complex tours involving stops at a variety of destinations such as the grocery store, dry cleaner, doctor, and library. Although it is clear that trip chains represent an increasing share of trips (see, for example, McGuckin and Srinivasan, 2005; and Levinson and Kumar, 1997), the implications of this trend are not entirely clear.

Some research suggests that trip-training is important for understanding mode choice decisions. For example, research indicates that unless the first trip in a chain is to work, the mode choice of a chain is determined by all the trips in the tour (Hanson and Schwab, 1986). Further, the complexity of a tour is found to have a negative influence on the decision to use transit (Henscher and Reyes, 2000 and Chen, 2008). Given that it more accurately reflects how people travel, Chen (2008) argues that it is important to use trip chains as the unit of observation, rather than a single trip, although this is rarely done.

Despite its importance, trip chaining is largely missing from studies of the relationship between travel behavior and land-use patterns. A study by Noland and Thomas (2007) is an exception. They demonstrate that residents of lower-density environments make more complex tours (e.g., tours having more stops) and rely more frequently on trip chaining than residents in higher-density environments. They found the most complex tours were made in medium-density (suburban) areas. They note that it is believed that trip chaining can be a relatively efficient means of accessing multiple destinations, although further research is needed to examine the relationship between trip chaining and total VMT.

A second often-overlooked complexity in travel behavior is household ***vehicle type decisions***. In particular, household decisions about where to live, what vehicles to choose, and how much to drive are all potentially made simultaneously, and travel behavior models must reflect this simultaneity in order to avoid obtaining biased results. Brownstone and Fang (2009) build on a model developed by Fang (2008), adding controls to treat residential density as endogenous (e.g., simultaneous with the vehicle choice decision). Specifically, they use the average density of the MSA as an instrumental variable. Using this approach, they find that an increase in density slightly reduces truck choice and utilization: doubling density reduces the likelihood of owning a truck by about 5 percent. However, doubling density reduces the *use* of trucks by 13.6 percent. Ownership of any vehicle is less elastic than truck ownership: doubling density reduces the likelihood of owning a vehicle by less than one percent.

Importantly, the combination of the effects of changes in vehicle ownership and use has a fairly large impact. Doubling density shifts vehicle ownership toward more fuel-efficient cars, and reduces the use of both trucks and (to a smaller extent) cars. The net effect is that the energy use of cars increases by a small amount (less than 2 percent) but the energy use of trucks declines by almost 41 percent. This amounts to a reduction in total vehicle gasoline consumption of 20 percent. Although energy use reductions of this magnitude are promising, the authors argue that large increases in density are unlikely to occur except in isolated developments.

The Context of Density

An important question for understanding how residential density affects travel behavior is whether context matters. Do isolated islands of residential density affect travel behavior, or does it need to be part of a larger region with relatively high densities? Cervero and Arrington (2008) compared transit-oriented developments (TODs) in five metropolitan areas and found that the context matters a great deal. Although the analysis is preliminary (it controls for few other built-environment characteristics or socioeconomic characteristics), it suggests that TODs in higher-density settings averaged lower trip rates than TODs in lower-density settings. For example, a TOD located 10 miles from the CBD with a surrounding residential density of 10 units per acre generates more than twice as many evening peak-period trips as one with a surrounding residential density of 20 units per acre.

They also found that the location relative to the CBD makes a difference. Their model predicts, for example, that a TOD located 5 miles from the CBD will generate about 30 percent fewer evening peak-period trips than one located 20 miles from the CBD.

These findings suggest that regional accessibility—a characteristic that is highly correlated with regional density—is important. Similarly, as discussed above, Ewing and Cervero (2001) find that VMT is much more responsive to regional accessibility than local density—regional accessibility's impact is about four times larger than the impact of local density. These findings are also supported by Kockelman (1997), also discussed above.

Regional characteristics are also important for predicting density's impact on mode choice. Several studies, including Cervero (2002), Zhang (2004), and Chen, *et al.*, (2008) find that in terms of mode choice density at the trip destination is more important than density at origin—reinforcing the notion that characteristics of destination locations are important factors in understanding the influence of density on travel behavior. Indeed, Chatman (2005) concludes that an exclusively small-area focus may be futile, because the density of the larger metro area represents the choice set of non-work activities for households who own autos, and therefore is more important.

1.2. Residential and Employment Density Requirements to Support Public Transit

The demand for and supply of public transit are interrelated: the demand for transit depends on its availability and level of service, among other things. On the other hand, the availability of transit is highly correlated with both residential and employment density because a critical mass of riders is needed to financially support the system. Sufficient levels of residential and employment density are also needed to provide the levels of ridership needed to ensure that transit is more energy efficient than auto travel.

A number of studies consider how much density is needed to support transit by calculating the density thresholds that provide enough passenger trips to make a transit stop economically viable. This section first reviews the literature published on both residential and employment density thresholds to support transit and then discusses additional factors that affect transit use, such as income, travel costs, individual attitudes toward travel, and characteristics of the built environment (the impact of

access to transit is discussed in the section on transit availability). The research makes it clear that relatively high levels of residential and employment density are needed to support a financially sound public transit system.

Key Findings

- Researchers acknowledge that higher densities provide a larger ridership base to support public transportation, but the exact threshold varies by area, transit type, and service level.
- Early research established a minimum residential density threshold of seven dwelling units per acre to support basic local bus service. This threshold was higher for more frequent bus service and for light rail and rapid transit, but was lower for commuter rail. Later research generally establishes higher minimum densities than this, perhaps because of population growth and changing development patterns.
- Higher employment density also increases transit ridership, although the required threshold varies by transit type.
- Other factors such as income, parking availability, and neighborhood design also affect the likelihood of taking transit. The interaction of decreased block size and increased density strengthen the impact of density on taking transit.

Residential Density Thresholds

Research beginning in the 1970s has established minimum thresholds for supporting transit, although later research suggests higher minimum thresholds. Some studies also find that the relationship between residential and employment density and transit ridership is nonlinear.

Early Studies of Residential Density Needed to Support Transit

Pushkarev and Zupan's (1977) seminal study was the first to establish minimum residential densities for cost-effective public transit. They establish a density threshold of at least seven units per acre to sustain basic bus service. They expand on these thresholds, shown below in Exhibit 1.2-1, in a later study (Pushkarev and Zupan, 1982 [cited by Seskin, *et al.*, 1996]).

Thresholds published by the Institute for Transportation Engineers (ITE) in 1989 (Meyer, *et al*., 1989) are similar to Pushkarev and Zupan's 1982 thresholds, and are widely cited. In this guide, the authors explain that transit systems are most productive "when density of development occurs linearly along a corridor, with heavy trip generators located at either end of the corridor, and other generators spaced along the corridor's entire length," where "trip generators" refer to residences or employment or other destinations. The authors develop density thresholds for various types of transit service to be cost effective. As shown in Exhibit 1.2-1 below, commuter rail requires the least amount of density (one to two dwelling units per acre), while frequent bus service requires the highest residential density (15 dwelling units per acre). According to ITE thresholds, different service levels require very different density thresholds. While a local bus that runs only once per hour only needs a residential density of four to five units per acre to be cost effective, frequent bus service (every 10 minutes) requires about three times that level.

Exhibit 1.2-1. Relationship between Residential Densities and Different Types of Transit Services

Boris Pushkarev and Jeffrey Zupan (1982) recommend the following densities (dwelling units per residential acre):	
Service Levels	**Density Thresholds**
Bus: minimum service, ½ mi between routes, 20 buses/day	4 dwelling unit/residential acre
Bus: intermed serv, ½ mi between routes, 40 buses/day	7 dwelling unit/residential acre
Bus: freq serv, ½ mi between routes, 120 buses/day	16 dwelling unit/residential acre
Light rail: 5-min peak headways	9 dwelling unit/residential acre, 25-100 sq-mi corridor
Rapid rail: 5-min peak headways	12 dwelling unit/residential acre, 100-150 sq-mi corridor
Commuter rail: 20 trains/day	1 – 2 dwelling unit/residential acre, existing track
The Institute of Transportation Engineers (1989) recommends the following minimums:	
1 bus/hour	4 to 6 dwelling unit/residential acre 5 to 8 million sq ft of commercial/office
1 bus/30 min	7 to 8 dwelling unit/residential acre 8 to 20 million sq ft of commercial/office
Lt. rail, feeder buses	9 dwelling unit/residential acre 35 to 50 million sq ft of commercial/office

Source: Holtzclaw, 1994

Later Studies Establish Higher Minimum Densities to Support Transit

However, several authors note the limitations of applying these thresholds to an urban landscape that has experienced, and still is experiencing, significant changes (Seskin, *et al.*, 1995, Messenger and Ewing, 1996). Messenger and Ewing (1996) examine work travel by bus in Metro-Dade County, FL and calculate a density threshold of 14.3 dwellings per acre to support bus service—than twice as large as that of Pushkarev and Zupan.[101]

More recent design guidelines of some transit agencies also indicate that it is appropriate to assume that higher densities are needed. Ewing (1997 [cited by Cervero *et al.* (2004)]) review 11 transit-oriented design developments across the United States and cites similar thresholds for basic and premium bus services as ITE, but finds much higher thresholds for rail services, of between 20 and 30 dwelling units per acre. Although these thresholds are from transit agency design guidelines, and are not based on research findings, this indicates that some transit agencies view the ITE thresholds as being too low (Cervero, *et al.*, 2004).

[101] Messenger and Ewing focus on bus travel because bus ridership is much higher than rail ridership in the County. In 1990, bus ridership exceeded rail ridership by a factor of more than 5 to 1.

Several studies find that the relationship between density and transit ridership is nonlinear. In a study of the San Francisco Bay area, Smith (1984, [cited in Seskin, *et al.*, 1996]) expands on Pushkarev and Zupan's threshold. Examining six U.S. metropolitan areas, Smith finds that when density increases from seven to 16 dwelling units per acre, transit use increases sharply. In the greater New York City area, this jump increases average weekday transit trips from 0.2 to 0.6 trips per person. Another study reports similar findings in an analysis of the Chicago area: a doubling of residential densities *more* than doubles transit use (Seskin, *et al.*, 1996).

Studying the San Francisco Bay area, Cervero *et al.* (2004) find that doubling residential densities near a transit station from 10 to 20 units per acre increases the likelihood that a station-area resident rail commuted from 24 percent to 43 percent. Quadrupling residential density from 10 to 40 dwelling units per acre increases the probability of commuting by rail to a surprising 67 percent.

Employment Density Thresholds

Some researchers find that employment density has a more consistent impact on transit use than residential density. Therefore, employment density thresholds may be more important in supporting public transit than residential density thresholds. Pushkarev and Zupan (1977), who created the original residential density threshold for transit, note that the effect of higher densities on transit trips is more effective if they connect residents to larger and denser nonresidential activity centers such as an urban downtown. High employment density near transit stations can create more concentrated work environments and more commercial activities that in turn create more destination opportunities for transit riders.

Several researchers document the levels of employment density at which transit use increases. Cervero (1993 [cited in Cervero *et al.* (2004)]) finds that the addition of 100 employees per acre is associated with a two percent increase in rail commuting. Frank and Pivo's research (1994) finds that the likelihood of a mode change—that is choosing to use transit (bus) or to walk for work trips instead of driving a single-occupant vehicle—increases substantially at two density points:

- At densities between 20 and 75 employees per acre, moderate shifts in mode choice occur.
- At densities of more than 125 employees per acre there is a significant jump in the choice to use transit or to walk over driving.

Based on these findings, the authors note that development with densities below 20 or between 75 and 125 employees per acre have little effect on mode choice.

As with residential density, research shows that higher employment densities are required for rail transit than for bus transit. A review of research on employment density thresholds conclude that bus transit requires 50 to 60 employees per acre and rapid transit (bus or rail) requires more than 60 employees per acre (Boudreaux, *et al.*, 2005).

Instead of looking at a threshold for transit, Newman and Kenworthy (2006) examine the effect of urban intensity, measured by both resident and jobs, on the decision to drive. The authors use long-

term data from cities around the world and find that an intensity of 35 persons per hectare, or about 14 residents or jobs per acre, significantly reduces auto dependence. Below that threshold, the authors find that the distance and time it would take to use alternative modes of transportation are too great and car use becomes "the norm," as in many of the new car-dependent suburbs that have densities of about 12 jobs/people per hectare.

Other Factors Affecting Transit Use

While residential and employment density are two of the most important factors affecting transit ridership, other factors also play a part, including income, travel time, and individual attitudes toward transit, as well as characteristics of the built environment, such as neighborhood design, land use mix, and walkability. A literature review of the topic cites the omission of these factors as a major limitation common to most of the studies that develop or discuss density thresholds to support transit (Seskin, *et al*, 1996).

A study of the Puget Sound region emphasizes that density thresholds alone will not guarantee transit ridership (Puget Sound Regional Council, 2004). Rather than establishing minimum density thresholds, this study takes the approach of considering a variety of **land use factors**:

> Evaluating support for high capacity transit is based on a range of factors, all of which are dependent on each other and/or interrelated. For example, increases in densities tend to vary with increases in mixed-use development, higher parking costs, and decreased parking availability. …. There is no magic number in any of the research in which high capacity transit becomes "supportable."

The study identifies both primary and secondary indicators related to land use that are needed to make judgments about whether the corridors can support high-capacity transit. The primary indicators identified are employment and residential density levels, set by the authors at a level between 30 and 45 residents and jobs per gross acre. The secondary indicators for land use included the following:

- Land use mix: measured by the ratio of jobs per household within an activity center
- Sufficient residential base: indicates level of residential activity that would support all-day transit travel as well as local commercial or recreational opportunities.
- Small average block sizes: indicates whether streets are pedestrian friendly
- Limited supply/high cost of parking: measures the ease and convenience of driving.
- Nearby dense, residential clusters: indicates sufficient population outside of activity center to take transit to activity center.

Cervero *et al.* (2004) also look at other **characteristics of the built environment** in combination with density. They find that density and neighborhood design positively interact with each other: when combined with small city blocks, higher residential densities increase transit use for commuting even more than when density is measured alone. Doubling residential density from 10 to 20 units per acre increases transit use from 20 percent to 24 percent of trips, but when combined with a decrease in average block size from 6 to 4 acres, transit use increased to 27 percent.

Consistent with the analysis of the Puget Sound region, an earlier study by Cervero (1994) finds that the strongest predictor of rail usage is whether residents living near stations have free parking at their place of work. Cervero finds that all else being equal, having free parking (whether it is free or paid for by an employer) decreases the likelihood of commuting by rail by about 40 to 50 percentage points. The **availability of parking** at a transit station may also impact transit use. Seskin, *et al*. (1996) find that having parking at a light rail station increases boardings by 50 percent and a commuter rail station with parking increases boardings by more than two times.

In addition to other characteristics of the built environment, individuals' characteristics may affect the density necessary to support a transit system. The research on how **income** affects various density thresholds is mixed. Messenger and Ewing (1996) find that areas with below-average incomes require lower densities to support transit than areas with above average incomes. However, Newman and Kenworthy (2006) find that the impact of income is less important in determining transit use than density.

Newman and Kenworthy (2006) note that **time constraints** are an important determinant of travel mode choice in an urban area. They explain that decisions about travel mode are determined by whether the time it takes to get to a destination by car is less than the time it would take to travel by bike, walking, or public transit.

A person's **attitudes and preferences** toward different travel modes may also factor into the conditions necessary to support transit. Bagley and Mokhtarian (2002) indicate that variables capturing individuals' attitudes and values have a greater impact on travel demand than residential location. Similarly, Cao *et al*. (2009) examine how attitudes toward travel affect mode choice in their study of how the built environment affects non-work travel. They find that preferring car dependence and biking or walking are negatively associated with transit use, while favoring transit is positively associated with taking transit. These results imply that people's attitudes toward travel persist despite neighborhood type or the degree of mixed uses available.

1.3. The Effect of Density on Home Energy Use

While the impact of urban form on transportation energy use has been studied extensively, its relationship to residential energy use is a relatively new area of exploration. This is surprising given the substantial GHG emissions associated with the residential sector, which produced more than one-fifth of total energy-related CO_2 emissions in 2006 (Energy Information Administration (EIA), 2007 [cited in Ewing and Rong, 2008]).

Our review identified four empirical analyses that focus on the relationship between GHG emissions and density. Though the existing research is limited and preliminary, it generally concludes that there is a negative relationship between density and GHG emissions, though the relationship is complex and not purely linear. In addition to the need for a larger body of literature, most of the studies discussed here rely heavily on existing data sets and are not based on primary research. This is problematic given the need to combine databases with different sampling frames. The compounding of measurement errors from equation to equation requires caution regarding the estimates. Further,

only one study has a broad geographic scale. The rest are based on case studies of particular regions or buildings, limiting the extent to which results can be generalized to other places.

Understanding the relationship between density and residential energy use requires analyses that consider multiple complex pathways. Factors considered in some of the studies reviewed here include electrical transmission and distribution (T&D) losses, energy requirements of different housing stocks, the energy embedded in construction materials and processes, and space and cooling requirements. The latter are associated with urban heat islands (UHIs), which are urban and suburban areas of warmth relative to surrounding rural areas because of the heat trapped by built surfaces during the day and slowly released at night.

This discussion of the literature is divided into three parts: studies that find an inverse relationship between density and emissions; studies that find a non-linear relationship; and a lifecycle analysis.

Key Findings

- Though the existing literature is limited, there is general consensus that higher density developments are associated with lower per-capita GHG emissions.
- Compact form is associated with lower emissions through a variety of pathways, including lower operational energy use in smaller and multifamily units, increased public transit use, and increased walking and biking.
- One estimate is that the average household living in a compact county would be expected to consume 17.9 million fewer BTUs of energy annually (about 20 percent less) than one living in a sprawling county, primarily a result of the prevalence of attached housing types and smaller house sizes.
- In very low density developments, carbon sequestration from preserved forestlands may offset anthropogenic GHG emissions; however, this has clear limits in terms of a GHG reduction strategy. For example, using just its own area, New Jersey could only support 450,000 residents living today's lifestyle on a carbon-neutral basis.
- Certain features associated with high-density living, such as large common spaces and amenities, may increase the GHG emissions of these developments appreciably.
- High-density housing does not automatically use less energy for operations than lower-density housing: the energy efficiency of household heating and cooling systems and appliances play an important factor. According to one estimate, an average urban household can consume 30 percent more energy than an average "green" suburban household.

Linear, Inverse Relationship between Sprawl and GHG Emissions

Two closely related studies conclude that GHG emissions have a linear, inverse relationship with density: higher densities are associated with lower GHG emissions per household. Rong (2006) developed a recent conceptual framework for her novel study linking sprawl and residential energy use and GHG emissions, and Ewing and Rong (2008) elaborated on this work. This framework identifies three connections between sprawl and residential energy use:

- Losses from the transmission and distribution of electricity (T&D);
- The housing stock itself—housing type and size; and
- Creation of UHIs, which can mean less energy use for heating during winter, but more energy use for cooling in the summer.

Using national level data, Ewing and Rong (2008) conduct an analysis of density and energy use and GHG emissions across the United States. They relate housing type and size, urban form, and the UHI effect using four different data bases,[102] including a sprawl index developed in earlier work by Ewing *et al.* (2003) for 83 U.S. metropolitan areas and 448 counties in 1990 and 2000. Ultimately, they do not account for the effects of T&D losses, which they deem as negligible.[103] Because the data are drawn from different sources with different sampling frames, the authors use a complex stepped analysis to link the data including a hierarchical linear model and several regressions.

Ewing and Rong find that the physical characteristics of housing units are related to energy use: detached houses require more energy than attached ones and households with larger house sizes consume more energy than equivalent households in smaller homes. In addition, the odds of living in a multifamily dwelling are seven times greater in compact counties than sprawling counties.[104] On the opposite side of the ledger, the UHI effect is found to cause a net savings in energy due to fewer heating days (though in hot climates, such as Texas, there is an energy penalty because of more cooling days).

On net, differences in house type and size dominate energy savings from the UHI effect, and the authors conclude that the average household living in a compact county would be expected to consume 17.9 million fewer BTUs of energy annually (about 20 percent less) than one living in a sprawling county.

Published comments on the study challenge some of the study's methods (Randolph, 2008) and dispute some of the fundamental premises of the article (Staley, 2008). Randolph (2008) argues that Ewing and Rong's "complex methodology linking three unrelated data sets renders their quantitative conclusions suspect." The author presents a simple engineering analysis showing that sprawl is more likely to affect energy use through increased vehicle miles traveled than house size or type. His calculations indicate that the average suburban household uses 45 percent more energy than an average urban household—58 percent of which is due to more VMT. He does, however note that

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[102] In a critique of this work Randolph (2008) notes that one of the data sets used, the EIA's 2001 Residential Energy Consumption Survey (2004), is "quite weak because of the small number of observations and the considerable variance."

[103] The authors note that T&D losses account for "less than 7 percent of the total electricity generated in the United States." (p. 7)

[104] In this case, a compact county has a value that is one standard deviation above the mean of the county sprawl index employed in this study. A sprawling county is one that falls one standard deviation below the mean value in this index.

Ewing and Rong's estimate that a household in a compact county would use 20 percent less energy (excluding transport) than one in a sprawling county are consistent with his calculations.

Notably, Randolph's calculations indicate that energy efficiency improvements in residences can save more energy and emissions than the effects of urban form and housing size and type. According to his calculations, the average suburban household uses 45 percent more energy than the average urban household (from more VMT, more heating, and electricity energy because of larger house size, as well as more lighting and appliances). That said, by his calculations an average urban household consumes approximately 30 percent *more* energy than an average "green" suburban household and 100 percent more than an urban "green" household. Conversely, a smaller, urban, multifamily, "green" household can consume one-fifth of the energy of a larger, suburban, average single-family household.

In other words, while energy efficiency measures can offset the impact of urban form on energy consumption, the combination of compact form and efficiency measures provide the best results. Randolph suggests that priority should be given to reducing energy use and related carbon emissions in the residential building sector through improved energy efficiency, but that minimizing sprawl "can be a real winner in our quest for more energy-efficient communities" if it is combined with efficient vehicles and compact, energy-efficient housing stock.

Staley (2008) argues that while Ewing and Rong's (2008) analysis is *empirically* sound, the data and methods used do not justify the conclusions. His critiques focus on their framing of the issue and the policy analysis. Specifically, Staley notes the following four weaknesses in the analysis:

- The failure to recognize the importance of consumer choice and trade-offs in policy recommendations;
- The failure to consider how technological change and innovation may impact future energy consumption; and
- The failure to recognize market-based alternatives to proposed increases in regulation, particularly energy pricing reforms.
- The use of "environmental alarmism" and a "sensationalist interpretation of the climate change literature," which suggests that immediate government intervention in housing and land use policy is necessary.

Ultimately, Staley argues that policies that promote energy conservation and spur innovations that improve energy efficiency and alternatives are more desirable than promoting density and smaller homes.

Non-linear Relationship between Density and GHG Emissions

Other studies do not find the same linear, monotonic relationship between population density and emissions suggested by Rong (2007) and Ewing and Rong (2008). Specifically, Andrews (2008) finds that net GHG emissions increase as density declines, but then begin to decline again in very low density areas. Like Ewing and Rong, Andrews also considers impacts from both infrastructure

(transportation, T&D loss, and waste management) and buildings (residential, commercial and industrial structures). But Andrews includes a more comprehensive assessment of landscape impacts—including carbon sequestration and deforestation in addition to UHI. He applies this model to nine municipalities in New Jersey with varying densities.

This study indicates that per-capita CO_2 emissions vary widely (by a factor of two) across the cases. Rather than a linear relationship between population density and emissions, he finds that when emissions are plotted against density they approximate an inverted 'U' shape, with post-war suburbs having the highest emissions per capita compared to both high density urban areas and low density rural areas. Andrews suggests that this pattern is due to the fact that as density increases, carbon sequestration decreases due to lack of forest cover, but higher density is also associated with a drop in deforestation (which releases CO_2), and decreases in the use of residential and transportation energy. Notably, he finds in most cases that buildings contribute more GHG emissions than personal transportation. This result contrasts Randolph's (2008) assertion that transportation is a larger emissions source than housing.

In the least dense town in Andrews' study, emissions were limited because carbon sequestration from preserved forestlands outweighed anthropogenic GHG emissions; however, forest-based sequestration has clear limits in terms of a GHG reduction strategy. For example, using just its own area, New Jersey could only support 450,000 residents living today's lifestyle on a carbon-neutral basis. The Census Bureau puts the 2007 population at approximately 8.5 million.

The densest city in the study had the smallest per-capita emissions because of smaller, multifamily housing units, walkable streets and access to public transit. Despite decreases in transportation-related greenhouse gas emissions with increases in density, the author cautions that only exceptionally high densities coupled with transit access and walkable destinations yield dramatic reductions in per-capita emissions. The high emissions for the 'mid-density' post-war suburbs are attributable to the lack of forests, auto dependence and large, single-family houses.

Andrews concludes that the causal relationship between land use and greenhouse gas emissions is complex and that it is difficult to isolate the net effect of individual policies. The author encourages regions to develop dense, transit-oriented areas and to preserve some land in forests as valuable carbon sinks.

Like Andrews, Myors *et al.* (2005) do not find a linear relationship between density and GHG emissions in their study. Analyzing energy consumption data from 45 multi-unit residential buildings in the Sydney metropolitan region in Australia, the authors find that per-capita GHG emissions from high-rise apartments are *higher* than those of mid-rise, low-rise or detached housing.[105] The majority of this analysis utilizes primary data collected through energy audits and power consumption monitoring. Unlike Andrews, the authors do not consider multiple pathways for greenhouse gas emissions—the buildings are assessed purely on stationary energy consumption. The most efficient housing typology is townhouses/villas (two or more detached dwellings with common or shared facilities). They attribute the inefficiency of high-rise buildings to the huge energy draw from heating and cooling common areas and maintaining amenities, such as gyms and swimming pools.

[105] The energy data for detached residential houses was drawn from existing publicly available data sets.

Life-Cycle Analysis Approach

Norman *et al.* (2006) provide a life-cycle analysis of energy use and GHG emissions of high- and low-density residential developments. They consider three major elements of urban development: construction materials for buildings and infrastructure (including residential dwellings, utilities and roads); building operations; and transportation (private automobiles and public transit). The analysis is applied to two Toronto area developments chosen to represent extreme ends of the density spectrum. Like most of the studies discussed above, this analysis utilizes national and/or regional averages of data rather than primary research to estimate the operational requirements for dwellings and transportation.

The authors find that the low-density suburban development is more GHG intensive (by a factor of 2.5) than the high-density core development on a per-capita basis. When GHG emissions are measured per unit of living space the factor decreases to 1.5. Much of the difference in emissions per unit of living space is accounted for by transportation sources and not building operations. That is, the per-unit emissions from building operations of the two developments are similar, but transportation-related emissions are higher in the low-density development. This result underscores the importance of the functional unit used in analysis and the overall complexity of relating density to residential energy use.

2. Neighborhood Characteristics Influencing Travel Behavior

Several characteristics of the built environment are shown to influence certain types of travel behavior, although the magnitude of the impacts is generally found to be small. The first of these is ***neighborhood design***, including features designed to encourage walking and bicycling, such as bike paths and sidewalks; some features of street patterns such as the absence of cul-de-sacs and grid-like street patterns, which both discourage driving and encourage walking and bicycling; and neighborhood accessibility to centers of activity such as employment, retail, and recreation. ***Mixed-use development*** is measured in a variety of ways but generally describes the diversity of land uses in an area, such as the mix of retail, commercial, and residential uses. ***Transit availability*** describes access to bus and/or rail transit within walking distance of the traveler's residence (generally thought to be about 400 meters) has a small influence on VMT and auto ownership. However, transit types are not created equal: bus transit provides better flexibility in connecting jobs and workers, but research indicates that it is more difficult to attract riders to buses than to rail transit.

2.1. The Influence of Neighborhood Design on Travel Behavior

Land use and zoning regulations encouraging compact, smart growth development patterns are becoming more common among municipalities. These neighborhood design efforts are led by concerns related to issues such as congestion, air quality, quality of life, and, more recently, climate change. Because of the interaction between land-use and transportation, urban land-use planners have adopted the role of traffic planners in many respects. Policy makers theorize that encouraging smart growth or New Urbanism principles may reduce auto dependency and encourage the use of transit, walking, and biking—an idea that is intuitively appealing. It seems obvious that neighborhoods characterized by pedestrian- and bike-friendly amenities and network patterns (including roads, sidewalks, and bikeways), density, and accessibility should encourage non-auto modes of transit.

The literature on the influence of neighborhood characteristics covers five major categories: network patterns, neighborhood type, accessibility, mixed-land use, and various measures of density. This section reviews the findings from the literature on the first three of these. Although most of the studies reviewed also include measures of land-use mix and density, these topics are discussed in detail in other sections of this literature review.

Characteristics of ***network patterns*** such as small block sizes, the absence of cul-de-sacs, grid-like street patterns, a high density of intersections, and limited residential parking, are all thought to discourage driving and encourage walking and bicycling. Network connectivity measures the degree to which a neighborhood exhibits these characteristics, which is also influenced by bikeway and highway density. Other features designed to encourage walking and bicycling include bike paths and sidewalks.

Many researchers identify two main ***neighborhood types***—traditional or suburban—and compare differences in travel patterns between residents of both types of neighborhoods. Suburban neighborhoods are associated with large lot sizes, limited diversity, and an auto-oriented design;

traditional neighborhoods are classified primarily as those with housing built before World War II, and are associated with smaller lot sizes and limited parking.

Last, ***accessibility*** variables are used to describe a neighborhood's access to centers of activity. These can include measures such as distance from employment, retail, and recreation. Some evidence suggests that research should take into account both neighborhood and regional accessibility measures, because travel behavior is influenced by a broader environment than the immediate neighborhood (see Ewing, 1995, for example).

This section is organized as follows. Studies that focus primarily on the impact of neighborhood ***network patterns*** on travel behavior (primarily VMT) are reviewed first, followed by studies that focus primarily on ***neighborhood type***, and then ***accessibility***. Then, studies of how neighborhood design influences ***non-motorized trips*** are reviewed.

Several issues make it difficult to generalize the results of studies on neighborhood design and travel behavior. In addition to studying a variety of characteristics of neighborhoods, there is also no single measure of "street patterns" or "accessibility," for example, making results of studies hard to compare. Last, studies use several measures of travel behavior. These include the number of total trips taken (trip frequency), distance traveled per trip (trip length), and mode choice. For vehicle trips, trip frequency and length taken together constitute total vehicle miles traveled (VMT). Other research focuses specifically on auto ownership or walking trips.

Despite its intuitive appeal, the research on the impacts of neighborhood design on travel behavior is far from clear. There is a great deal of variation in findings of studies, and consensus on very few points. But in this body of literature, the methodological quality of studies matters a great deal, and must be considered before drawing conclusions. For this reason Boarnet and Crane (2001b) explicitly warn against simply counting up the number of studies and deciding that the most common result has been proven to be correct by the preponderance of the evidence.

For example, data on the travel choices of individuals is typically more convincing than aggregate data on travel patterns, which obscure many of the complex relationships between neighborhoods, socioeconomic characteristics, and travel behavior. Boarnet and Crane (2001b) also note that many studies lack a clear framework for travel behavior. They describe these as "ad hoc" models examining the association between measures of urban form and travel behavior, but argue that interpreting the results of these studies can be difficult, because the causal theory is not well established.

Even studies that provide a framework for understanding travel theory can fall short, because of the complexity of the interactions between travel behavior and neighborhood design. The studies reviewed here include both studies with and without a behavioral framework, although, as Boarnet and Crane suggest, results of the former are given more weight than results of the latter.

Key Findings

- Residents of compact environments tend to choose walking or public transit over driving more often than residents of other environments.

- However, researchers caution that modal choice may be influenced by residential self selection. That is, people are likely to choose neighborhoods based on their current travel preferences. Those who prefer to drive less are more likely to reside in neighborhoods built around transit, or in high-density neighborhoods with a mix of land uses. Studies that do not correct for the bias introduced by self-selection may misrepresent the relationship between the built environment and travel behavior. However, in general, the influence of built environment variables is weakened—but not eliminated—with controls for residential self selection.
- Whether auto trip frequency is associated with differences in the built environment is an open question. Some researchers theorize that environments designed to be more accessible tend to lower the costs associated with travel. This, in turn, may lead to a higher trip frequency to be associated with more accessible environments (Crane, 1996), although findings are mixed. Some carefully controlled studies indicate that auto trip frequencies depend more on household socioeconomic characteristics and varies little with respect to accessibility.
- There is a general consensus that the trip length and mode choice varies by neighborhood. Trip lengths tend to be shorter in traditional neighborhoods that are accessible to retail, jobs and other destinations.
- Rates of auto ownership tend to be lower in more accessible neighborhoods.
- Some studies suggest that accessibility to non-work destinations along a transport corridor – rather than either trip origin or destination – to work may be influential in mode choice selection.
- In general, much of the literature suffers from important flaws, such as empirical strategies that do not account for the residential location decision. The measured influence of neighborhood design on travel behavior is sensitive to the empirical strategy used for analysis.
- As a whole, the literature strongly suggests a need for future longitudinal research covering a large sample of households moving from one neighborhood form to another, as well as a control group of non-movers.

The Influence of Network Patterns on Travel Behavior

Grid-like street patterns *can* encourage walking by providing relatively direct routes. Similarly, they tend to disperse auto traffic by providing multiple routes to destinations, reducing heavy flows of traffic along any one route (Ewing and Cervero, 2001). However, the effect of grid-like street patterns in isolation is not clear (Crane, 1996). Grid patterns with narrow streets tend to slow auto traffic, thus increasing the cost of driving and encouraging the use of non-auto forms of transit. Larger grids with wide streets and few pedestrian amenities are less likely to encourage walking and bicycling (Ewing and Cervero, 2001). It seems intuitively clear that sidewalks and bike paths should encourage walking and biking, although not necessarily whether these trips will substitute for motorized forms of transit or complement them. As discussed below, specific characteristics of network patterns may not be *directly* relevant to travel behavior. Instead, their impact may be

indirect, and depend on how they affect the price of travel by affecting trip distance and/or travel speeds.

The studies reviewed in this section and the neighborhood design variables included in each study are summarized in Exhibit 2.1-1 below. In addition to grid-like street patterns, other aspects of network patterns studied include the presence of sidewalks or bikeways, road density, the number of cul-de-sacs, and other pedestrian amenities. Other neighborhood characteristics, such as employment and population density and transit availability are also included as independent variables.

Exhibit 2.1-1. Definitions of Neighborhood Design Used in Studies of Network Patterns

Author, Year/Geography	Neighborhood Design Variables
Studies with no correction for self-selection bias	
Bhat, *et al.*, 2009 San Francisco Bay Area	Influence on **auto ownership** of: • Type of residential area (CBD, urban, suburban, rural) • Employment density • Population density • Land use mix • Single family or multifamily dwelling units • Local transportation network: bikeway density, street block density, highway density, road density
Hess and Ong, 2001 Portland	Influence on **auto ownership** of: • Pedestrian environment factor • Density • Land use mix • Accessibility to transit • Light rail corridor
Holtzclaw, et al, 2002 Chicago, Los Angeles, San Francisco	Influence on **auto ownership** of: • Residential and retail density • Pedestrian and bicycle friendliness: Presence of bike paths and sidewalks • Availability of bus and train service per hour • Number of jobs accessible within 30 minutes by transit
Cervero and Kockelman, 1997 San Francisco Bay Area	Influence on **VMT and mode choice** (mainly for non-work trips) of: • Density: Population, employment, accessibility to jobs • Diversity of land use • Design: Grid or curvilinear pattern, four way intersections, number of cul-de-sacs, street width, sidewalk width, block length, proportion of blocks with pedestrian friendly characteristics such as sidewalks, bike lanes per acre, off street parking availability
Guo, *et al.,* 2007 San Francisco Bay Area	Influence on **number of auto trips and non-motorized trips** of: • Land use mix in terms of fraction of use (residential, commercial and other) • Population density • Highway density • Bikeway density • Street connectivity • Regional access: number of employment, retail and recreational opportunities near residence

Author, Year/Geography	Neighborhood Design Variables
Zhang, 2004 Boston and Hong Kong	Influence on **mode choice** of: • Public parking supply • Population density at origin • Job density at origin • Population at destination • Job density at destination • % non-cul-de-sac at origin • % cul-de-sac at destination • Land use balance at origin • Land use balance at destination
Studies with correction for self-selection bias	
Boarnet and Crane, 2001b Orange County/Los Angeles and San Diego	Orange County: influence on **non-work auto trips** of: • Population density • Retail density • Service jobs density • Percentage of street grid within ¼ mile of the residence that is characterized by four-way intersections San Diego: influence on **non-work auto trips** of: • Street network: grid-like; mixed; or dense • Distance from CBD • % Residential • % Commercial • % Vacant
Boarnet and Sarmiento, 1998 Orange County/Los Angeles	Influence on **non-work auto trips** of: • Population density • Retail density • Service jobs density • Percentage of the street grid within ¼ mile of the residence that is characterized by four-way intersections
Chatman, 2009 San Diego and San Francisco-Oakland-San Jose MSAs	Influence on number of **non-work trips by mode** of: • Number of retail workers within ¼ mile and 1 mile radius of home • Residents per road mile within 1 mile of home • Presence of heavy or light rail within ½ mile • Distance to central business district • Presence of sidewalks • Four-way intersections within ¼ mile of home
Kitamura, *et al.*, 1997 San Francisco Bay Area	Influence on number of **trips by mode** (person trips, transit trips, non-motorized trips) • Presence of sidewalks • Distance to transit • Parking spaces available • Mixed land uses: Distance to nearest park • High density: Presence of backyard

As in other aspects of travel behavior, the impact of residential self-selection is an important methodological issue in the relationship between neighborhood design and travel behavior. Failure to account for the likelihood that households locate in neighborhoods that fit their preferences for driving leads to biased results. Studies that ignore the impact of self selection are likely to

overestimate the influence of characteristics of the built environment on travel behavior, although it is not clear by how much. Studies in this section are organized by whether or not they attempt to correct for self-selection bias.

Studies with No Correction for Self-Selection Bias

The six studies in this section generally find that the relationship between street patterns and travel behavior is statistically significant, but weak. Three of these primarily address auto ownership; the remaining three studies use VMT and mode choice as dependent variables.

Studies on Auto Ownership

The study finding the strongest association between network patterns and travel behavior is Bhat, *et al.*, (2009) although their results are mixed. They use data from the San Francisco Bay Area, and project that a 25 percent increase in bike lane density will result in a small decrease in the ownership and use of motor vehicles (not always statistically significant) and an increase in the use of non-motorized transportation (statistically significant). Street block density influenced the type of autos owned but actually decreases the use of non-motorized transit. Specifically, a 25 percent increase in street block density is projected to result in a statistically significant increase in the use of small cars and a decreased usage of non-motorized transit. The authors suggest that increased traffic from the increase in the number of street blocks leads to safety concerns and hinders the use of non-motorized modes of transit.

They also include price effects of travel, and find that an increase in the fuel cost leads to a statistically significant decrease in the holdings of minivans and vans. They conclude that this reflects a shift in the ownership of vehicles from larger vehicles to smaller, fuel efficient, vehicles. As expected, the results indicate that an increase in fuel cost results in a significant increase in the use, and intensity of use, of non-motorized modes of transportation. Overall, however, the results reflect a rather small elasticity of vehicle holdings and use to fuel cost.

Hess and Ong (2001) conduct a case study of Portland, Oregon, and find that the neighborhood characteristics—pedestrian environment factor, transit accessibility, and light rail corridor—are statistically insignificant in a model predicting auto ownership. The most important statistical determinants of the probability of auto ownership are demographics (household income, household size, residence in a single family home, the presence of a male householder), and mixed land uses. Household density (households per acre) is not significant. Hess and Ong suggest that certain groups of people may locate their households in high-density, mixed-use environments because of their preference not to own a car.

Holtzclaw (2002) also does not find a statistically significant relationship between auto ownership and the pedestrian- and bicycle-friendliness of the community, but does find one between VMT *per vehicle* and pedestrian- and bicycle-friendliness (although this relationship is weak). Using data from Chicago, Los Angeles, and San Francisco, he finds that auto ownership and average annual distance driven are primarily a function of neighborhood residential density, average per capita income, average family size, and the availability of public transit. Also in contrast to Hess and Ong, Holtzclaw finds that population density (households per residential acre) has the strongest correlation to vehicle ownership and residential density (households per total acre) has the strongest correlation to VMT per vehicle.

Studies on VMT and Mode Choice

The study finding the strongest association between network patterns and VMT or mode choice is Cervero and Kockelman (1997), although the relationship is not always as expected. Using data from the San Francisco Bay Area, they find that two characteristics of street patterns have a significant impact on non-work travel. The proportion of blocks with quadrilateral shapes (an indicator of grid-like design) has a *positive* relationship with VMT—opposite of the New Urbanist hypothesis. The proportion of intersections that are four-way is negatively related to VMT, as expected. They also find that neighborhood retail mix is significantly associated with mode choice for work trips, as is accessibility (a measure of proximity and compactness). Micro-elements of neighborhoods, such as sidewalk widths and presence of street trees, were excluded from the predictive models because they were found to have little bearing on travel demand once things like land-use diversity and demographic attributes were included.

Cervero and Kockelman conclude that that pedestrian-friendly and mixed-use neighborhoods are associated with commuting by transit and non-motorized modes, although they describe the impacts as being fairly small relative to the sociodemographic variables. They also note that it is unlikely that any one factor in isolation will have much impact on travel behavior, but that in combination they are likely to yield larger results.

Guo, *et al.*, (2007) also find that although some characteristics of the built environment promote non-motorized travel, but that this travel generally complements rather than substitutes for individuals' motorized trips. Based on data from the San Francisco Bay Area, they find that built environment characteristics including bikeway density, commercial density and street connectivity have a significant effect on the number of non-motorized trips taken by individuals, but do not result in lower auto use. The authors differentiate between complementary and substitutive trips by comparing parameter estimates: if the estimates associated with motorized and non-motorized modes are both statistically significant and have opposite signs, they conclude that the built environment factor leads to substitution between the modes. If they are both statistically significant but have the same signs, they conclude that the built environment factor promotes use of both motorized and non-motorized modes. If only one of the two estimates is statistically significant, then the effect of the built environment on mode use is complementary.

Zhang (2004) presents case studies of Boston and Hong Kong to determine the relative importance of land-use characteristics on mode choice in each city once socioeconomic characteristics and travel costs are taken into account. Street pattern variables are only available for Boston, where Zhang found that increased network connectivity (percentage of non-cul-de-sac intersections) at trip origin had a marginal positive effect on non-driving modes, while decreased network connectivity at trip destination increased the likelihood of driving alone for all trips (destination was insignificant for work and non-work models).

As a group, land-use variables improve the model's explanatory power for predicting mode choice for both Boston and Hong Kong without (in most cases) changing the direction or significance of the model's other travel cost and socioeconomic variables, implying that land use has an independent influence on mode choice.

In Hong Kong, the densest city in the world, the city offers nearly ideal land-use attributes for non-driving travel, as demonstrated by the fact that there are an average of .066 cars per household member. However, the city still employs a strong fiscal policy to restrain the growth in demand for auto use. In both cities land-use and pricing had roughly equal influence on the probability of driving. Zhang concludes that land use is necessary but not sufficient to influence travel, and that land-use strategies should be combined with pricing strategies.

Studies with Correction for Self-Selection Bias – Instrumental Variables

Two related studies, by Boarnet and Sarmiento (1998) and Boarnet and Crane (2001b), use the same data and a similar approach. Their trip data are from 769 residents of Orange County/Los Angeles who recorded their trips over a two-day period in 1993. Both studies also uses instrumental variables (IVs) to correct for the self-selection of individuals who prefer not to drive into neighborhoods that are conducive to other modes of transportation. The instrumental variables are used to first estimate a model of the choice of residential neighborhood, and this predicted neighborhood choice is then used in the model predicting travel behavior. Because the instrumental variables are not correlated with travel behavior they remove the selection bias in the second-stage model of travel behavior.

In both studies, for each level of geography (census block group, census tract, or ZIP code) they use the proportion of the population in the area that is Black; the proportion of the population that is Hispanic; the proportion of the housing stock that was built before 1940; and the proportion of the housing stock that was built before 1960 as instruments to predict residential choice.

The first of these studies, by Boarnet and Sarmiento (1998), finds that land-use variables do not have a significant effect on non-work trips. They find that none of the land-use variables (population density, retail density, service jobs density, and the percentage of the street grid within one-quarter mile of the residence that is characterized by four-way intersections) have a significant effect on non-work trips in both base and IV models. However, they note that there are weaknesses in their choice of IVs. Their tests for over-identification reject the assumption that two of the four IVs are exogenous, and therefore may not be valid instruments.

Their results demonstrate the importance of the level of geography over which land-use variables are measured. That is, characteristics of larger areas may be better predictors of travel behavior than the individual's immediate neighborhood. For example, Boarnet and Sarmiento estimate non-work trips separately using land-use variables measured at block group, census tract, and zip code-level geographies. They find that in the block group and census tract models, the income and socio-demographic variables show the same pattern and the land-use pattern variables remain insignificant. However, for zip code geographies, the IV model suggests that residence in a zip code with higher service employment density is associated with slightly more non-work automobile trips, and that residence in a zip code with higher retail density is associated with fewer non-work automobile trips (this is significant only at the 10 percent level).

Boarnet and Sarmiento conclude that the analysis does not provide evidence for the link between non-work travel and land-use patterns, but suggest that geographical scale and the use of different modeling techniques—such as better IVs—can impact the evidence.

The second study, by Boarnet and Crane (2001b),[106] base their model of travel behavior on microeconomic theory, assuming that households choose the number of trips by each travel mode in order to maximize utility. They also extend the previous study by including analysis for San Diego. These data are from a 1986 survey that collected data about socioeconomic characteristics over the phone. Subsequently, respondents completed a travel diary with detail about trips taken by household members on a designated travel day.

They find that the relationship of land use to auto trip frequency is complex and sensitive to both the form of the model and the level of geography studied. In general, non-work auto trips are more strongly associated with socioeconomic characteristics of travelers (such as income, number of children in the household, age) than land-use patterns. They find that IVs in the census block group and tract-level geography models for Orange County do not change the basic conclusion: land-use variables are statistically insignificant. However, in the ZIP code-level model, the number of service jobs is significantly associated with non-work auto trip frequency. Surprisingly, for San Diego, the IV results are more supportive of the New Urbanist travel hypothesis than the original results: they provide some evidence that grid-oriented street patterns and commercial concentrations are associated with fewer non-work auto trips. Specifically, people living in neighborhoods with higher densities of commercial land have slower non-work car trip speeds and take shorter non-work auto trips, suggesting that to the extent that land-use variables influence auto trip frequency, they do so by influencing the price of travel.

As noted by Boarnet and Sarmiento, difference in results between the base and IV models indicates that correction for self-selection bias is vital in identifying influences of land use that might otherwise be missed. In addition, given that the IVs used here are subject to the same weaknesses as those used by Boarnet and Sarmiento, the use of different modeling techniques—such as better IVs—can impact the evidence.

Studies with Correction for Self-Selection Bias – Attitudinal and Personal Preference Variables
Kitamura, *et al*., (1997) use a different approach to help correct for self-selection bias. They add personal preference variables related to driving and neighborhood type to help directly explain household residential location decisions in five neighborhoods in the San Francisco Bay Area. In the base model, they find that measures of residential density, public transit accessibility, mixed land use, and the presence of sidewalks are significantly associated with transit trips and non-motorized trips (but not with total person trips, which the authors find is largely determined by demographic and socioeconomic characteristics). These same variables are also significantly associated with modal split (fraction of auto, transit, and non-motorized trips) in the expected direction.

However, incorporating personal attitudes into the model reduces the impact of the built environment on travel behavior significantly. They use 39 attitude statements relating to urban life to create eight factors: pro-environment; pro-transit; suburbanite; automotive mobility; time pressure; urban villager; TCM;[107] and workaholic. The authors find that non-motorized trips are strongly associated

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[106] See also Boarnet and Crane (2001a).

[107] Transportation control measures (TCM) is primarily defined by these attitude statements: "I would be willing to pay a toll to drive on an uncongested road"; "More lanes should be set aside for carpools and buses"; and "We need to build more roads to help decrease congestion."

with being pro-environment, pro-transit, and automotive mobility. Further, as a whole the entire group of attitudinal variables are more important in explaining variation in travel behavior than either the group of socio-economic or neighborhood variables. They conclude that lifestyle choices are relevant to both selection of residential location and travel behavior.

Chatman (2009) also includes variables on personal attitudes and preferences to address the problem of self selection. He defines the residential self-selection hypothesis, as it is discussed in the literature on travel behavior, as being three non-mutually exclusive hypotheses:

- People decide where to live based in part on how they expect to/prefer to travel;
- People are not significantly constrained in their selection of neighborhood type so preferences and neighborhood characteristics are highly correlated (e.g., people have the flexibility to exercise their preferences); and
- Regardless of where they actually live, self-selectors are more responsive to the built environment.

However, he notes it is not likely that these three hypotheses are true in every urban area. For example, some households seeking housing near transit may be unable to find it, which would lead to underestimates of the relationship found between the built environment and travel behavior (see also Cao, 2009).

In Chatman's empirical analysis of the relationships between the built environment, non-work travel frequency by mode, and residential choice, he finds that four-way intersections (a measure of pedestrian connectivity) is significantly associated with walk/bike trips, as is distance to the CBD, the presence of a light rail station within ½ mile, and the presence of sidewalks on both sides of the street (significant at the 10 percent level). Transit trips are significantly related to the number of retail employees within a 1-mile radius (significant at 10 percent level, distance to the CBD, and the presence of a heavy rail station within ½ mile. Surprisingly, auto trips are positively related to residents per road mile within 1 mile, a variable intended to represent road congestion due to intense development.

In order to correct for self-selection, Chatman includes survey respondents' personal attitudes and preferences, measured using questions about their criteria for selecting their current residence. He finds that doing this does not change the coefficients on the neighborhood characteristics in the base model very much. He notes that the change in coefficients for all nine statistically significant built environment measures is less than 10 percent, and in seven of the nine cases it is less than 3 percent. Therefore, he concludes that residential self-selection does bias estimates of the influence of the built environment, but only modestly.

Interestingly, the influence of the built environment on travel behavior was stronger for households claiming not to place a value on transit availability than other households. The implication of this is that the third part of the self-selection hypothesis might not always be true—that is, self-selectors might be *less* responsive to the built environment than others.

Leck (2006) conducts a meta-analysis of the impact of urban form on travel behavior that includes 17 primary studies in total. However, only a small number of these studies are relevant to street patterns: he analyzes three different primary studies of the impact of grid-like street patterns (Boarnet and Sarmiento, 1998, reviewed above; Crane and Crepeau, 1998; Greenwald and Boarnet, 2001); and two studies of the ratio of sidewalks (Cervero, 2002; Cervero, 1994) on the probability of commuting by transit. He finds that both grid-like street patterns and the sidewalk ratio are insignificant. Leck's assessment of this aspect of the literature on neighborhood design is consistent with this review: the preponderance of the evidence suggests that network patterns either have no effect on travel behavior, or have an ambiguous effect.

The Influence of Neighborhood Type on Travel Behavior

Many neo-traditional and New Urbanist communities have been developed in recent years, typically featuring such design characteristics as smaller lots, homes built close to the street, alleyways with rear-loading garages, narrow streets, pedestrian-friendly walkways, community green space and mixed-use buildings. The studies reviewed in this section take a somewhat more macro view of neighborhood characteristics than the previous section, comparing the travel behavior of residents of different categories of neighborhoods.

All of these studies except Shay and Khattak (2005) incorporate measures of attitudes and preferences toward modes of travel as a method of controlling for self-selection bias. Further, all but one finds that neighborhood type influences travel behavior even after accounting for the possibility of self selection (although they are unanimous in finding an impact of self selection), and the general consensus is that this influence is stronger for the number of non-motorized trips than for the number of auto trips.

The key difference between the studies reviewed in this section is the methodological approach. Five of the nine studies rely on the same set of data collected from eight neighborhoods (four traditional, four suburban) in Northern California. Studies based on these data (by Handy and Cao) generally use a "change" approach. That is, they compare the travel behavior of individuals over time and in different neighborhoods. Three of the remaining studies use a more typical cross-sectional analysis; and the remaining study uses an interesting approach that examines how the role of the built environment varies according to how well people are matched with their neighborhood. The "change" approach studies more consistently find an impact of neighborhood type on travel behavior than the other studies.

Assessing the literature as a body, the heavy reliance on one data set may be considered a weakness of the literature. To the extent that these data have flaws or cannot be generalized to other places, there is a clear need for additional research using different data collection methods and other regions of the country. These five studies are discussed first, followed by studies using other sources of data.

Exhibit 2.1-2. Definitions of Neighborhood Design Used in Studies of Neighborhood Type

Author, Year/Geography	Neighborhood Design Variables
Bagley and Mokhtarian, 2002 San Francisco	Influence on **VMT, transit miles, and walk/bike miles** of neighborhood type: • Traditional neighborhood factors: higher population density, more convenient to public transit, smaller home size, lack of backyard, less parking availability • Suburban neighborhood factors: higher speed limit, greater distance to nearest grocery store and park, greater ease of cycling, less likely to have grid street network
Cao, et al., 2007a Northern California	Influence on **auto ownership** of: • Land use mix: Number of business types within 400 m • Outdoor spaciousness • Neighborhood preferences: Accessibility and outdoor spaciousness

Cao, et al., 2007b
Northern California
	Influence on **auto ownership, driving, and walking** of:
	• Changes in the built environment
	  – Changes in accessibility
	  – Changes in outdoor spaciousness
	• Changes in physical activity options
	• Changes in safety
	• Changes in socializing
	• Changes in attractiveness
	• Distance to nearest fast food
	• Number of business types within 400 m

Cao, 2009 Northern California	Magnitude of influence on **non-work trips (auto, walk/bike, transit)** of: • Accessibility: Distance to destinations • Proximity to different land uses • Presence of walking or biking infrastructure • Age and style of homes in neighborhood: Pre-WWII homes = traditional, newer homes = suburban • Location of commercial centers: Number of establishments within 400 and 800 meters
Cao, *et al.*, 2009 Northern California	Influence on **non-work trips (auto, transit, walking/bicycling)** of: • Accessibility: Distance to destinations • Number of business types within 400 and 800 meters • Neighborhood type: Traditional or suburban
Handy, *et al.,* 2005 Northern California	Influence on **vehicle miles driven and change in driving or walking** of: • Physical activity options: Bike routes and sidewalk presence • Accessibility: Access to downtown, mall, freeway and transit • Outdoor spaciousness: Size of yards • Parking availability • Suburban or traditional neighborhood: Pre-WWII homes define neighborhood as traditional; newer homes as suburban
Khattak and Rodriguez, 2005 North Carolina	Influence on **auto trips, external trips (trips that do not begin and end in the neighborhood), and walking trips** of: • Neo-traditional neighborhood • Conventional suburban neighborhood

Author, Year/Geography	Neighborhood Design Variables
Schwanen and Mokhtarian, 2005 San Francisco Bay Area	Influence on **commute mode choice** of: • Dissonance in terms of land use patterns between current neighborhood and preferences (based on pro-high density factor)
Shay and Khattak, 2005 North Carolina	Influence on **auto ownership** of: • Neighborhood type (neo-traditional or suburban)

Studies based on eight neighborhoods in Northern California

The following five studies use data from a survey of recent movers and non-movers from eight neighborhoods in Northern California. The authors consider the data to be quasi-longitudinal, because although they do not survey the same people over more than one time period (which would produce true longitudinal data), they ask respondents questions about their behavior at different points in time.

In addition to questions about values and preferences, respondents were asked to describe their travel behavior—commute trips, non-work trips, and walking trips. Specifically, respondents were asked to report how often they use auto, walking/biking, and public transit from their home to pre-specified non-work destinations in a typical month. The pre-specified destinations include church and civic building; service provider, restaurant and coffee, store, a place to exercise, and out of the house without a particular destination. They were also asked to estimate how many miles they drive in a typical week. They also reported their changes in travel behavior from either just before the move or from one year ago (for the non-movers) using five-point scales (e.g., they drive “a lot less now”, “a little less now”, “about the same”, etc.).

Importantly, local characteristics of destinations are not measured, and thus cannot be included as independent variables in models of travel behavior, although a number of studies find that these are significant (see, for example, Zhang (2005) and Ewing and Cervero (2001)). Further, the pre-specified trip destinations mean the data on non-work travel is not comprehensive, and could bias the results if travel behavior related to excluded categories of destinations differs from the included categories. A more common method of data collection involves trip diaries, in which respondents record specific details about their trips over a period of time (periods of one day up to seven days are common). The lack of detail collected about travel behavior likely introduces measurement error, but not bias, to the results, making it less likely that studies will find significant results.

Handy, *et al.*, (2005) is the first of the studies using these data, and examines the relationship between travel behavior and neighborhood type in two ways. First, they use standard multivariate analysis of cross-sectional data. Doing this, they find that differences in travel behavior between suburban and traditional neighborhoods are largely explained by attitudes.

More intriguingly, they examine changes in behavior over time and in different settings. This quasi-longitudinal analysis shows significant associations between changes in travel behavior and changes in the built environment, even when personal preferences are accounted for. They find that the built environment has the strongest influence on walking-related travel patterns. They suggest that higher accessibility reduces the cost of walking and may encourage more walking as a substitute for driving.

Accessibility also reduces the cost of driving, but the survey reveals that residents who moved to a more accessible neighborhood actually drove less. The impact of the built environment is more strongly associated with changes in non-motorized transit than with driving.

Cao, et al. (2007a), focus on the effects of the built environment on auto ownership. Similar to Handy, *et al.*, they find important differences in results depending on whether they examine cross-sectional differences in travel behavior or examine changes in an individuals behavior associated with moving to a different neighborhood. Using cross-sectional analysis, they find that socio-demographics have a dominant role in predicting auto ownership (particularly mobility needs—defined by household size, the number of household members within driving age, and the number of workers in the household—and purchasing power). They find that once preference factors are included, the built environment has no effect on auto ownership. With a quasi-panel model, however, they find that although residential self-selection accounts for a portion of the measured influence of the built environment on auto ownership, there is some remaining causal relationship between the built environment and auto ownership.

Cao, *et al.* (2007b), reach similar—but broader—conclusions about the impact of the built environment on travel behavior than the previous study. They use structural equations modeling, a method that allows multiple directions of causality, to study changes in travel behavior among 547 people who moved within the previous year. They find that even controlling for attitudes and preferences, the built environment matters. Specifically, changes in auto ownership are positively associated with post-move changes in outdoor spaciousness and distance to the nearest fast food (used as an indicator of lower accessibility). Importantly, they also find that an increase in accessibility is most important predictor (among those tested) in reducing driving, even with controls for self selection. They also find that some qualities of the built environment influence walking. These findings suggest a direct causal influence on auto ownership, driving, and walking of the built environment.

In terms of magnitude of impact, they find that the influence of built environment variables on driving is similar to that of socio-demographics. A limitation of the study is the lack of a control group of non-movers, because changes in auto-ownership were not measured for non-movers.

They also analyze the residential location choices of households who relocated to a different neighborhood and find clear evidence of self-selection. In fact, differences in the new neighborhood's accessibility are entirely determined by attitudinal factors: households who prefer high-accessibility neighborhoods are more likely to move to neighborhoods with this characteristic, as are those who prefer to minimize daily travel. People who value the safety of cars are more likely to move to lower-accessibility neighborhoods.

Cao, *et al.*, (2007b) point out a limitation of this study and virtually all research to date on the relationship between the built environment and travel behavior. Their design captures only current attitudes and preferences, not changes in attitudes and preferences. It is possible that a change in attitudes and preferences partly prompted the move, which, if true, would account for some of the measured effect of the built environment. Better longitudinal data could better capture changes in attitudes and preferences over time.

Cao, *et al.*, (2009) use cross-sectional data and find that neighborhood type has an independent effect on trip frequency by mode even after controlling for travel attitudes and residential preferences, and its influence is stronger for non-motorized trips than for auto trips. The study finds that after accounting for socio-demographics and attitudes and preferences, neighborhood type remains an important predictor of the frequency of trips for each mode type. A higher number of neighborhood businesses tend to predict a higher number of non-auto trips, as does mixed land use. Furthermore, the perception of good physical activity options in the neighborhood (measured by respondent statements about bicycle routes, sidewalks, parks and open spaces, and good public transit service), encourages biking and walking.

Cao (2009) uses an innovative approach to explore the magnitude of the impact of residential selection on travel behavior. The study applies propensity score stratification to control for selection bias. That is, residents are classified into strata based on their characteristics. Then Cao compares travel behavior between residents living in traditional and suburban neighborhoods that were grouped into the same stratum. The results show that without controls for residential self selection, the causal influence of neighborhood type is overestimated by 64 percent for utilitarian walking frequency and 16 percent for recreational walking frequency. Cao concludes that although the observed influence of neighborhood type on walking is often overestimated, there is strong evidence that the built environment can stimulate meaningful changes in walking behavior.

Studies using varying sources of data

Bagley and Mokhtarian (2002) is the only study reviewed here that concludes that once attitudes, lifestyle, and socioeconomic characteristics are accounted for, neighborhood type has little impact on travel behavior. They score residential location types in five neighborhoods in San Francisco as either suburban or traditional (or somewhere in between) according to several factors based on data on land use, the roadway network, and public transit obtained from site surveys conducted in 1992. These factors include access to parking, grid street network, and distance to the nearest grocery store and park. Demographic, socioeconomic, attitudinal, lifestyle, and travel-related data are collected through mail surveys and travel diaries. Lifestyle preferences are measured by survey respondents' indications of which subjects they read about within the last month, how they spent the last weekend, and what activities they participated in during the last year. A total of 963 households completed the survey, and from these, 515 individuals were selected for this analysis.

Like Cao, *et al.*, (2007b), they use a structural equations model that allows multiple directions of causality (rather than the far more typical single direction allowed in many statistical models), they find that neighborhood type has little independent influence on travel behavior. Specifically, nine equations were used, which estimated nine endogenous variables: two measures of residential location type, three measures of travel demand, three attitudinal measures, and one measure of job location.

Surprisingly, the only significant effect of residential location type on travel demand is the positive effect of a *suburban* location on transit use (due to the availability of BART). The lack of significant relationships found suggest that associations between neighborhood type and travel behavior seen in other studies may not be the result of causality, but the result of previously omitted variables such as attitudes and lifestyle.

Like Cao (2009), Khattak and Rodriguez (2005) find a strong influence of neighborhood type on walking-related travel. They account for residential self-selection by choosing eight attitudinal variables related to neighborhood and transportation preferences. They use a mail-in survey to collect sociodemographic characteristics, attitudinal information, and travel information (through a travel diary that captures data on trips and miles by travel mode and trip purpose). Using these data, they compare the travel behavior of residents of a neo-traditional neighborhood with those of a conventional suburban neighborhood, both in North Carolina's Research Triangle. Both neighborhoods have similar access to regional networks; the major difference is the level of transit service, which is comprehensive in the neo-traditional neighborhood and nearly non-existent in the conventional neighborhood.

The travel behavior of *households* between the two neighborhoods is different in all of the expected ways (fewer total trips, fewer auto trips, less total distance traveled for the neo-traditional neighborhood residents). Interestingly, the travel behavior of *individuals* in both neighborhoods was quite similar. That is, when travel behavior is normalized by household size, some differences in travel behavior disappear. Households in the neo-traditional neighborhood were smaller than those in the conventional neighborhood, with 2.89 and 3.34 people per household, respectively. However, even with attitudinal variables included in the model to account for self-selection, mode choice remained significantly different, with more transit and walking trips taken by neo-traditional neighborhood residents.

The share of trips that are internal to each neighborhood is also interesting: this share is about 21 percent of all trips for the neo-traditional neighborhood and 5.3 percent for the conventional neighborhood. The apparent importance of local accessibility suggests that even neo-traditional neighborhoods with poor regional accessibility might reduce VMT.

Using the same data as Khattak and Rodriguez (2005), Shay and Khattak (2005) find that residents of neo-traditional neighborhoods own fewer cars, take fewer auto trips, travel shorter distances and spend less time driving than their peers in conventional neighborhoods. Shay and Khattak do not use the attitudinal variables in the dataset, so unlike the previous study it does not make any attempt to control for residential self-selection.

Schwanen and Mokhtarian (2005) use an interesting approach that examines how the role of the built environment varies according to how well people are matched with their neighborhood—that is, how well their current location expresses their attitudes and preferences. They use data from a mail survey of households in three neighborhoods in the San Francisco Bay Area (one urban, two suburban), and find that the role of the built environment varies according to how well people are matched with their neighborhood.

They define four categories of residents: true urbanites are urban residents with urban preferences; urban dissonants are those who would prefer neighborhoods with suburban characteristics but live in urban areas; true suburbanites are suburban residents with suburban preferences; and suburban dissonants are suburban residents with preferences for neighborhoods with characteristics more likely to be found in urban areas. That is, neighborhood type *dissonance* is the mismatch between a commuter's current neighborhood type and her preferences. *Consonant* residents are better matched according to their preferences with their current neighborhood.

Using these categories of residents as a method for measuring self selection, they find that neighborhood type has an independent, significant effect on commute mode choice even after controlling for socio-demographics and taking into account residential self selection. That is, they find that dissonant urban residents are more likely to drive to work than consonant urbanites, but not quite as likely as consonant suburbanites. So living in an urban area does appear to reduce the likelihood of driving to work even if residents would prefer to drive. On the other hand, consonant and dissonant suburban residents have similar travel behavior, suggesting that the lack of travel options in suburban neighborhoods inhibit expression of travel preferences more than urban neighborhoods. That is, personal preferences do not entirely dictate travel behavior, and neighborhood structure has an independent effect on commute mode choice.

The Influence of Accessibility on Travel Behavior

A number of studies focus primarily on accessibility—that is, the distance to destinations such as employment, shopping, and recreation—and how it influences travel behavior. Note that in some studies, accessibility refers broadly to a variety of destinations; in other studies, it refers more narrowly to access to employment. Ideally, measures of accessibility capture both the distance to destinations as well as the utility of the destinations (Koenig, 1980). An important methodological issue in this body of literature is whether accessibility is measured at the local or regional level. Ewing and Cervero (2001) suggest that the effects of local accessibility are small compared to those of regional accessibility, implying that high-density, mixed-use developments in the middle of nowhere offer at best modest impacts on VMT.

As always, residential self-selection is also important. Of these studies, only Krizek (2003) controls for residential self selection, using data on changes in travel behavior over time and in neighborhoods with different characteristics. The studies consider different measures of travel behavior, making the results difficult to compare. Two studies find that accessibility seems to reduce VMT (Kockelman and Krizek); one study finds a significant influence of accessibility on mode choice and another does not (Srinivasan and Krizek); one study finds that improved accessibility to destinations is associated with higher trip frequency—by any mode—to those destinations (Zhang); and another finds that walk trips are strongly and positively related to accessible environments, but auto trips are not.

It appears that all of these studies are consistent with the idea that accessibility increases trips overall but reduces VMT by increasing the likelihood of choosing non-auto modes trips. However, given that each of these studies presents only one piece of the picture, more research is needed to confirm this. In particular, it is possible that non-auto trips are not substitutes for auto trips, but taken in addition to auto trips, which could result in higher trip frequencies but little or no change in VMT (see, for example, Guo, *et al.*, (2007), discussed above).

Kockelman (1997) investigates the relative significance of demographic and land-use variables on household VMT, auto ownership, and mode choice. She uses data from 1990 San Francisco Bay Area Travel Surveys and land-use data from hectare-level descriptions provided by the Association of Bay Area Governments. After controlling for demographic characteristics, the measures of accessibility, land use mix, and land use balance were highly statistically significant and influential in their impact on household VMT, automobile ownership, and mode choice. However, the impact of

density was negligible except in vehicle-ownership models. In many cases, balance, mix, and accessibility were found to be more relevant than several household and traveler characteristics that often form a basis for travel behavior prediction.

Srinivasan (2002) analyzes the relationship between mode choice and neighborhood characteristics in the Boston metro area. Her study is innovative in two ways. First, rather than analyzing single trips (which include only one destination), she analyzes *tours*, which capture more complex (and more typical) travel in that it can include multiple destinations in one outing, such as a stop at a day care center or coffee shop on the way to work. Second, she includes measures of accessibility at the home location, at the destination, and *along the corridor between the two*. Transport corridor measures of accessibility include transit access, non-work accessibility by auto, and pedestrian convenience.

Exhibit 2.1-3. Definitions of Neighborhood Design Used in Studies of Accessibility

Author, Year/Geography	Neighborhood Design Variables
Kockelman, 1997 San Francisco Bay Area	Influence on **VMT and auto-ownership** per household and **personal-vehicle choice and walk/bike choice** of: • Accessibility • Land-use balance • Land-use mix: dissimilarity index and entropy • Density
Krizek, 2003 Puget Sound	Influence on **VMT, person miles traveled, number of trips, and number of trips per tour** of: • Neighborhood accessibility • Regional accessibility • Workplace neighborhood accessibility • Workplace regional accessibility • Change in neighborhood accessibility • Change in regional accessibility
Shay and Khattak, 2007 Charlotte, NC region	Influence on **auto ownership** of: • Density • Land use • Neighborhood type • Accessibility
Srinivasan, 2002 Boston	Influence on **mode choice** of: • Land use diversity: Measures of texture including entropy, homogeneity, and contrast to depict the mix and balance of open space, residential, and commercial land use • Network type: Density and proportion of streets, cul-de-sacs, and intersections • Accessibility: To non-work activities and employment via public transit options and auto routes • Pedestrian convenience: Sidewalk width, percentage of roads with sidewalks, ad percentage of roads with speeds over 30 mph
Zhang, 2005b Boston	Influence on **trip frequency and time use** of: • Accessibility to all establishments • Accessibility to retail establishments • Accessibility to service establishments

She finds that for work tours, accessibility to non-work opportunities along a corridor between home and work appeared to be more important than other measures of accessibility for mode choice. Increased accessibility via public transit at the home location was not significantly associated with mode choice, but corridor-level accessibility via transit was. Accessibility to non-work destinations was significant for work tours but not for non-work tours. Both the travel cost and time variables were significantly related to mode choice for both work and non-work tours. Neither pedestrian convenience at home or at the destination was significant in influencing mode choice for either work or non-work tours.

Krizek (2003) uses a panel study approach to investigate the travel behavior (VMT, number of tours, and number of trips per tour) of households before and after moving to a new neighborhood. The data are from the first general-purpose travel panel survey in the United States, conducted from 1989 to 1994. The survey is used to track sociodemographic and travel behavior of approximately the same households in the Puget Sound region (households who move out of the region are replaced) over time. Travel behavior is recorded once annually over a two-day period. Importantly, the data allow observation of the same households in neighborhoods with different characteristics. To the extent that attitudes and preferences remain stable over time, these longitudinal data at least partially eliminate self-selection bias.

These data allow Krizek to estimate "base" models—those that estimate travel behavior of households in their current neighborhood—and "change" models—those that estimate changes in travel behavior between a current and previous neighborhood. He found that accessibility (in terms of distance to both employment and retail locations), both at the neighborhood and regional level, is associated with lower VMT, a reduced number of trips per tour, but an increase in the number of tours.

Zhang (2005b), using data from Boston, finds that better accessibility to a variety of non-work activities increases the time and trip frequency associated with those activities. For example, better accessibility to schools increases the time spent traveling and the number of trips taken to schools. The same is true for increases in accessibility to social activities and shopping.

In analyzing the predictors of auto ownership in North Carolina, Shay and Khattak (2007) conclude that the most important factors are socio-demographic (household size, the presence of children, income, etc.), but that the difference in auto ownership in the most and least accessible environments is also substantial. Overall trip frequency is positively associated with the level of accessibility, confirming the findings of other studies that increased accessibility leads to higher trip frequencies. Auto ownership is found to be less sensitive to the characteristics of the built environment than the number of trips.

Influence of Neighborhood Design on Non-motorized Trips

Several characteristics of the built environment are found to be associated with the choice to travel by foot, although not all of the characteristics sometimes touted as doing so are found to be significantly associated. Network connectivity—indicated by grid street patterns and four-way intersections—is generally positively associated with walking, but block length is not found to have an effect.

Findings of the impact of mixed land uses on walking are mixed. Importantly, only one (Chatman, 2006) of the studies in this section takes into account residential self-selection. He does this using data from survey questions about households' residential location choice process.

Exhibit 2.1-4. Definitions of Neighborhood Design Used in Studies of Non-motorized Trips

Author, Year/Geography	Neighborhood Design Variables
Boer, *et al.,* 2007 10 largest CMSAs in U.S.	Influence on **walking trips** of: • Density: Average number of dwellings per acre • Mixed land use: Business diversity • Street network: Degree to which streets are in a grid system • Block lengths: The average length of the long side of the city block
Chatman, 2006 California	Influence on **mode choice** of: • Residential density • Employment density • Retail density • Traffic volume • Transit proximity and access • Pedestrian connectivity: four-way-or-more intersections within ¼ mile
Forsyth, *et al.,* 2007 Twin Cities, Minnesota	Influence on **walking trips** of: • Employee density: measure of mixed use • Street pattern: measure of walkability • Pedestrian design: Presence of amenities such as sidewalks, trees, bus shelters, and interesting architecture • Destinations: Variety of land uses
Rodriguez and Joo, 2004 Chapel Hill, North Carolina	Influence on **mode choice** of: • Population density: population at trip origin and destination at the block group level • Street characteristics: presence of walking and biking paths • Topography: slope

Several studies find a significant relationship between street patterns and walking. For example, Chatman's study of transit-oriented developments in California (2006) concludes that pedestrian connectivity as characterized by the number of four-way intersections is associated with the number of walking trips. As the number of four-way intersections increases one standard deviation, the number of non-motorized trips increases by more than 25 percent.

Forsyth, *et al*., (2007) find that walking in the Twin Cities, Minnesota, is also affected by several aspects of pedestrian infrastructure and amenities. They measure a variety of street pattern characteristics, including the number of access points, number of intersections, road length, and number and ratio of four-way intersections. They find that several measures of more connected street patterns—a characteristic that the authors note is difficult to change—are found to have a positive correlation with walking. In addition, total mean miles walked per day is positively correlated with pedestrian infrastructure such as sidewalks, street lights, and traffic calming methods. Although statistically significant, the estimated increases in miles walked were small. There was no association between mixed use development and miles walked.

However, the authors find no strong positive correlations between measures of the built environment and *total physical activity* (measured using both a seven-day travel/walking diary and an accelerometer over seven days). Mixed land uses, measured as employee densities in several retail categories (such as food stores, eating and drinking places, miscellaneous retail), had a statistically significant *negative* correlation with total physical activity.

Overall, the findings suggest that people have a fixed physical activity budget, similar to a travel time budget, and that people who do more leisure time physical activity do less for transport and vice versa. Therefore, although changes in the built environment may encourage mode changes from driving to walking, they may not affect public health.

In one of the first empirical tests of the impact on walking of design guidelines—based on the New Urbanism Smart Scorecard—Boer, *et al.* (2007) find mixed results. They use data on households in the 10 largest consolidated metropolitan statistical areas from the 1995 National Personal Transportation Survey (NPTS) to study six different built-environment characteristics: business diversity, fraction of four-way intersections, housing density, median housing age, parking pressure, and block length. Built environment characteristics are measured within ¼ mile of the respondent's residential location because ¼ mile was the median distance of a walking trip in the 1995 NPTS.

They find that the probability of walking in a neighborhood varied depending upon some characteristics of the built environment. Higher levels of business diversity are associated with more walking up to a point—in neighborhoods with more than four types of businesses, introducing new types of businesses has no additional impact on walking. Boer, *et al.*'s findings are in conflict with those of Forsyth, *et al.*, who find that mixed use has no association with walking. The differences between the studies may be a result of the measures used for mixed-land use, which are business diversity and employee density, respectively.

Boer, *et al.*, also find that higher percentages of four-way intersections are associated with more walking. The highest level of housing density (14 or more units per acre) also was associated with a higher probability of walking, but not densities below 14 units per acre. However, short block length did not appear to be associated with walking, perhaps because of other New Urbanism-style characteristics also present in the neighborhood. Similarly, higher parking pressure and older median housing age did not significantly affect walking.

The authors conclude that some, but not all, of the New Urbanism Smart Scorecard criteria have a correlation with walking. Further, to the extent that they do affect walking, the magnitude of the impact is limited. Therefore, they conclude that more than one built environment characteristic in a neighborhood must be changed in order to create an environment to encourage walking.

Rodriguez and Joo (2004) survey commuters to the University of North Carolina, Chapel Hill, and also find that non-motorized travel behavior is affected by some neighborhood design attributes such as the presence of sidewalks, biking paths and overall connectivity. However, their findings differed depending on whether characteristics were measured at the respondent's residential location, at their destination, or along their travel route. They find that the presence of walking or cycling paths and the population density measured at each respondent's residence were not consistently related to mode

choice. However, the presence of sidewalks *in the shortest route* to a destination can be linked to higher walking rates. A variable not often included in travel studies—the presence of sloping terrain—is linked to a decreased number of walking and biking trips. These findings support the idea that mode choice is related to a larger area than the household's neighborhood, including destination and route characteristics.

2.2. The Influence of Mixed-Use Development on Travel Behavior

In general, the research on the relationship between the built environment and travel behavior demonstrates that mixed-use development does influence travel behavior. The research varies somewhat depending on model type, measures used to characterize mixed-use development, and the type of trip and travel mode in question. This section summarizes the research in terms of how patterns of mixed-use development impact different forms of travel.

Exhibit 2.2-1. Categories of Mixed-use Development Used by Various Authors

Mixed Use Variable Name	Author, Year
Employment Accessibility	• Bailey et al. 2008 • Cervero and Duncan 2003
Commercial Diversity	• Boarnet and Crane 2001 • Cao *et al.* 2009 • Cervero 1996 • Dargay and Hanley 2004 • Vance and Hedel 2007
Service Density	• Boarnet and Crane 2001 • Boarnet and Sarmiento 1998 • Cervero and Duncan 2003 • Cervero and Duncan 2006
Retail Diversity	• Boarnet and Crane 2001 • Boarnet and Sarmiento 1998 • Cervero 2002 • Cervero and Duncan 2003 • Cervero and Duncan 2006 • Chatman 2003
Land-use Diversity	• Cervero and Duncan 2003 • Cervero and Kockelman 1997 • Frank and Pivo 1994 • Guo *et al.* 2007 • Kockelman 1996 • Leck 2006 • Rajamani *et al.* 2003 • Sun *et al.* 1998 • Boarnet and Crane 2001

To better understand how each study examines mixed-use development, Exhibit 2.2-1 categorizes the land use variable(s) used by each author whose work is discussed in this section, and shows the wide range of variables used to measure mixed use (the Attachment defines each authors' mixed-use development variables in more detail). Various measures of density and diversity are used as well as

accessibility, and variables are used in a variety of combinations. The inconsistency in measures of mixed use make it challenging to summarize the findings of the literature, as findings related to "mixed-use" development depend on what measure is used.

A number of studies that examine the relationship between the built environment and travel behavior show that mixed-use development affects travel behavior including the *frequency* of auto trips, VMT, and mode choice. Studies that do not include controls for the impact of self selection are discussed first, followed by those (relatively few) that do.

Key Findings

- There is limited research on whether mixed-use development decreases the number of driving trips, and findings are inconclusive. One study concludes that mixed-use development has different impacts on discretionary and maintenance trip-making, and on those with and without access to a car; a second finds no significant relationship.
- Households living in mixed-use development neighborhoods own fewer cars.
- The weight of the evidence suggests that the effect of mixed-use development on travel behavior is similar to the effect of neighborhood density. One study finds that the effect of mixed-use development on mode choice is stronger when measured at the workplace than when measured at home.
- The results of research examining the influence of mixed-use development on vehicle miles traveled are mixed, varying with trip purpose and with how land use mix is measured. This is also true for the influence of mixed-use development on the likelihood of using alternative modes of transportation (transit, walking, and biking).
- A few researchers have controlled for the effect of self-selection on the relationship between mixed-use development and travel behavior. The effect of including instrumental variables on the effect of mixed-use development varies. Vance and Hedel do not find any true impact of mixed land use on travel behavior, but Boarnet and Sarmiento find a significant impact at the zip code level. Cao, *et al.*, use measures of attitudes toward travel to correct for self-selection bias. They find that self-selection explains some of the observed travel behavior, but that mixed land uses also have the effect of discouraging auto use and facilitating use of public transit, walking, and bicycling.

Trip frequency

The research on the relationship between land use mix and the number of trips taken is inconclusive. In a study of the San Francisco Bay area, Guo *et al.* (2007) finds that mixed-use development *increases* the number of auto trips a person takes taken for non-work maintenance purposes (grocery shopping, personal business, and medical visits). For discretionary trips (recreation, meals, social, and non-maintenance shopping), land use mix is found to generally *decrease* the number of motorized trips taken, but to increase the number of trips for single parents and people with access to cars. In contrast, Sun *et al.* (1998) finds no relationship between land use mix and the number of trips.

Auto ownership

The reduction in auto trip frequency is consistent with the findings of another body of research showing that people living in neighborhoods characterized by mixed-use development own fewer cars. Cervero (1996) finds that while the influence of mixed-use development is weaker than neighborhood density, it still negatively impacts the number of vehicles a household owns. Dargay and Hanley (2004) look at both the likelihood of a household having at least one car and having more than one car relative to the odds of not owning a car at all. The authors find that mixed-use development has a positive, significant effect on both, but more strongly affects having more than one car. Kockelman (1996) found that measures of land use balance (but not land use mix) had a significant effect on automobile ownership. Land use balance measures the degree of balance across several distinct land uses in a developed area: residential, commercial, public, offices and research sites, industrial, and parks and recreation.

Vehicle Miles Traveled

The findings on the relationship between mixed-used development and vehicle miles traveled are mixed. Cervero and Duncan (2006) find that mixed land uses reduce VMT, but that some types of land-use mix have more impact than others. They separate the effect of mixed-use development into what they call "jobs-housing balance" and "retail-housing mix." They find that having "occupationally matched" jobs nearby (i.e., jobs in the same category as that held by the survey respondent) have roughly twice the effect on vehicle miles traveled as retail-service access. Incorporating the elasticities for work and shopping trips into the effect of mixed-used development, the authors find that a mix of jobs and housing reduce vehicle miles traveled 72.5 percent more than a mix of shopping and services and housing.

Kockelman (1996) finds that mixed-use development has a significant negative effect on vehicle miles traveled both for all trips and for home-based work trips. Bailey *et al.* (2008) also finds a negative relationship between mixed land use and VMT. In contrast, Cervero and Kockelman (1996) find that mixed-use development only has a significant effect on vehicle miles traveled for non-work trips, but is insignificant in their model predicting vehicle miles traveled for all trips. Chatman (2003) finds that mixed-used development, as measured by retail share at both the workplace and residence, does not have a significant effect on personal commercial vehicle miles traveled or choosing to commute by car. He speculates that retail share may be a poor measure of mixed-use development, or it may be that his models may have excluded other variables that have an impact on travel choices, such as parking availability.

Cervero and Kockelman (1997) find that land use mixing decreases the likelihood of traveling by car, although its influence is fairly small. Adding built environment variables to the model predicting daily VMT for all purposes adds about three percentage points in explanatory power to a model that excludes these variables; it adds about five percentage points in explanatory power to the model of the likelihood of auto travel for non-work purposes (travel for personal business, shopping, and social-recreation).

Mode choice

By reducing the likelihood of driving, mixed-use development increases the likelihood of using alternative modes of transportation, including non-motorized modes and public transit.

Public transit use
Frank and Pivo (1994) use data from Puget Sound in Washington and find that mixed-use development does not have a significant effect on transit use for non-work travel, but has a significant positive effect on both transit use and walking for work trips.

Cervero and Kockelman (1997) find that living in a neighborhood with commercial conveniences increases the likelihood of commuting by a non-personal vehicle mode for non-work trips by nearly three-quarters, holding other factors constant such as transit availability, commute distance, and socio-demographic characteristics. In a meta-analysis of three studies on the impact of mixed-use development on travel behavior, Leck (2006) finds that land use mix significantly decreases the probability of commuting by automobile.

Cervero (1996) reaches similar conclusions, finding that mixed-use development decreases the likelihood of auto commuting, but that this effect is much weaker than the influence of neighborhood density. Cervero quantifies this finding, noting that holding the number of automobiles per household constant, density decreases the probability of commuting by car by about 60 percent, whereas living in a mixed-use area only lowers the probability of auto commuting by five percent or less. Cervero also finds that the presence of mixed uses has the strongest influence on the likelihood of walking or biking when the commute is one mile or less.

Cervero (2002) separates the influences of mixed-use development at commute destination and origin. He finds that the influence of mixed land use on transit use is stronger when measured at the workplace than when measured at home. In contrast with Cervero and Kockelman (1997), Cervero finds that the relationship between mixed land use at home and transit use is insignificant. He finds that among the "3 Ds" of the built environment (i.e., density, diversity, and design), diversity has the strongest influence on transit use.

When generalized to all methods of transit, researchers find that mixed-use development increases transit use for all trips (Cervero 2002) and for work trips (Cervero 1996, Frank and Pivo 1994, Leck 2006), but does not significantly affect non-work travel (Rajamani *et al.* 2003).

Walking and biking
Several studies find that people are more likely to walk in neighborhoods characterized by mixed-use development (Cervero 1996, Cervero and Duncan 2003,[108] Kockelman 1996,[109] Rajamani *et al.* 2003).

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[108] Cervero and Duncan only found land-use diversity at origin to be significant in predicting walking. The land-use diversity at destination variable is no significant in the model.

[109] Statistically significant at the 10% level.

The findings from the literature on the influence of mixed-use development on biking are mixed. Several studies find that mixed-use development increases the likelihood of biking (Cervero 1996, Kockelman 1996[110]). However, both the Cervero and Duncan (2003) and Rajamani *et al.* (2003) find that mixed-use development does not have a significant impact on biking.

When broken down by trip purpose, the influence of mixed-use development on the use of non-motorized travel modes varies. Mixed-use development increases the likelihood of walking for work trips (Frank and Pivo 1994) and non-work trips (Rajamani *et al.* 2003), but does not have a significant effect on shopping trips specifically (Frank and Pivo 1994). Guo *et al.* (2007) finds that only one measure of mixed-use development (the fraction of commercial land use in a one mile radius) increases the number of non-motorized trips for shopping and recreational trips. The other three measures of mixed-use development in their model (land-use mix within a .25 mile radius, land-use mix within a 1 mile radius, and fraction of residential land use within a 1 mile radius) are not significant.

The effect of mixed-use development on travel behavior varies with the distance to nearby amenities. Dargay and Hanley (2004) find that people are more likely to walk or take transit than drive when amenities are just a short walk away. On the other hand, having amenities a long walk away decreases the likelihood of choosing to walk over driving, but has no significant effect on transit use. Similarly, while Cervero (1996) finds that the presence of mixed-use buildings very close to one's residence (within 300 feet) increases the likelihood of walking or biking and using transit and decreases the likelihood of driving, having non-residential amenities slightly further away (300 feet to one mile away) has the opposite effect.

Studies with controls for self-selection bias

As noted in Section 1, an important issue in research on the relationship between the built environment and travel behavior is that households' choice of residential location and travel choices are made simultaneously. That is, people choose to live in walkable, transit-oriented neighborhoods because they prefer not to drive, and that preference motivates their travel behavior rather than the built environment itself. Regardless, many studies lack variables or statistical techniques to correct for self-selection bias. But a few researchers have attempted to account for self-selection in their research by altering their empirical approach.

Two of the studies – Vance and Hedel (2007) and Boarnet and Sarmiento (1998) – use similar very similar approaches but reach nearly opposite conclusions. This may be a result of the geographic areas studied – Southern California and Germany, which has better transit availability and higher densities.

Vance and Hedel (2007), in a study of residents of Germany, use instrumental variables to account for residential self-selection. Ideally, instrumental variables capture socio-demographic composition and land use characteristics of the neighborhood but not travel behavior. The four selected instruments include: percentage of buildings built before 1945, percentage of buildings built between 1945 and

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[110] Statistically significant at the 10% level.

1985, percentage of residents over 65 years of age, and the percentage of foreign residents.[111] They measured the impact of both commercial density and commercial diversity on adults' weekday automobile travel, and find that living in areas with greater commercial density has a significant effect on car use and distance traveled. However, commercial diversity is not significant in predicting car use.

Boarnet and Sarmiento (1998) also add instrumental variables to their model to correct for self-selection. Again, the authors select instruments designed to avoid correlation with travel behavior. These include the percent of the population that is black, the percent Hispanic, the proportion of housing stock built before 1940, and the proportion of the housing stock built before 1960. The authors find that the relationship between mixed use development and non-work auto trips becomes significant when the instrumental variables are added to the model, though only in the models using zip code land-use variables (rather than block group or tract land-use variables). Residence in a zip code with higher service employment density is associated with more non-work automobile trips and residence in a zip code with higher retail employment density is associated with fewer non-work automobile trips.[112] The authors conclude that their findings suggest that when studying the relationship between the built environment and travel behavior, it is important to both control for residential location choice and to examine different levels of geographic detail.

Cao *et al.* (2009) construct and compare models that include measures of attitudes toward travel in order to correct for self-selection bias with those that do not. They find an impact of both attitudes and mixed land uses, and conclude that mixed land uses tend to discourage auto travel and facilitate the use of transit and non-motorized modes.

2.3. The Influence of Transit Availability on Travel Behavior

The two main types of public transit available in the U.S. are bus and rail. Buses systems have obvious advantages over rail systems: they do not require large infrastructure investments, they have flexibility to respond to changes in the geographic distributional employment, and they are less expensive to operate. The main shortcoming of a bus is that it is not a train. That is, bus travel is an inferior good—the higher a person's income, the less likely it is that they will ride the bus. In contrast, rail transit riders have relatively high incomes. Rail transit's problems, however, are well known: despite massive investments in transit over the last decades, the use of transit has been declining since at least 1940. Although roughly 30 percent of households live within ¼ mile of a transit stop, transit's share of all trips is small—on the order of about 1 percent. In short, cars are usually faster, more comfortable, and more flexible than either rail or bus transit.

However, in some environments, the use of transit is much higher. One key ingredient of transit demand is clearly transit supply—the frequency and quality of service. Transit supply, in turn, is dictated more by residential or employment density than any other measure of demand. As stated by

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[111] Given research indicating that recent immigrants and the elderly have different travel patterns than the rest of the population (see the section, Income and Demographic Influences on Travel Behavior), it is not clear that Vance and Hedel succeed in selecting satisfactory instrumental variables.

[112] The retail employment density variable is only significant at the 10% level.

Badoe and Miller (2000), "… the better the transit service, the more people will use it; the more people potentially available to use a given service, the higher the level of service which can be cost-effectively provided."

Badoe and Miller note that relatively few studies explicitly include measures of transit supply in their analyses of urban form impacts; however, when these measures are included, they are often found to be significant in explaining mode choice, VMT, and other travel behaviors. The results of studies that include measures of transit supply are described below. This is followed by a review of the literature on the determinants of transit ridership, and then a review of studies that examine the benefits and costs of public transit from a social perspective.

Key Findings

- Despite massive investments in transit over the last several decades, the use of public transit has been declining since at least 1940. A small share—roughly 1 percent—of all trips is taken via public transit.
- The demand for and supply of transit are interrelated: better transit service (especially more frequent service) increases demand for transit; and the supply of transit depends on the number of potential users of the system.
- Although demand for transit depends in part on the supply, it is largely a function of other factors, such as population, population density, personal and household income, percent of the population that is college students or recent immigrants, and the percent of households without a car.
- Studies of the impact of transit availability on travel behavior using data from the U.S. are mixed. Some find significant impacts on travel behavior; others do not.
- Where significant impacts of transit availability are found, the magnitude of these impacts is small. In general, researchers conclude that large increases in the supply of transit would be required to achieve modest reductions in auto dependence.
- Rail transit is likely to be more effective in reducing auto use in some cities than in others. Elasticities of auto dependence with respect to distance to the nearest transit stop vary widely by city.
- Studies of the impact of transit availability on travel behavior using data from other countries generally find a significant relationship, although the magnitude of impacts is generally found to be small.
- Although many researchers do not address the impacts of the price of auto ownership and use (such as congestion and parking price and availability) on transit use, those that do find it to be more important in influencing transit use than increases in the supply of transit. The cost of transit use is an important factor in determining transit ridership.
- Although rail transit reduces congestion generally, producing benefits for both users and non-users, rail transit's deficits are sufficiently large that many systems cannot be justified on the basis of improvements to social welfare.

- One of the primary benefits of new rail investments may be shorter commute times for riders, although not all new rail lines demonstrate statistically significant gains in ridership.
- Denser, more centralized cities are more successful in drawing new riders to transit than other cities.

Impact of Transit Availability on Travel Behavior

One of the complexities of synthesizing literature on the impact of transit availability on travel behavior is the variety of measures of both travel behavior and definitions of transit availability used. Studies using both data from the U.S. (shown in Exhibit 2.3-1) and from other countries (Exhibit 2.3-2) are reviewed in this section. The findings of the two groups of studies are quite different. Generally, transit availability is found to have a larger impact on travel behavior in studies using data from other countries than those using U.S. data.

The studies relying on U.S. data are mixed in terms of their findings about whether transit availability is a significant predictor of travel behavior. Two studies of auto ownership find that transit availability is not significant; three do. One study of mode choice finds that transit miles supplied are significant, the other finds that the presence of subway or streetcar (an indicator of transit service quality) is significant, but the distance to the nearest transit stop is not.

Where it is found to have a significant effect on travel behavior, the magnitude of the impact of transit availability is estimated to be small. Bento, *et al*., (2005) is one of the only studies that accounts for the possibility of self selection. They estimate than an increase in transit miles supplied of 10 percent increases the probability of taking transit by 0.5 percent, and conclude that attempts to reduce auto dependence by increasing the supply of transit will have only modest success. Kim and Kim (2004) conduct a simulation and project that access to transit within .1 mile of households would reduce vehicle ownership by 9 percent and reduce VMT by 11 percent. Given the enormous investment that would be required to provide this level of transit access, these projections indicate that transit access has a relatively small impact on auto ownership and VMT.[113]

As shown in the differences between the findings of U.S. and international studies, as well as in Zhang (2005), the response to transit availability varies across urban areas. Zhang (2005) finds that in Boston, the response to an increase in transit availability is relatively large (a 7.6 percent decrease in the degree of auto dependence with a 10 percent reduction in the distance between home and the nearest transit station). In Portland, the same improvement has a 0.12 percent decrease in the degree of auto dependence, and in Houston, the effect is a 0.08 percent decrease. Clearly, the same approach will not work in every urban setting.

[113] Roughly 30 percent of U.S. households now live within 400 meters (about ¼ mile) of a transit stop).

Exhibit 2.3-1. Influence of Transit Availability on Travel Behavior – U.S. Data

Author/Year	Geography	Dependent Variable(s)	Definition of Transit Availability	Transit Availability Significant?	Magnitude of Impact	Conclusion
Chatman, 2003	National	Mode choice	Distance to nearest transit stop; presence of subway/streetcar (RAIL)	N / Y	not discussed	Subway/streetcar availability (RAIL) significantly decreases the likelihood of driving to work; distance to nearest transit stop is not significant
Hess and Ong, 2002	Portland metro area	Auto ownership	Dummy for good transit accessibility; light rail line within 1/4 mile	N / N	N/A	Both measures of transit accessibility are statistically insignificant
Bento, et al., 2005	114 urbanized areas; 26 cities with rail transit	VMT; auto ownership; commute mode choice	Rail miles supplied; bus miles supplied	N - VMT (except in two-car families); Y - auto ownership; Y - mode choice	An increase in transit miles supplied of 10% increases probability of taking transit by 0.5%	Attempts to alter urban form and increase the supply of public transit are likely to have modest impacts on auto dependence
Shay and Khattak, 2007	Mecklenburg and Union Counties in North Carolina	Auto ownership; trip generation	Median distance of all parcels in neighborhood to bus stop	N / N	N/A	Bus accessibility is statistically insignificant
Zhang, 2005	Boston, Portland, Houston	Degree of auto dependence (perception of alternatives to auto)	Distance to nearest transit station	Y	In Boston, a 10% reduction in distance between residence and transit station is associated with a 7.6% decrease in the degree of auto dependence; elasticities in other cities are much smaller	Vehicle ownership is most important factor in auto dependence
Deka, 2002	Los Angeles County	Auto ownership	Transit availability	Y	Small	Significant improvements will be needed in transit services for a slight decrease in auto ownership among the general population.
Kim and Kim, 2004	National	Auto ownership; miles driven	Distance to public transit	Y / Y	Adding transit within .1 miles of residence is projected to reduce vehicle ownership by 9 percent and VMT by 11 percent	The primary determinants of vehicle ownership are number of licensed drivers and income

Exhibit 2.3-2. Influence of Transit Availability on Travel Behavior – International Data

Author/Year	Geography	Dependent Variable(s)	Definition of Transit Availability	Transit Availability Significant?	Magnitude of Impact	Conclusion
van de Coevering and Schwanen, 2006	31 cities in North America & Europe	Total distance by public transit, average commuting time, share of commuting by transit	Ratio transit to road supply; rail density	Ratio - Y / N / Y (marginal); density - Y / Y (marginal) / N	not discussed	There are variations in the elasticity of travel behavior with respect to transit availability across Europe, Canada, and U.S.
Vance and Hedel, 2007	Germany	Vehicle use, auto distance traveled	Walking minutes to public transit	Y / Y	Each additional minute in walking time increases daily kilometers driven by 0.15	Distance to public transit is significantly, negatively related to vehicle use and daily distance traveled by car
Woldeamanuel, et al., 2009	Germany	Auto ownership	HH satisfaction with accessibility to transit; bus stop or train station w/in 1-2 km	Y / Y - Transit station w/in 1-2 km significant in cross-sectional but not longitudinal model	Satisfaction with transit access is more important than proximity to transit	There are significant variations in car ownership between households, but changes in auto ownership of a given household over time are insignificant.
Buehler, 2009	Germany, US (National Household Travel Survey)	Daily auto travel distance	Proximity to transit stop (w/in 1000 m)	Y	Living within 400 m of a transit stop in US reduces daily VMT by 6.5 km	Access to transit has a larger impact on travel behavior in the U.S. than in Germany, perhaps because Germany's higher gas prices mean that Germans at all distances from transit are encouraged to economize on driving.
Dargay and Hanly, 2004	Great Britain	Mode choice; car ownership	Bus frequency; walk time to bus stop	Y / Y	not discussed	Frequency of bus service is more important than distance to the nearest bus stop in determining public transit use
Potoglou and Kanaroglou, 2008	Hamilton, Canada	Auto ownership	Number of bus stops within walking distance	Y - negative but marginal effect on probability of owning three or more cars	Marginal	Residence in a single-family home, the number of individuals with a driver's license, and the number of individuals working more than 6 km from the residence are the most important determinants of car ownership

The findings of studies of the relationship between transit availability and travel behavior that use data from other countries are more consistent than U.S.-based studies. Transit availability is nearly always found to have a significant effect on travel behavior (Exhibit 2.3-2). Most of the studies do not measure the magnitude of the effect of transit availability on travel behavior. Of those that do, Potoglou and Kanaroglou (2008), studying one city in Canada, find that the effect of transit availability is marginal. Vance and Hedel (2007) is one of the few studies to account for the possibility of self selection. They find that in Germany, each additional minute in walking time to a public transit stop increases daily kilometers driven by 0.15. Relative to average daily travel distance in Germany of roughly 30 km per day,[114] the increase in daily VKT from additional walking time seems small.

The largest impact found is in Buehler (2009), who compares auto travel in the U.S. and Germany and finds differences in the response to access to transit between the two countries. He finds that transit access has a larger impact in the U.S. than in Germany, perhaps because the higher gas prices in Germany encourage Germans to economize on driving regardless of their distance from a transit stop. Specifically, he finds that living within 400 meters of a transit stop in the U.S. reduces daily VMT by about 6.5 km (4 miles).

Two studies—those by Woldeamanuel, *et al.*, (2009) and Dargay and Hanly (2004) suggest that transit service quality has an important impact on transit use. Woldeamanuel, *et al.*, find that household satisfaction with transit accessibility is more important than actual proximity to transit in determining auto ownership. Similarly, Dargay and Hanly find that the frequency of bus service is more important than the distance to the nearest bus stop in determining public transit use. These findings are similar to those of studies on the determinants of transit ridership, discussed in the next below.

Determinants of Transit Ridership

Studies of the determinants of transit ridership have important policy implications. If transit consumption is function primarily of factors other than transit supply, then increasing transit supply may be an ineffective approach to increasing transit ridership (and thus decreasing auto use). The results of the studies described here suggest that transit supply plays a relatively minor role in transit ridership, so increasing transit supply is likely to have a positive but weak effect on transit ridership.

In their study of the social benefits of rail transit, Winston and Maheshri (2007) found several aspects of transit price and service to have a statistically significant effect on demand. As expected, fares have a negative effect on demand. In large transit systems (New York City and seven others such as Boston and Chicago), greater track density, connectivity, and non-linearity (tracts in both East-West and North-South directions) increase demand for rail, while a greater average distance between stations reduces demand. Greater average distances between stations also reduce demand for rail in medium and small systems.

Taylor, *et al.*, (2009) reach similar conclusions about the determinants of transit ridership. They use data from 265 urbanized areas, and find that although much of the variation in transit ridership is

[114] Authors' calculations based on data from Buehler (2009).

outside of the control of transit agencies, transit service levels are important. They find that transit fares and service frequency account for roughly a quarter of the observed variance in per capita transit ridership across urbanized areas. The importance of transit fares and service frequency suggests that transit operators should focus efforts on improving the service on existing lines generally rather than extending new lines, thereby focusing expenditures and service improvements on one or a few lines.

They use two-stage simultaneous equation regression models to account for the simultaneity between transit service supply and consumption. They first model transit service supply, and then use the predicted service supply as an instrumental variable in a second model predicting transit service demand. Doing this, they find that most of the variation in transit ridership is explained by factors related to regional geography (such as population and population density), metropolitan economy (personal and household income), population characteristics (percent of college students, recent immigrants, and Democratic voters), and auto/highway system characteristics (percent carless households).

Benefits and Costs of Transit

This section discusses five separate studies of the benefits and costs of public transit: two by Baum-Snow and Kahn; two by Bailey and her colleagues; and one by Winston and Maheshri. Bailey, *et al.*, and Winston and Maheshri take relatively broad views of the benefits and costs of rail transit and come to opposite conclusions. Bailey, *et al.*, examine the reductions in fuel consumption and congestion that results from rail transit, and conclude that rail transit produces large benefits even for non-transit users. Winston and Maheshri, on the other hand, take into account the monetary cost of rail transit and find that with only one exception, rail transit reduces social welfare. In contrast to the more commonly cited congestion and pollution reduction benefits of public transit, Baum-Snow and Kahn find that the primary benefit of new rail investments is reduced commute times.

Bailey and colleagues

Bailey's (2007) analysis focuses on the benefits of transit, which she calculates as being the additional fuel that would have been used if the same travel were undertaken via private vehicle. She also calculates fuel savings from the reduced congestion because of public transit. In total, she estimates that public transit saves 1.4 billion gallons of fuel per year in the U.S. Further, if public transit services were expanded and ridership doubled, fuel savings from public transit would double to 2.8 billion gallons per year. The energy use and other costs related to public transportation improvements and extensions required to double ridership are not included in the analysis.

Bailey, *et al.*, (2008) take a step further and incorporates the influence of public transit on land-use patterns, hypothesizing that transit increases densities, shortening trip distances and VMT even for non-transit users. To the primary effects of public transportation calculated in the previous study, they estimate that the secondary effects of transit use—its effects on land-use patterns and their influence on travel patterns—to be twice as large as the primary effects. They do this by modeling the relationship between land use, transit availability, and travel behavior, again using data from the 2001 National Household Travel Survey. They find a significant correlation between transit availability and reduced automobile travel, independent of transit use. Presumably these effects are linked to rail transit, given its permanence relative to bus transit.

The assumption that this correlation is equivalent to causation is an important one. Other researchers have concluded that although rail transit is a facilitator of land-use patterns, it is *not* a cause. For example, Knight and Trygg's (1977, cited in Badoe and Miller, 2000) study provides evidence that land-use policies, other government policies, and the local and regional economic climate must be coordinated with transit investments in order for positive land development impacts to occur.

Winston and Maheshri

In contrast to Bailey and her colleagues, Winston and Maheshri (2007) study 25 urban rail systems in operation between 1993 and 2000 and find that, with the exception of BART in the San Francisco Bay area, every system reduces social welfare. They calculate the net benefits of urban rail transit systems as the difference between users' consumer surplus and transit agency deficits that must be subsidized. (They note that on average, farebox revenues cover about 40 percent of the operating costs of rail transit.)

Winston and Maheshri estimate demand (in passenger miles) for rail transit as a function of average fare, network density and network connectivity, and city characteristics (such as gas prices, weather, and average commute time). They estimate a short-run total cost equation as a function of output (in passenger miles), prices of labor and fuel, and network variables. They use a short-run total cost equation because of regulations that constrain rail transit agencies from optimizing their operations by adding or abandoning track and stations. They assume these regulations prevent rail transit from operating in long-run equilibrium.

They estimate the marginal cost per passenger mile of rail transit to be about 65 cents in comparison to the average fare per passenger mile of about 20 cents. They also find that some of the large rail transit systems provide large consumer surplus, but that these pale in comparison to their massive deficits. They also factor in congestion savings to road users and the administrative costs of collecting taxes to subsidize the transit deficits, and find that all systems except BART reduce social welfare. They estimate that, if costs were reduced by 20 percent (which they suggest is plausible given the experience with privatization in foreign cities), the systems in New York City and Chicago could also produce positive net benefits.

Winston and Maheshri discount any environmental benefits resulting from rail transit ridership, citing its low load factor, high use of electricity, and use of petrochemicals such as kerosene and bunker fuel, as well as the energy intensity of constructing and expanding new systems, although these assumptions are not thoroughly investigated. As discussed in Chapter 3, the literature on transit efficiency from a greenhouse gas perspective suggests that rail transit does have environmental benefits relative to auto use.

Missing from the calculus in Winston and Maheshri's study is the policy objective of transit systems to provide mobility for the poor. Deka (2002) points out that the two primary policy justifications for public transit subsidies—providing mobility for the poor and reducing auto ownership and use—are mutually exclusive. The former objective suggests that transit should concentrate in central cities; the latter suggests that transit should be extended to moderate- and high-income suburbs, because higher-income households have higher rates of auto ownership and use than lower-income households. Because of the low likelihood of coaxing moderate- and high-income individuals out of their cars,

Deka recommends directing transit services to the segments of the population most likely to use the services.

Baum-Snow and Kahn

Baum-Snow and Kahn (2000) measure the benefits of new investments in rail transit in five MSAs by examining changes in transit use and housing values. They study Boston, Atlanta, Chicago, Washington, D.C., and Portland, the five MSAs with discrete rail transit improvements during the 1980s. One goal of each of the projects was to reduce congestion throughout the city, although two projects (Chicago's and Boston's) were focused on specific locations in the city.

Baum-Snow and Kahn create a measure of each census tract's proximity to rail transit, and find that there is a small but significant amount of mode switching away from autos toward public transit. They also find that the improvements in transit infrastructure have a small, positive effect on housing prices and rents.

Baum-Snow and Kahn (2005) study rail transit systems in 16 cities from 1970 to 2000, a period over which the share of commuters using transit in these cities fell by about half despite investments that improved access to rail transit. They found that in nine of the 16 cities, rail transit experienced small but statistically significant gains in the share of commuters using public transit as a result of the investments. In four cities, they did not find evidence that new rail lines drew new commuters to transit. In the remaining three cities (Atlanta, Washington, and Boston), there were sizeable impacts on ridership from new rail lines.

In cities experiencing gains in ridership, the authors identify significantly reduced commute times as the main benefit of new rail lines. They conclude that the number of new riders will depend heavily on the travel speed of the rail line relative to other modes of travel. That is, it must be faster than driving during rush hour. They suggest, however, that most of the riders on a new rail line are likely to be former bus users.

Baum-Snow and Kahn find that denser, more centralized cities are more successful in drawing new riders to transit than other cities, and suggest that rail transit is more likely to pay off where its speed allows it to be a competitive alternative to the automobile.

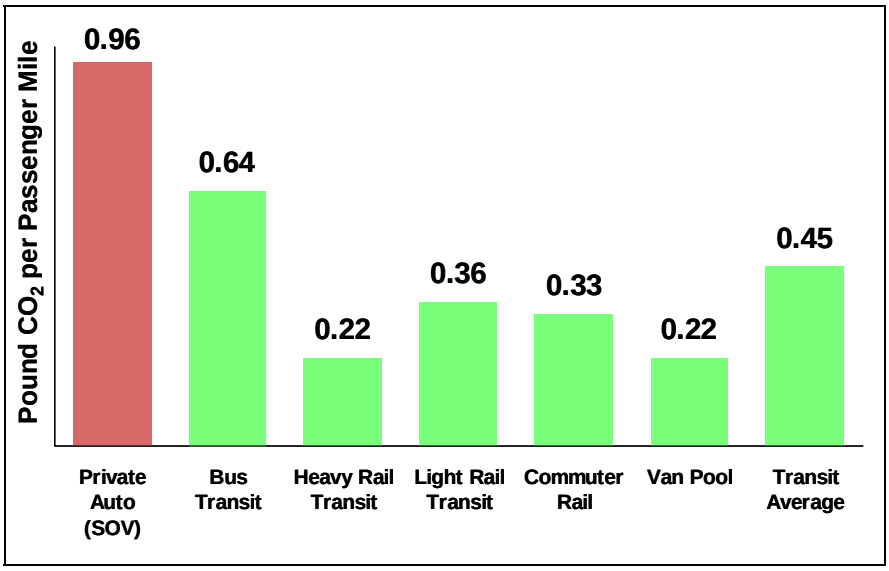
3. Transit Efficiency from a Greenhouse Gas Perspective

The transportation sector today is responsible for 28 percent of all greenhouse gas (GHG) emissions in the United States, up from about 25 percent in 1990 (Kockelman *et al*., 2009). The growth in energy use and, by extension, GHGs from the transportation sector are expected to continue rising. The U.S. Department of Energy projects that transportation energy use will increase 48 percent by 2025 despite improvements in the efficiency of vehicle engines (EPA, 2006).

The most important greenhouse gases (GHGs) produced by the transportation sector include gases that occur naturally – CO_2, methane (CH_4), and nitrous oxide (N_2O) – as well as synthetic chemicals that warm the atmosphere – hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6) (APTA, 2009). The transportation sector is the largest source of CO_2 emissions in the U.S., accounting for about 30 percent of the nation's total. Much of the literature – and therefore this review – focuses on CO_2 emissions, which represent about 96 percent of the transportation sector's GHG emissions (EPA, 2006).

Existing research generally supports the view that an expansion of capacity and ridership of public transit (in particular rail and bus services) is a viable strategy for reducing GHG emissions. As shown in Exhibit 3.1 below, average CO_2 emissions for public transit per passenger mile (PPM) is lower for public transit than private auto travel.

Exhibit 3.1. Estimated CO_2 Emissions per Passenger Mile for Transit and Private Autos



Source: FTA, 2010.
Note: Estimates are calculated as units of fuel used x (lbs CO2 / unit of fuel) / passenger miles

Public transit's efficiency varies considerably, however, suggesting that local context is an important determinant of its effectiveness in reducing GHG emissions. Several factors affect the relative

efficiency of public transit, including the source of fuel and levels of ridership. Public transit's relative efficiency is also affected by its indirect or secondary effects, such as reductions in congestion and facilitation of denser development. However, there is some disagreement in the literature about the importance of these secondary effects.

The most accurate comparison of efficiency between public transit and private auto travel is a comparison of "lifecycle" emissions that includes direct (tailpipe) emissions as well as emissions related to the extraction of crude oil, construction of transportation infrastructure, and manufacture and disposal of vehicles (EPA, 2006).

3.1. Key Findings

- In comparisons of direct, or tailpipe, emissions, public transit produces fewer GHG emissions than single-occupant vehicles, although this conclusion is heavily dependent on levels of ridership.
- In order to fully understand the carbon cost of transit, life-cycle analysis that includes direct emissions as well as those related to construction of infrastructure and manufacture of vehicles is necessary. The dominant contributions to GHG for on-road and air modes are from direct tailpipe emissions. In comparison, rail's energy consumption and GHG emissions are more strongly influenced by non-operational components such as station construction and infrastructure operation.
- Some empirical evidence supports the expansion of public transit as a viable strategy to reduce GHG emissions, although legitimate critiques of this position exist. These criticisms include the energy intensity of the life-cycle of rail, and the difficulty in increasing public transit ridership.
- The GHG emissions of any mode of transport are dependent on the fuel source used. This varies by geographic region and may change over time with the emergence of new technologies.
- The level of ridership or 'load' of public transit impacts whether or not it is more energy efficient than automobile use. Under current loads, rail transit is more efficient than auto use, but diesel buses are less efficient. This is a particularly important consideration for the efficiency of proposed developments given the apparent challenges inherent in attracting new transit riders, particularly to buses.

3.2. Public Transit as a Strategy for Reducing GHG Emissions

A number of researchers conclude that public transit is more efficient than single occupancy vehicles.[115] As demonstrated in Exhibit 3.1, direct (or tailpipe) emissions are lower per passenger mile for public transit than for autos. Several studies attribute secondary impacts on GHG emissions to public transit as well, which increases estimates of emissions reductions from expanding public transit service.

[115] See also Transit Cooperative Research Program, 2008.

The American Public Transit Association's (APTA) (2009) guidance for calculating GHG emissions includes both emissions generated by transit and the potential reduction of emissions through efficiency and displacement of more GHG intense modes. APTA divides transit GHG emissions into two categories: emissions produced by transit (the "debit" side of net transit emissions, which are primarily tailpipe emissions); and emissions displaced by transit (the "credit" side). APTA argues that public transit displaces emissions through three main mechanisms. The first is mode shifts from SOVs to transit. The cars taken off the road lead to the second mechanism, which is congestion relief and thus improved fuel efficiency due to reduced idling and less stop-and-go traffic. Third, "the land-use multiplier" is the result of transit enabling denser land-use patterns that ultimately promote GHG reducing behaviors, such as shorter trip lengths, walking and cycling, and reduced car ownership.

Considering both direct reductions in emissions from more energy-efficient travel as well as reduced congestion from fewer cars on the road, Davis and Hale (2007) find that transit services reduced U.S CO_2 emissions by 6.9 million metric tonnes in 2005. They calculate that an individual switching their mode of commuting from a SOV to an existing transit route can reduce their CO_2 emissions by 4,800 pounds per year, an amount greater than the combined impact of adjusting thermostats and winterizing a home, replacing an old refrigerator, and replacing light bulbs (APTA, 2008b). The authors also argue that public transit facilitates higher density land uses that allow for fewer vehicle miles of travel, although they acknowledge that it is difficult to measure this impact.

Bailey (2007) reaches similar conclusions, finding that public transit ridership reduces U.S. fuel consumption by 1.4 billion gallons per year. Bailey also models the effect of doubling national public transit ridership. The results of this simulation indicate that such an expansion would roughly double the total national fuel savings to 2.8 billion gallons per year (or more if improved coordination between land use plans and public transportation could replace even more car travel).

A critical assumption for Bailey's conclusions is that ridership *can* be doubled by improvements to existing routes and new routes and modal extensions. Work by Baum-Snow and Kahn (2000) casts some doubt on this assumption. Their research shows that the share of commuters using transit in 2000 was about half as large as the share in 1970 despite investments that expanded access to rail transit in 16 cities over this period. This suggests that Bailey's projections may be overestimated. Further, they argue that most of the riders on a new rail line are likely to be former bus users, not new public transit users.

In addition, the energy use and other costs related to public transportation improvements and extensions are not included in Bailey's analysis, which would clearly increase the carbon footprint of public transit.

Similarly, Brown, *et al.*, (2008) quantify transportation and residential carbon emissions for the 100 largest U.S. metropolitan areas and find that both residential density and the availability of public transit are positively associated with lower individual carbon footprints. Finally, Kockelman, *et al.*, (2009) calculate the potential emissions savings for a 1 percent shift away from automobile use to various modes of public transport. Their analysis assumes that average vehicle occupancies (AVOs) remain constant (i.e., transit service rises with demand). They conclude that a shift from single occupancy vehicles (SOV) to public transit may result in reduced carbon emissions; however they are

more cautious in their predictions noting that this any type of meaningful reduction would require an increase in AVO on buses.

Litman (2009) provides an in-depth analysis of the benefits of rail based on an analysis of transportation system performance in major U.S. cities. The analysis divides U.S. cities and their metropolitan regions into three categories: large rail; small rail; and bus only. The study finds that rail travel uses about a fifth of the energy per passenger-mile (PPM) as automobile travel, due to its high mechanical efficiency and load factors (the ratio of the total number of riders to the total theoretical capacity), thereby decreasing GHG emissions per passenger mile traveled.

Beyond its mechanical efficiency, Litman notes there may be further GHG reductions due to rail's potential to reduce congestion by shifting drivers onto transit and have impacts on land use (e.g., transit oriented development). Specifically, through a matched pair analysis he finds that Large Rail cities have about half of the per capita congestion costs as other comparable size cities. Litman argues that transit-oriented development reduces trip generation through the creation of 'more accessible land use."[116] Though he does not provide a systematic, empirical assessment of the effect of reduced traffic generation, reduced congestion, and land-use impacts on GHG emissions, he suggests that overlooking them underestimates the potential reductions associated with rail transport.

3.3. Life-cycle Analysis

The notion that public transit is more efficient from a GHG perspective is generally corroborated by life-cycle analysis of multiple modes of transportation in the United States. Life-cycle analysis assesses the environmental aspects and impacts associated with a product, process or service by considering the relevant energy and material inputs and releases from raw material to final disposal. In the case of transit, a full LCA includes raw materials extraction, manufacturing, construction, operation, maintenance, and end of life vehicles, infrastructure and fuels for all transit options. Chester and Horvath (2009) indicate that this type of cradle-to-grave analysis is critical to addressing the environmental impacts of transportation.

Chester (2008) provides a comprehensive life-cycle energy, GHG, and criteria air pollutant inventory for the passenger transportation modes of automobiles, urban buses, heavy rail transit, light rail transit and buses in the U.S. Each modes' inventory includes an assessment of the vehicles, infrastructure and fuel components. He concludes that public transit trips have significantly less GHG emissions per passenger than personal auto trips.

Chester finds that the life-cycle estimate of energy inputs and emission outputs for each transportation mode increase significantly compared to estimates based solely on the vehicle-operating phase alone. (The study examines carbon dioxide, nitrous oxide, and methane in its analysis of GHG.) Life-cycle GHG emissions are 47-65 percent greater than vehicle operation for automobiles, 43 percent for buses, 39-155 percent for rail, and 24-31 percent for air systems per passenger miles traveled.

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[116] Studies of the impact of transit-oriented development on travel behavior are reviewed thoroughly in the section, Transit Availability.

The dominant contributions to GHG for on-road and air modes are from operations – direct tailpipe emissions. In comparison, rail's energy consumption and GHG emissions are more strongly influenced by non-operational components such as station construction and infrastructure operation (although this can be diminished by reducing concrete use or switching to lower energy input and GHG-intensity materials) (Chester and Horvath, 2009). The EPA (2006) also estimates that the lifecycle emissions for the nation's transportation system are considerably higher than for the operating phase alone. They estimate that the emissions are 27 to 37 percent higher than direct fuel combustion emissions. These LCA findings underscore the complex nature of calculating the GHG emissions associated with a given transit mode.

3.4. Critical Perspectives on Public Transit

Through he does not conduct a detailed life-cycle analysis O'Toole (2008) does consider many of the energy costs associated with the construction of new rail lines (which Litman, discussed above, does not do). O'Toole suggests that the combination of emissions due to construction, low ridership and high greenhouse gas emission rates per passenger mile mean that new rail transit lines may end up using more energy per passenger miles than buses or cars. The starkly different outcome of these two studies underscores the complexity involved in these efficiency calculations. For example, a key assumption in efficiency calculations is the source of energy for public transit (e.g., the hydropower available in the Pacific Northwest has a much lower carbon footprint than coal). A weakness of O'Toole's analysis is that he uses national averages for each mode to calculate the energy use of public transit rather than conducting a more nuanced analysis.

Using Portland's North Interstate light rail as his exemplar, O'Toole calculates (based on the environmental impact statement for this project) that construction of the line would cost 3.9 trillion BTUS and only save about 23 billion BTUs per year. By these calculations, it would take 172 years for the savings to repay the costs in energy. He further argues that over this period the efficiency of cars would have increased to such an extent that there would be no real savings in terms of energy usage. This analysis does not consider possible reductions in congestion and shifts in land-use patterns, factors that Litman (2009) suggests are linked to lower emissions.

O'Toole suggests that an emphasis on technological advances can reduce CO_2 emissions more effectively than rail transit and at a lower cost. Rather than expanding rail service, O'Toole suggests the following transportation strategies to reduce GHG emissions:

- Deploy buses powered by alternative energy sources e.g., biofuels and hybrid-electric motors;
- Focus bus service on heavily used routes;
- Construct new roads, toll systems, and coordinated traffic signals to reduce highway congestion; and
- Provide incentives for people to purchase more fuel-efficient cars.

A potential critique of O'Toole's call for increased bus service is found in Litman (2009). He argues that rail generally attracts more riders than buses, particularly *discretionary riders* (those who have a

choice about transportation modes). He suggests that drawing in more of these riders is an important part of reducing congestion, which in turn reduces GHG emissions. Specifically, he finds that 'large rail' city residents drive 10-40 percent less than 'small rail' or 'bus only' cities, and attributes this to rail's leverage effect on vehicle ownership and land use. Baum-Snow and Kahn's (2000) finding that most of the riders on a new rail line are likely to be former bus users (not new public transit users) supports Litman's assertion.

O'Toole's emphasis on fuel efficiency is supported by others, including Hensher (2002, 2008) who assesses the efficacy of six potential policies that aim to reduce CO_2 emissions in the Sydney, Australia metropolitan area. These include:

- A 10 cent/km variable charge on the main road network between 7 a.m. and 6 p.m.;
- Doubling bus frequency;
- A combination of the variable network charge and doubled bus frequency;
- Reducing rail and bus fares by 50 percent;
- Improving fuel efficiency by 25 percent; and
- Imposing a carbon tax.

The author finds that three of these policies impact emissions in a meaningful way: a variable road network charge; a carbon tax; and improvements in fuel efficiency. The first two result in an increase in use of public transit by increasing the cost of driving, while the improvement in fuel efficiency largely impacts fuel consumption. Of these three instruments, Hensher finds that the one that is the most effective used in isolation is increased fuel efficiency. Of note, he does *not* find that doubling bus frequency will reduce emissions. Ultimately, the author advocates both a variable user charge and improved fuel efficiency as the optimal combination of strategies to reduce CO_2 emissions.

Similarly, in a scenario analysis of how California could reduce transportation GHG emissions 80 percent below 1990 levels by 2050, Yang, *et al.*, (2009) advocate a portfolio approach that includes changing travel behavior and improving fuel efficiency.

Although O'Toole considers impacts of improvements in auto fuel efficiency, he does not consider potential reductions in GHG emissions through energy efficiency improvements of rail. These types of savings are quantified by Sfeir and Chow (2007) in their analysis of the potential energy saving measures for San Francisco's Bay Area Transit (BART) train cars. The energy efficiency measures (EEMs) related to retrofits analyzed in this paper could save an estimated 130 million kWh of electrical energy each year, or 43.1 percent of the BART cars' total electrical energy usage. Furthermore, the EEMs included in this report that could be implemented in BART's new cars may save an estimated 179 thousand kWh/car-year. That savings of this magnitude are not considered in O'Toole's analysis of rail's emissions over time is a serious weakness of the study.

3.5. Fuel Sources

The literature generally assumes a strong correlation between GHG emissions and energy inputs because of the heavy use of fossil fuels for most modes of transport. However, Chester and Horvath's (2009) comparison of two light rail systems highlights the weakness of this assumption. They compare San Francisco's Muni Metro and Boston's Green Line, noting that San Francisco Bay Area's electricity is 49 percent fossil fuel-based and Massachusetts' is 82 percent. The result is that the Green Line (which is the lowest operational energy user and roughly equivalent in life-cycle energy use to the other rail modes) uses less energy than the Muni Metro but has greater GHG emissions. This highlights the importance of identifying the fuel source in any evaluation of a transit system's GHG emissions (as well as identifying the probable fuel source in proposed developments).

Another fuel-related consideration in calculating future GHG emissions from particular transit sources is the use of emerging technologies, such as biofuels. Chauhan and Singh (2009) suggest that using biodiesel as a fuel source for transport would reduce overall CO_2 emissions. They cite studies indicating that the combustion of 1:1 of diesel fuel leads to the emission of about 2.6 kg of CO_2 versus 1.0 kg of CO_2/kg of biodiesel.

Exhibit 3.5-1. Potential CO_2 Emissions Savings for Alternative Fuels Following 1 Percent Change in Light Duty Vehicle (LDV) Miles

Alternative Fuels	Lbs CO_2e per VMT	Δ CO_2e/yr (billion lbs)	% Savings of U.S. Total CO_2e Emissions
Cellulosic Ethanol	0.11	25.5	0.16
Biodiesel	0.40	18.9	0.12
Hydrogen	0.72	11.6	0.07
Compressed Natural Gas	0.88	7.9	0.048
Liquefied Natural Gas	0.95	6.4	0.04
Corn Ethanol	0.96	6.1	0.038
Methanol	1.12	2.4	0.015
Gasoline (Base Case)	1.23	0	0

Assumptions:
1. U.S. LDV VMT/yr = 2.27 billion miles (NHTS 2001)
2. 2003 Avg. LDV fuel economy = 20.3 MPG (EPA 2006)
3. 25 lb CO_2e/gal gasoline (EPA 2007b)
4. lb CO_2e/BTU of alternative fuels derived from Figure 6
5. Remaining 99% LDV miles fueled by gasoline
6. Biofuels estimates do not include the potential affects of increased emissions from land use changes.

Source: Kockelman, *et al.*, 2009

Kockelman, *et al.*, (2009) also explore the potential savings from biofuels, though they caution that the array of production methods and the possibility of causing direct and indirect land conversions

may offset their emission savings. They provide a summary of the potential CO_2 savings from switching 1 percent of the total U.S. light-duty vehicle fleet (cars and trucks) to a variety of alternative fuels (see Exhibit 3.5-1). While they include hydrogen in their analysis, they note that issues with its energy production, distribution and use prevent it from being a realistic option in the near term.

3.6. Levels of Ridership/Load Factors

There is broad consensus in the literature that in order to assess transit's relationship to GHG emissions, calculations must consider a given mode's emissions per passenger mile (PPM). It is intuitive that higher levels of ridership, or 'loads,' decrease emissions PPM. For example, Chester and Horvath (2009) find that emissions PPM of an SUV with two passengers are equivalent to a bus with eight passengers. Similarly, O'Toole notes that the most energy-efficient transit network is in New York City, where its buses average 60 percent greater loads than the rest of the country (more than 17 passengers versus fewer than 11).

Exhibit 3.6-1. Estimates of CO_2 Emissions Savings from a 1 Percent Shift Away from Automobile Mode, Assuming Current Average Vehicle Occupancy and Power Train Technology

Mode	BTU/paxmile	Current Avg. Ridership (pax/veh)	% Savings of Total U.S. CO2e Emissions
Automobile (gasoline)	3448	1.6	-
Bus (diesel)	4160	9	-0.55%
Light Rail (electric)	1160	25	0.70%
Subway/Rapid Rail (electric)	860	23	0.97%
Regional Rail (diesel & electric)	1471	33	0.76%

Assumptions:
1. AVO = 1.6 persons (Davis & Diegel 2007)
2. U.S. LDV VMT/yr = 2.27 billion miles (NHTS 2001)
3. Transit yearly energy use, passenger and vehicle mileage (APTA 2007)
4. In APTA 2007, Subway/Rapid Rail is listed as Heavy Rail, and Regional Rail is listed as Commuter Rail.
5. Gasoline Emissions: 0.00022 lbs CO2e/BTU (EPA 2007a)
6. Diesel Emissions: 0.00024 lbs CO2e/BTU (EPA 2007a)
7. Electricity Emissions: 0.00039 lbs CO2e/BTU (EIA 2000)

Source: Kockelman, *et al.*, 2009

Kockelman, *et al.*, (2009) provide a concise illustration of the importance of load in their analysis of emissions savings for a 1 percent shift away from automobile use to various modes of public transport. They run the data under two different scenarios: 1) assuming that current loads remain constant; and 2) assuming maximum average vehicle occupancies. Under the first scenario, GHG benefits result from the shift to rail transit, which is more efficient per passenger mile than automobile use. However, the shift from autos to buses provides no GHG benefits—in fact, there are increased

CO_2 emissions from diesel buses (see Exhibit 3.5-1). This is because at nine passengers per vehicle, bus AVOs are currently too low to provide GHG benefits (Davis and Diegel 2007). Eleven passengers per vehicle are needed to make an average bus ride equivalent to automobile travel (assuming the average 1.6-persons per automobile AVO).

Under the second scenario, the savings are significant, including a 0.136 percent savings in total U.S. CO_2 emissions from buses alone. Though they recognize that the latter scenario is highly unlikely, it provides a sense of the striking difference that loads make on PPM.

4. Income and Demographics Influences and Other Trends That Affect the Relationship between Residential Density and Climate Change

This section reviews five topics related to transportation and land-use trends that provide a context for the discussion of residential density and its potential impact on the climate. The trend toward ***employment decentralization*** that has occurred since at least the 1950s means that the classic monocentric model of a city is an increasingly poor fit for explaining the way urban areas are structured and thus how people travel. In many metro areas, commutes from one suburb to another are now more common than commutes from a suburb to downtown. The dispersal of jobs has important implications for the viability of public transit as an alternative to the auto, and particularly for rail transit with its inflexible routes.

Trends in ***work versus non-work trips*** show the increasing importance of non-work trips, which also has implications for the use of public transit and for travel patterns. Non-work travel tends to be more complex than work trips (with more destinations combined in a single excursion), and thus to be less well suited to travel by public transit. It is also often discretionary, and therefore more likely than work trips to be influenced by accessibility to shopping, services, and recreation, travel time and pricing, and other factors.

Trends in ***personal vehicle versus commercial truck traffic*** suggest that the latter is becoming an increasingly important source of carbon emissions. However, virtually nothing has been written about the relationship between land use, urban form, and freight and commercial VMT. Given projections for rapid growth in commercial truck traffic in the future, this is a topic that deserves more attention.

The trend toward increasing numbers of ***two-worker households*** has important ramifications for households' decisions about residential location in relation to employment location. Decentralizing job locations in combination with the need to accommodate the commutes of two workers means that most households do not choose their residential locations to minimize commutes into the central business district.

Last, ***income and demographic characteristics*** that are thought to influence travel behavior are discussed. These include income, age, gender, race/ethnicity, immigrant status, and household structure. A more recent addition to the literature is the study of personality or attitudes and how they influence travel behavior. A few researchers are finding that variables that measure personality and attitudes are powerful additions to variables that capture socioeconomic characteristics in explaining travel behavior.

4.1. Employment Decentralization Trends

The migration of people and jobs away from city centers into increasingly distant suburbs represents a long-standing trend in the United States. The dispersal of jobs and workplaces from city centers has been documented with empirical evidence since at least the 1950s and, despite efforts to reverse the trend, continues to the present. As a result, more than twice as many commutes are from suburb to suburb than from a suburb to the central city. While there is some disagreement as to whether central business districts have experienced a slight gain or loss in overall employment, there is wide consensus that jobs outside the city, in suburban, exurban and rural areas, have grown exponentially. Combined, these two factors result in a progressive trend toward employment decentralization.

Given that more people now work outside the city than downtown, the classic monocentric model of a city is an increasingly poor fit for explaining the way urban areas are structured. There is considerable debate over what urban form should replace this outdated theory, with some arguing for a polycentric model, others claiming dispersion, and still others positing a nonlinear spatial evolution process.

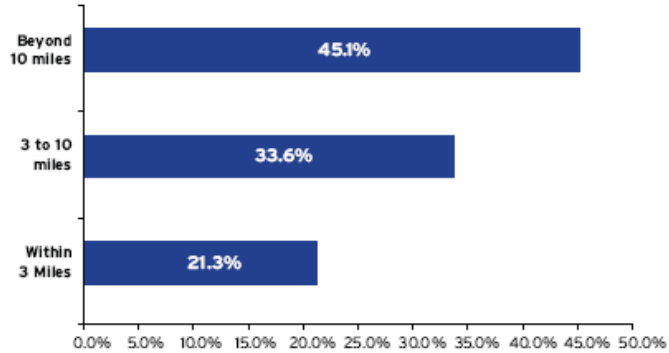
Key Findings

- Jobs are increasingly located further away from the city center rather than closer. Less than a quarter of jobs (21 percent) are now located in the central business district. In comparison, almost half (45 percent) are located farther than 10 miles from the downtown area of the city.
- The denser metropolitan areas are losing employment share, while less dense cities are gaining employment share. The 30 most dense cities accounted for over half of total employment in 1951 (54 percent) but only 40 percent of total employment in 1996.
- The monocentric city model does not apply to many cities. Instead, each city has a unique spatial evolution, and a polycentric model or dispersal pattern rather than a monocentric model may be more appropriate to describe most cities' development.
- More commutes are from one suburb to another than from the suburbs to a central city.

Where Jobs Are Located Today

The norm today for the majority of employees is to work further from the city center rather than closer (Giuliano et al., 2008; Glaeser and Kahn, 2001; Kneebone, 2009; Lee, 2007). Kneebone (2009) analyzes employment share for the 98 largest metropolitan areas using Zip Code Business Patterns data from the Census Bureau's Business Register for the years 1998 to 2006. Exhibit 4.1-1 illustrates the results of the study, which find that in 2006, only 21 percent of employees in the largest 98 metropolitan areas worked within three miles of the downtown area. In contrast, over twice that share (45 percent) worked more than 10 miles away from the city center.

Exhibit 4.1-1. Geographic Distribution of Jobs Within 35 Miles of the CBD, 98 Metro Areas, 2006



Source: Brookings Institution analysis of ZIP Code Business Patterns data

Kneebone also finds that the larger the metropolitan area, the higher the probability that people work more than 10 miles away from downtown. Exhibit 4.1-2 indicates that almost 50 percent of jobs in larger metros like Chicago or Dallas locate more than 10 miles away on average. Comparatively, just 27 percent of jobs in smaller metros like Boise or Syracuse locate the same 10 miles away. Still, a large majority of jobs in small metro areas (72 percent) are located more than 3 miles from the CDB.

Kneebone also analyzes the distribution of jobs within metropolitan areas, and finds that job location varies widely across industries. More than 30 percent of jobs in utilities, finance and insurance, and educational services industries are located within three miles of downtowns. In comparison, just over 21 percent of all jobs are within three miles of central business districts.

Exhibit 4.1-2. Distribution of Jobs within 35 Miles of the CBD by Metro Area Employment Size, 98 Metro Areas, 2006

Employment Class Size	Number of Metro Areas	Total Number of Jobs Within 35 Miles of CBD	Share of Jobs		
			Within 3 Miles of CBD	Within 3 to 10 Miles of CBD	Beyond 10 Miles from the CBD
Large (>500,000 jobs)	45	62,453,654	19.6%	30.9%	49.5%
Small (<500,000 jobs)	53	14,957,838	28.3%	45.1%	26.6%
All Metro Areas	**98**	**77,411,492**	**21.3%**	**33.6%**	**45.1%**

Source: Brookings Institution analysis of ZIP Code Business Patterns data, from Kneebone (2009).

Changes in Job Location over Time

Jobs have dispersed in two dimensions in recent decades. The spread of jobs within market areas, away from the central business district, is referred to as *decentralization*. Jobs have also spread from more dense MSAs to less dense MSAs, a process referred to as *deconcentration*. Both trends are now a more general phenomenon than used to be thought the case (Carlino and Chatterjee; 2002; Giuliano et al, 2008; Glaeser and Kahn, 2001; Richardson and Gordon, 2004; Kneebone, 2009; Lee, *et al.*, 2006; Lee, 2007; Richardson, 2008).

Employment Deconcentration

Carlino and Chatterjee (2002) examine 297 metropolitan statistical areas over 45 years, and demonstrate that the share of all employment in the most job-dense MSAs declined over this period. They use County Business Patterns data, which contain full- and part-time employees covered by the Federal Insurance Contributions Act (FICA) to define employment density.[117] Exhibit 4.1-3 shows the share of all jobs accounted for by the 30 most employment-dense MSAs in each year. In 1951, the 30 most dense MSAs accounted for 54 percent of total employment across the 297 MSAs. But by 1996 the 30 densest MSAs only accounted for 40 percent of total employment in these areas.

Exhibit 4.1-3. Cumulative Employment Shares of MSAs Ranked by Employment Density*

Decile	1951	1959	1969	1979	1989	1996
1	54%	51%	49%	41%	41%	40%
2	64%	63%	61%	61%	63%	59%
3	75%	75%	73%	72%	71%	70%
4	83%	82%	80%	78%	79%	77%
5	88%	87%	86%	84%	84%	84%
6	92%	91%	90%	88%	88%	88%
7	95%	94%	93%	92%	92%	91%
8	97%	97%	96%	95%	95%	94%
9	99%	98%	98%	98%	98%	98%

* The top nine deciles contain 30 MSAs each and the bottom decile contains 27. The cumulative employment share for the tenth decile is not reported because it is always unity.

With only a couple of exceptions, employment share for every cumulative category declined from one observation year to next. As mentioned, the 30 densest cities accounted for 54 percent of total

[117] Employees who are exempt from FICA, such as government employees, the self-employed, and railroad workers are generally not included in the County Business Patterns data.

employment in 1951 but only 40 percent of total employment in 1996. Correspondingly, the cumulative employment share of cities below the first decile rose from 46 in 1951 to 60 percent in 1996. There is a clear declining trend in the employment share of dense metropolitan areas and corresponding rise in the share of less dense ones.

Carlino and Chatterjee suggest that deconcentration results because an increase in employment causes congestion costs to rise faster for job-dense MSAs than those with lower employment density. Given an increase in employment in the economy, the job-dense MSAs will grow less rapidly than less dense MSAs, and the employment share of the densest MSAs will decline, as shown in Exhibit 4.1-3.

Employment Decentralization

Kneebone (2009) found that nearly all metropolitan areas she studied (95 out of 98) saw a decrease in the share of jobs located within three miles of downtown between 1996 and 2006. The number of jobs in the top 98 metropolitan areas increased overall during this time period. However, the outer parts of these metropolitan areas saw employment increase by 17 percent, while the urban core gained less than one percent in jobs. Overall, the area within three miles of downtown lost 2.1 percent of metropolitan job share between 1998 and 2006 while the share of jobs located more than 10 miles from downtown grew by 2.6 percent.

Exhibit 4.1-4 shows that metropolitan areas decentralize at different rates. More than half of the metro areas (53) studied experienced rapid decentralization, while 30 experienced moderate decentralization, 12 cities shifted to the middle, and three cities actually experienced an increase in the number of jobs within three miles of downtown. Although the majority of metro areas fall into the rapid decentralization category, the 30 cities that experienced moderate decentralization distinguish themselves from the greater majority in that, while losing job share around their downtowns, the 3 to 10-mile ring gained job share along with the outer ring of above 10 miles. While jobs shifted outward in these 30 metropolitan areas, these cities, including Las Vegas and San Francisco, did not experience the rapid pace of decentralization that many other metro areas did.

Exhibit 4.1-4. Change in the Geographic Distribution of Jobs by Metro Type, 98 Metro Areas, 1998-2006

		1998 Share of Jobs			2006 Share of Jobs			Change in Share of Jobs 1998 to 2006		
No. of Metros	Type	Within 3 Miles	3 to 10 Miles	More Than 10 Miles	Within 3 Miles	3 to 10 Miles	More Than 10 Miles	Within 3 Miles	3 to 10 Miles	More Than 10 Miles
53	Rapid Decentralization	20.7%	36.0%	43.4%	18.5%	34.3%	47.2%	-2.2%	-1.7%	3.9%
30	Moderate Decentralization	27.6%	30.3%	42.1%	25.5%	31.5%	43.0%	-2.0%	1.2%	0.9%
12	Shift to the Middle	28.8%	32.0%	39.2%	27.3%	34.9%	37.8%	-1.5%	2.9%	-1.4%
3	Gains in the Center	26.9%	44.5%	28.6%	28.1%	42.3%	29.6%	1.2%	-2.2%	1.0%
98	**Total**	**23.3%**	**32.4%**	**42.5%**	**21.3%**	**33.6%**	**45.1%**	**-2.1%**	**-0.5%**	**2.6%**

Source: Brookings Institution analysis of ZIP Code Business Patterns data from Kneebone (2009).

In contrast, cities experiencing a shift to the middle actually saw the share of their jobs located more than 10 miles from downtown drop during this period. As a whole, the 12 cities in this category experienced an increase of almost 3 percent in the middle ring while the inner and outer rings saw about a one-and-a-half percent decline in share. These cities gained employment in the 3- to 10-mile ring, either at a faster rate than the urban core and outer ring (e.g. Boston or Allentown) or while downtown and outer-ring jobs declined (e.g. Greensboro and Youngstown).

The only three cities that experienced gains in the core ring were Milwaukee, WI, Chattanooga, TN, and Oxnard-Thousand-Oaks-Ventura, CA. Of these three, only one saw the share of jobs in the urban core increase by more than one percent. This city, Oxnard-Thousand-Oaks-Ventura, is a fast-growing region anchored by two central business districts, in "boomburbs" that have sustained double-digit population growth each decade between 1950 and 2000, and have continued to grow since 2000. Moreover, Oxnard and Ventura are located in a county with strong urban containment policies influencing development.

Richardson and Gordon (2004) point out that although there has been a great deal of press about recent center city revivals and reurbanization, trends in land-use patterns continue to be dominated by suburbanization and exurbanization. In a study of New York City, Los Angeles, and Chicago 1996 Zip Code Business Patterns data, Glaeser and Kahn (2001) found that average employment share of activity in each metropolitan area's major county dropped from approximately 47 percent to less than 40 percent from 1950 to 1993.

Similarly, in a study of six major metropolitan areas using Census Transportation Planning Packages data from 1980 to 2000, Lee (2007) found that all downtown areas lost employment share. Although decentralization has occurred within all six of these areas, there is significant variation in spatial trends. These findings are also consistent with a trend toward employment decentralization, with suburban county employment growing faster than core county employment (Lee, 2007; Richardson, 2008).

Decentralization of Employment across Industries

The trend toward decentralization of employment is occurring in virtually every industry. Kneebone (2009) found that in almost every major industry, jobs shifted away from the city center between 1998 and 2006. Of 18 industries studied, 17 experienced employment decentralization. Transportation and warehousing, finance and insurance, utilities, and real estate and rental and leasing showed the greatest increases in the share of jobs located more than 10 miles away from downtown.

Glaeser and Kahn (2001) offer several explanations for employment decentralization. They review 335 metropolitan areas and that find cities that specialize in services—which require high levels of human capital—are relatively centralized, while cities that specialize in manufacturing tend to sprawl. They theorize that dense urban areas facilitate the speedy flow of ideas, and industries that require high human capital are more idea-intensive.

They also find that the main determinant of the degree of suburbanization is the demand of workers for suburban lifestyles. As workers move out to the suburbs, industries will follow and shift their workplaces to access their employees.

Differences in Decentralization by Region

Although almost every major metropolitan area experienced job dispersal, there are differences in the degree of decentralization by region. Glaeser and Kahn (2001) find that the Midwest is the most decentralized, while the West and Northeast are the most centralized regions.

Kneebone (2009) examines trends in employment decentralization across regions, and finds that although all four regions of the U.S. saw employment share shift away from the urban core, the South experienced the greatest decentralization in employment between 1998 and 2006. Southern cities experienced the largest decrease in urban core job share among the regions (2.8 percent), coupled with a 4.8 percent increase in the outer-ring. The West experienced the next largest decrease in urban core job share, followed by the Midwest and then the Northeast. As a whole, all regions experienced employment decentralization, and regional patterns are less extreme than thought.

Implications of Changing Job Location for Urban Form

The continuing trend of employment decentralization indicates that the traditional view of the monocentric city is a poor approximation for the reality of most American cities (Giuliano *et al.*, 2008; Glaeser and Kahn, 2001; Lee, 2007). Although criticisms of the classic monocentric model are not new, they have become more justified over time, in light of increasing evidence of decentralization. There is much debate as to what form, if any, cities are following in their evolution. Previous literature has posited that cities are following a polycentric form instead of a monocentric model (Anderson and Bogart, 2001). Glaeser and Kahn (2001) argue that in some cities, jobs are dispersed without any centering. Another view is that cities do not evolve in a uniform, linear manner, and each city has its own growth form, with some leaning towards polycentric and others simply dispersed (Lee, 2007).

In the past, the monocentric model was useful in understanding several aspects of urban form and travel behavior, including why housing prices decline with distance from city center, commute times rise with distance from central business district, and the poor live in the city center. Glaeser and Kahn (2001) demonstrate that more recently, the model is not useful for many cities. First, in metropolitan areas where employment is centralized, housing prices decline with distance from downtown. However, in decentralized metropolitan areas, this decline is much milder. Second, in a centralized city, commute times rise with distance from the central business district, because of sprawl and congestion. In contrast, in decentralized metropolitan areas, commute times barely rise with distance from the central business district. Logically, when jobs are in the suburbs, people who live in the suburbs have shorter commutes. Lastly, the theory of the monocentric city theory holds that the poor live in the city center because of the demand for land among the rich or because the poor use time-intensive public transportation. The implication is that income will be higher in the suburbs than in the city center. However, in more decentralized cities, poverty is also more dispersed. This connection suggests that the poor may not be clustered in central cities. When jobs are in the suburbs, the poor are also more likely to be in the suburbs.

As the consensus on the outdated nature of monocentric model has solidified, it has been replaced by debate about what model metropolitan areas follow (Giuliano *et al.*, 2008; Glaeser and Kahn, 2001; Lee, 2007). Some have argued that instead of a monocentric model, metro areas today follow a polycentric form. According to this view, suburban employment is much more decentralized than the monocentric model allows, and a better model posits that employment is spread evenly throughout the suburbs. However, others argue that metro areas do not follow a polycentric form, but rather are just diffuse (Glaeser and Kahn, 2001). In the vast majority of metropolitan areas, suburban employment is much more dispersed than central city employment. As this is the case, suburban employment is best thought of as being decentralized, not polycentered. Many policies that hinge on the monocentric model, such as the location of the poor, need reexamining if suburban employment is not centered as monocentricity and polycentricity suggests.

Lee (2007) offers a third perspective: that metropolitan spatial evolution may be more nuanced than a simple either-or division. Rather, the evolution should be thought of as more than a linear process from monocentric to polycentric, polycentric into dispersed, etc. A more plausible scenario is that some metropolitan structures are undergoing the transition to a polycentric structure, and others are more likely to diffuse. In other words, cities evolve in different ways. For example, New York and Boston follow a more monocentric model, whereas San Francisco and Los Angeles follow a more polycentric model, and Portland and Philadelphia illustrate job dispersion.

Implications of Changing Job Location for Commuting Patterns

Employment decentralization has important implications for commuting patterns. Commutes are far less likely to be "traditional" commutes from a suburb to a central city today than they were in the past. In 2000, 46 percent of all metropolitan commutes were from suburb to suburb. In comparison, only 19 percent of commutes were from the suburbs to the central city. Reverse commutes from the central city to the suburbs made up another 9 percent of all metropolitan area commutes, and commutes from central city to central city another 26 percent. The large majority of the former were commutes within the central city; a small percentage was commutes from one central city to another central city (Pisarski, 2006).

4.2. Trends in Work versus Non-Work Trips

Over the past decades, the share of all trips taken to go to work has fallen by more than half—from about 32 percent of trips in 1969 to about 15 percent of trips in 2001 (see Exhibit 4.2-1). Other measures do not show such precipitous declines (total miles traveled for work is down by about 5 percentage points, for example), but it is clear that understanding non-work travel is increasingly important in the debate about land-use patterns and the climate.

Work travel and non-work travel are different in a number of important ways. Non-work trips are often discretionary, and may be more influenced by the relative location of residential and non-residential uses of the built environment, travel time, pricing, and other factors.[118] For example,

[118] See, for example, Zhang, 2005.

Cervero and Kockelman (1997) find that living in mixed-use development has a significant effect on VMT for non-work trips, but its effect on VMT for all trips is insignificant. On the other hand, given its complexity (such as variation in destinations and trip chains that combine several destinations in one tour), non-work trips may be less influenced by public transit options than work trips.

This section reviews historical trends in work and non-work travel, as well as factors that may explain these trends. The definition of what constitutes a work trip is an important methodological issue in the literature on work versus non-work trips. The traditional definition of "home-based work trips" counts only trips directly to and from work, without intervening stops. However, more than half (54 percent) of weekday commuters stop for a non-work purpose during their commute, indicating that the traditional definition underestimates work-related travel (McGuckin and Srinivasan, 2005).

Some studies use the concept of a work tour—which includes the total travel between home and work including stops for non-work purposes—to better capture travel related to commutes.[119] These differences in definitions limit comparisons across studies.

Key Findings

- The proportion of trips made for work purposes has decreased over time as the number of non-work trips has increased at a faster rate than the number of work trips.
- The decreased share of work-related travel is not due to a decline in workers or fewer trips taken per worker, but to more non-work trips taken per person. The increase in the proportion of non-work travel has occurred across all income groups.
- The built environment may impact the number of non-work trips, although more research is needed to identify the most important factors. Research demonstrates that for some types of non-work trips, the accessibility of the destination increases the time spent traveling and the number of trips taken to that destination. However, an increase in the variety of shopping and recreational opportunities may also be responsible for the increase in non-work travel.
- Commute length is a determinant of non-work travel: a longer commute (time) decreases non-work travel. This suggests that households may have a budget for total travel time, so that savings in commute times are used to support more non-work trips.
- Non-work auto trips are sensitive to the costs of travel when measured by time. Faster trips encourage non-work auto trips, but longer trips (distance) discourage non-work auto trips.

Growth in Proportion of Non-Work Trips

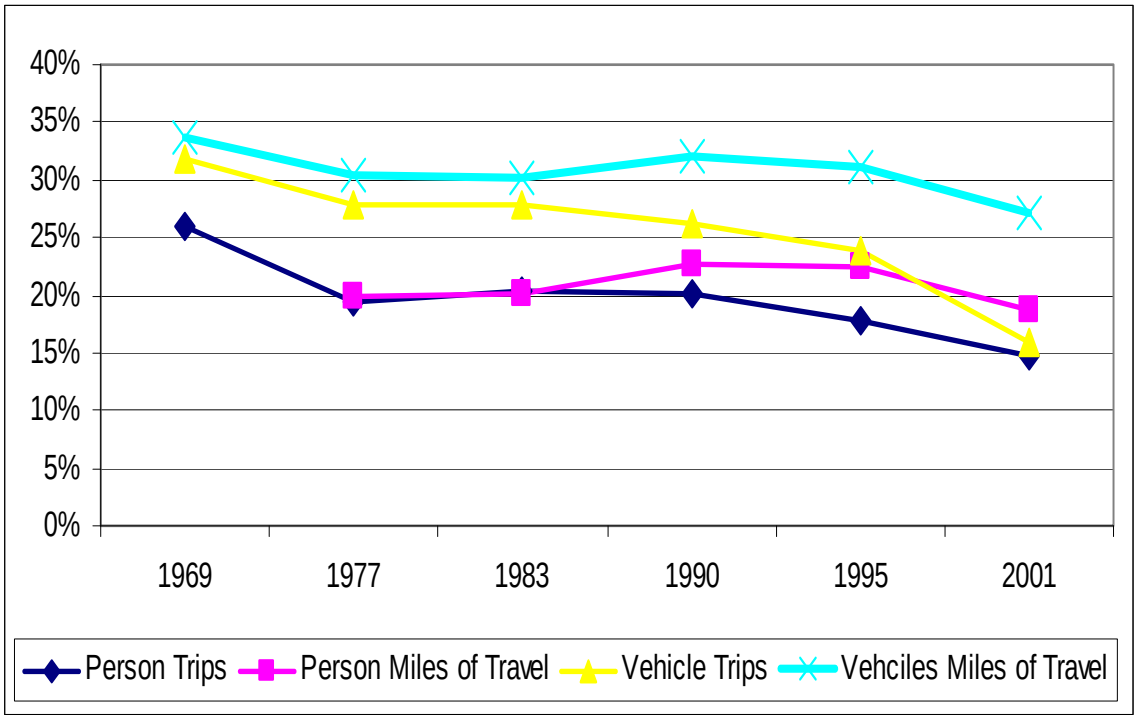
During the 1970s, 1980s, and 1990s, the proportion of travel dedicated to trips to and from work—measured in a variety of ways—has decreased. McGuckin and Srinivasan (2005) analyze decennial

[119] Further, some research defines work tours as those that incorporate stops of 30 minutes or less; others place no limit on the length of the stop (or "dwell time").

Census, National Personal Travel Survey (NPTS),[120] and National Household Travel Survey (NHTS) data. They find that work travel decreased from 25 percent of all person trips in 1969 to 16 percent in 2001, and decreased from 34 percent of vehicle miles traveled to 27 percent in 2001. As a result, households are spending more time on travel for non-work purposes, such as family and personal errands, shopping, and social and recreational purposes.

Exhibit 4.2-1 shows the decreasing proportion of work travel by a variety of measures. Overall since 1969, vehicle miles of travel for work trips have decreased by about seven percentage points, while vehicle trips have fallen by more than half and person trips for work purposes has fallen by more than 10 percentage points.

Exhibit 4.2-1. Trends in Travel to Work as a Proportion of All Travel, 1969-2001



Data from 1969, 1977, 1983, 1990, and 1995 NPTS and 2001 NHTS.

Source: McGuckin and Srinivasan, 2005.

The declines in the share of VMT and trips for work occurred despite the increases in labor force participation over this period, when baby boomers and women joined the workforce in large numbers.

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[120] The 1995 NPTS includes adjustments to its survey methodology that may affect comparison of trends across studies. For the 1995 survey a travel diary was used in lieu of memory recall and new techniques were used to capture additional trips that may have been overlooked previously. Therefore, some researchers warn against the use of comparisons between pre- and post-1995 NPTS and NHTS data. Others, such as Hu, *et al.*, (2004) adjust the 1990 NPTS data to be more comparable to later iterations of the survey. The adjusted 1990 data show an increase in person trips for work between 1990 and 1995 and a decrease in person trips for work between 1995 and 2000.

The proportion of workers has increased from 37 percent of the total population in 1970 to about 46 percent during the 1990s (McGuckin and Srinivasan, 2005).

Nelson and Niles (2000) examine changes in work and non-work travel in more detail and show that the largest growth in personal trip frequency occurred for shopping and "other family and personal business" trips. The number of vehicle miles traveled for these two trip categories more than doubled between 1977 and 1995.

Factors Affecting Non-work Travel

Several researchers explore the factors that may explain the increases in non-work travel. These factors include labor market changes, the spatial organization of the built environment, commute length, and the price of travel. For research that relies on the traditional definition of home-based work trips that excludes work trips with intervening stops, the increase in this latter category of trips has contributed to the increased share of trips made for non-work purposes.

Socio-demographic Changes

McGuckin and Srinivasan (2005) suggest that the decrease in the proportion of work-related travel between 1990 and 2001 is not due to a decline in workers, nor to fewer work trips taken per worker. In fact, NHTS data show that 20 million workers were added in that decade and the average number of daily work trips per worker remained relatively unchanged between 1990 and 2001, decreasing only from 1.16 to 1.14. Instead, households simply added trips for other, non-work purposes. The authors calculate that between 1990 and 2001, the average American adult added only 22 work trips but also added 45 trips per year for social recreation, 35 for shopping, 31 for family or personal errands, and 76 for other purpose trips.

One factor that has likely contributed to the growth in non-work travel is general increases in income levels. Nelson and Niles (2000) hypothesize that these increases may allow households to pursue more leisure activities, thus traveling more for non-work purposes. The authors use Census data to point out that between 1977 and 1983, real disposable income increased 8 percent and real personal consumption expenditures increased 7 percent. However, they do not research the relationship between rising income and non-work travel, suggesting this as an area for further research. But clearly factors other than just income growth are associated with the growth in non-work travel. Gordon *et al.* (1988) find that while higher-income households make more trips overall, the increase in non-work travel between 1977 and 1983 occurred in all income groups. Similarly, McGuckin and Srinivasan (2005) look at 2001 travel data by income group and find that across all income groups, workers spend more time traveling for non-work purposes than for work purposes. However, the difference in time spent on non-work and work trips was larger for households with higher incomes than households with lower incomes.

Built Environment

Although the literature is inconclusive on the impacts of changes in the built environment on non-work trips, decentralization is one plausible explanation for the increase in non-work trips over the past decades. Gordon, *et al.* (1987, cited in Gordon, *et al*., 1988), argue that the process of suburbanization, in which firms and households have relocated and settled closer to each other, has permitted efficiencies for work travel, facilitating shorter commutes and relieving congestion.

However, in a 1988 study, they observe much larger increases in non-work travel in suburbs than in central cities between 1977 and 1983-84. Based on this observation they hypothesize that efficient spatial settlement relative to job locations has reduced commute trip costs in terms of time and distance, which in turn has allowed people to take more leisure trips. That is, one consequence of suburbanization was a dramatic increase in non-work travel.

Nelson and Niles (2000) note that Gordon, *et al*. (1988), failed to control for differences in population growth between suburbs and central cities in their analysis. With these controls, the differences in the growth of non-work trips in the two types of areas are much smaller than Gordon, *et al.*, observed. Although they acknowledge that decentralization could be a factor in the growth of non-work trips, they reject the argument that it is the most important factor. Instead they argue that the changing commercial marketplace, specifically a large increase in the variety and opportunity for shopping, eating out, and other non-work activities, has caused more non-work trips per person. In addition, the increase in "mass retailers" (i.e., discount department store and superstores such as warehouse clubs and home centers) and clusters of stores has made it easier to shop and more efficient to combine trips into the same travel tour, making non-work trips more attractive.

Research on the impact of accessibility—availability of destination opportunities and the travel time or distance to reach a destination—on non-work trips suggests that to the extent that both decentralization and changes in the commercial marketplace improves accessibility, both are likely to increase travel for non-work purposes. Zhang (2005) finds that better accessibility to a variety of non-work activities increases the time and trip frequency associated with those activities.[121] For example, better accessibility to schools increases the time spent traveling and the number of trips taken to schools. The same is true for increases in accessibility to social activities.

However, Zhang finds that an increase in shopping accessibility is associated with fewer shopping trips but longer travel times. Zhang explains this contradiction by noting that using his measure of accessibility (incorporating both travel time/distance and destination opportunities), regional shopping centers with a higher concentration of stores will produce higher accessibility scores than local retail and convenience stores. Therefore, to the extent that people shop at large, regional shopping centers, they may take fewer overall trips but spend longer amounts of time traveling there. To better understand this finding, Zhang recommends that local shopping trips and regional shopping trips be examined separately.

Commute Length

The idea that households have a relatively constant travel time budget and allocate the budget between work and non-work travel was proposed by Zahavi and Ryan (1980). More recent research supports this idea, which implies that commute length is a determinant of non-work travel. Gordon *et al.* (1988) suggest that by reducing the time and distance traveled for work, suburban spatial patterns allow for more time for non-work travel.

In more recent research, Purvis *et al.* (1996) find an inverse relationship between work trip duration and non-work trip frequency. The authors calculate demand elasticities of trips and find that a 10

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[121] See also Bhat and Gossen, 2003 and Levinson, 1999.

percent decrease in regional work trip duration yields a 1.2 percent increase in regional home-based shopping or other trips and a 0.9 percent increase in regional home-based social or recreation trips. They also find that the impact of work trip duration on shopping trip generation has increased over time.

Further, the authors find that working households who do not commute have the highest trip rates for home-based shopping, social, recreation, or other trip purposes. They suggest two possibilities for this finding. Non-commuting workers may participate in more out-of-home non-work activities than workers who commute long distances, or commuting workers may chain their trips to work with non-work activities on both ends of their commute, making it appear as though they do not take any home-based work trips.

Purvis *et al*. (1996) also find that multi-worker households are more sensitive than single-worker households to the effect of work trip duration on non-work travel for shopping trips. However, they find the opposite effect for social/recreation trips—single-worker households are more sensitive to the effect of work trip duration on the amount of time spent on social/recreation trips compared to multi-worker households. The authors suspect that these findings may provide insight on how commuting congestion affects or induces additional travel.

Travel Costs

Also consistent with the hypothesis of a relatively constant household travel time budget, research indicates that people take more non-work trips when travel times are shorter Boarnet and Crane (2001) explore the effect of travel costs (defined as travel time)[122] on the number of non-work auto trips. They theorize that households will choose the number of trips they take based on their time travel "budget," which is a function of the value they place on time, captured by income and other sociodemographic characteristics. Using data from San Diego and Orange County, they find that higher median trip speeds, and thus shorter travel times, increase the number of non-work auto trips per person, but that higher median distance decreases non-work auto trips.

Trip-Chaining

Another factor affecting the decrease in work trips is an artifact of a definition of work trips that may be increasingly outdated. That is, workers are increasingly combining non-work destinations with their commutes, called trip-chaining. As noted above, some studies do not count trip chains that include a non-work stop as a work trip. McGuckin and Srinivasan (2005) demonstrate this trend by isolating:

- Home-based work trips (no stops between work and home),
- Home-based non-work trips (no stops between home and non-work destination), and
- Non-home based trips (trips with neither end at home).

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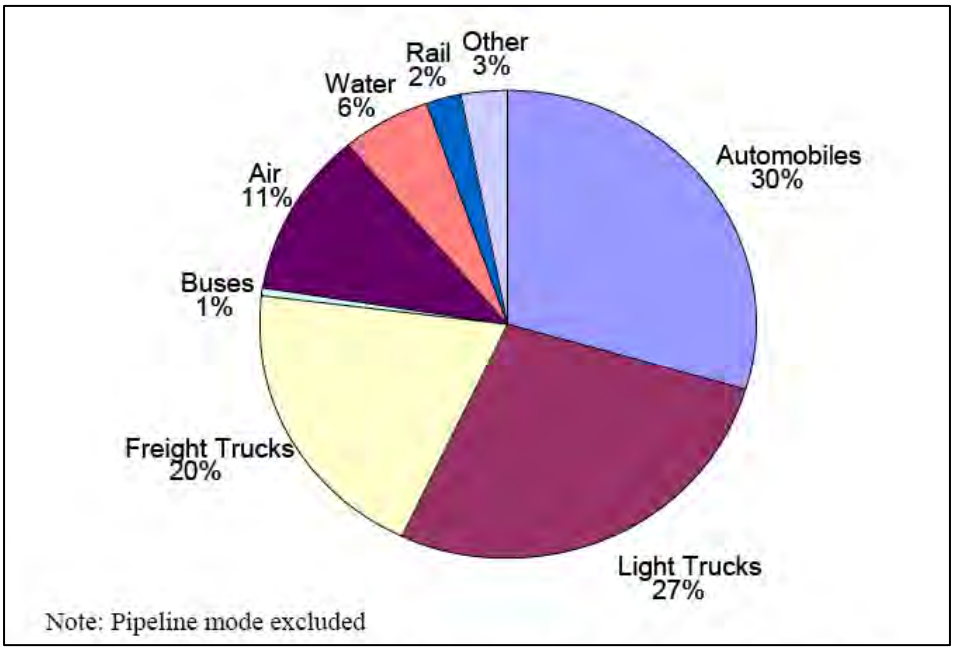
[122] Studies that include measures of travel costs—including those reviewed here—typically define "cost" as travel time. Monetary costs, such as for car ownership and gas prices, are often excluded because there is little variation in these costs across drivers, particularly in studies that focus on one or a small number of metropolitan areas.

They find that weekday, home-based work trips have decreased between 1990 and 2001 while weekday, home-based non-work trips and weekday, non-home based trips have increased among the working age population. An example of a non-home based trip may include a trip from a coffee shop to work that occurs after a home-based non-work trip (from home to the coffee shop). The decline in home-based work trips may imply that more people are adding stops to their commute that, according to this typology, changes a home-based work trip into a home-based non-work trip followed by a non-home-based trip. As noted above, 54 percent of workers make stops during their commute.

4.3. Trends in Personal Vehicle and Freight and Commercial Truck Traffic

The large majority of the literature on the relationship between land-use patterns and climate change focuses on the travel behavior of drivers in personal vehicles—commuting trips and those taken for non-work purposes. The focus on travel behavior is appropriate: the transportation sector is a significant source of carbon emissions, representing 28 percent of the U.S. total emissions in 2008 (Kockelman, *et al.*, 2009). Further, personal vehicles (automobiles and light trucks) account for the majority of total emissions, accounting for about 57 percent. The next largest category, freight trucks[123] (including light duty commercial trucks) accounts for another 20 percent (see the pie chart, from Southworth, *et al.*, 2008).

Exhibit 4.3-1. Share of 2005 U.S. Transportation CO_2 Emissions by Mode



This section reviews historical trends in both types of traffic, as well as projections for the future. These trends provide some context for the role of commuting and non-work trips in contributing to climate change relative to that of other transportation modes.

[123] Definitions vary by authors, but freight is generally defined to include the transport of goods and VMT associated with deliveries. Commercial traffic is generally defined to include service workers such as plumbers, construction vehicles, and trash pick-up.

Key Findings

- The transportation sector is a significant source of carbon emissions, accounting for 28 percent of emissions in the U.S. in 2008.
- Personal vehicles, which include automobiles and light trucks, make up the majority of total emissions, representing 57 percent. The next largest category, freight, which includes light duty commercial trucks as well as heavy trucks, accounts for another 20 percent of emissions.
- Freight traffic on urban highways is growing much faster than private vehicles. Within freight, truck share is growing much faster than other modes.
- Little research has been conducted on the relationship between land use, urban form, and freight and commercial VMT.

Growth in Transportation Sector Emissions

In addition to being a significant source of carbon emissions, the transportation sector is a rapidly growing source of emissions in the United States. Total U.S. greenhouse gas (GHG) emissions rose 13 percent between 1990 and 2003, while those from the transportation sector rose 24 percent (Kockelman, *et al.*, 2009). From 2007-2050, the EPA estimates that the transportation sector's CO_2 equivalent (CO_2e) emissions will increase by 2 billion metric tons. About half of this growth will come from passenger vehicles, 20 percent from heavy-duty trucks, and the remaining 30 percent from other modes including air, rail, and water modes (EPA, 2007, cited in Kockelman, *et al.*, 2009).

Exhibit 4.3-2, from Southworth, *et al*. (2008), indicates that highway VMT increased between 2000 and 2005 for both personal vehicles (autos and light trucks) and commercial trucks, in roughly similar proportions. Fuel consumption by heavy trucks declined over this period, however, because of improvements in the average miles per gallon reported for these trucks, offsetting the rise in VMT.

Although growth in VMT was roughly similar for private vehicles and heavy trucks from 2000-2005, longer-run trends indicate that freight traffic (VMT) on urban highways is growing much faster than private vehicles. Exhibit 4.3-3 from Bronzini (2008) shows growth in VMT on urban highways for the ten-year period ending in 2006. The increase in VMT for passenger vehicles was about 23 percent, compared with much larger increases in truck traffic of almost 39 percent to over 42 percent, depending on the type of truck.[124] The growth is a result of expanding international trade as well as innovative manufacturing and distribution supply chain practices such as just-in-time delivery (Bronzini, 2008).

[124] Combination trucks are considered freight; single-unit trucks are considered commercial; and other 2 axle 4 tire vehicles include some commercial and some private use.

Exhibit 4.3-2. Transportation Energy and Carbon Totals for the United States

Estimated Annual Totals:	Year 2000	Year 2005	% Change 2000-2005
Highway VMT (trillion miles)[a]			
Total	2.74	2.99	9.1
Autos and other 2-axle 4 tire vehicles	2.52	2.75	9.1
Trucks[b]	0.205	0.223	8.8
Highway Fuel Consumed (billion gallons)[a]			
Total	162.6	174.3	7.2
Autos and Light Trucks	126.0	139.3	10.6
Heavy Trucks	35.2	33.5	-4.8
Highway Energy (Quads)[c]			
Total	20.8	22.0	5.8
Autos and Light Trucks	15.7	17.2	9.6
Heavy Trucks	4.8	4.6	-4.2
Carbon Emissions (million metric tons)[d]			
Highway Travel	399.6	430.2	7.7
Autos and Light Trucks	305.1	338.0	10.8
Heavy Trucks	93.5	88.9	-4.9

[a] Source: Highway Statistics 2000 and 2005, Table VM-1
[b] Includes 2-Axle, 6 or more tire single unit as well as combination trucks.
[c] Source: Transportation Energy Data Book 2007 (Table 2.7)
[d] Based on data reported in Transportation Energy Data Book 2007 (Tables 2.7 and 11.4)

Note: Energy reported in gross BTU[2]

Exhibit 4.3-3. Vehicle Travel on Urban Highways in the U.S. (billion VMT)

Year		Passenger Vehicles	Other 2 Axle 4 Tire Vehicles	Single Unit Trucks	Combination Trucks	Total
1996	VMT	940	508	30.7	42.7	1522
	%	61.8	33.4	2.0	2.8	100
2006	VMT	1158	716	43.7	59.2	1977
	%	58.6	36.2	2.2	3.0	100
Increase in VMT		218	208	13.0	16.5	455
% Increase		23.2	40.9	42.3	38.6	29.9

Source: Federal Highway Administration, *Highway Statistics*, various issues, Table VM-1.

For overall expected growth, total freight tonnage is forecasted to double between 2002 and 2035. Of the five freight modes (air, water, pipeline, truck, and railroad),[125] trends indicate that truck's share of this freight is increasing because of its scheduling and routing flexibility. Kockelman, *et al.,* (2009) estimate that over the last 15 to 20 years, truck's share of all freight ton-miles[126] has increased from 26 percent to 32 percent. At the same time, truck energy efficiency (ton-miles per pound of CO_2) has fallen 10 percent. The study suggests that this drop in energy efficiency is due to decreases in operational efficiency (e.g., more miles where trucks are traveling empty) since truck fuel economy has remained constant or increased over the same time period.

Gaps in Research on Truck Traffic

According to Bronzini (2008), virtually nothing has been written about the relationship between land use, urban form, and freight and commercial VMT. In lieu of national studies, Bronzini reviewed eight state- or city-level freight studies (New York, Atlanta, Chicago, Houston, Norfolk, VA, Ohio, New Jersey, and Washington) and one study examining an interstate corridor. Truck traffic and truck share of vehicular traffic is expected to grow in all states surveyed.[127]

The studies reviewed provide limited insight into the factors that determine truck VMT. The traffic levels reported in the eight state- or city-level studies indicate that major port and logistics centers are significant contributors to truck VMT. However, the interstate freight-related study, which focused on the states along the I-10 corridor, found no strong correlation between any of the truck traffic data and the number of intermodal facilities.[128] Based on the data, it is difficult to make a case for a pattern in freight distribution activities in explaining observed urban truck annual average daily traffic and VMT. The author suggests this may be due to the confounding effects of other variables, including the fact that the truck data include commercial vehicles as well as freight vehicles.

Bronzini suggests several areas for additional research on the relationship between urban form and freight and commercial traffic. Lower-density development is positively associated with freight and commercial truck VMT, but little empirical research exists to determine whether this relationship is causal or to identify the factors that influence this relationship. Moreover, the literature available on whether employment and residential dispersal has affected commercial VMT growth is mixed and needs further research for clarification. Studies of how big box retailing and the increase in direct shipment of goods to consumers' homes (through catalog and internet shopping) affects goods movement within a metropolitan area. Finally, the influence of urban form on commercial VMT in metropolitan areas with major ports, airports, and distribution centers deserves more attention.

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125 Among the freight modes, rail is the most fuel efficient. According to the EPA, in 2001 air carriers used 7.5 times more energy to carry a ton-mile than the average truck, 17 times more than ships, and 83 times more than rail (EPA 2006, cited in Kockelman, *et al.,* 2009).

126 A ton-mile is one ton of freight shipped one mile.

127 Not all states had specific projections of growth in VMT for truck traffic, so results are not reported here.

128 An intermodal facility is a location where freight changes between trucks and another mode of transportation.

4.4. Trends in Two-Worker Households

A much-discussed planning approach to reducing travel-related greenhouse gas emissions is to balance the location of jobs and housing. The theory behind a "jobs-housing balance" is that a balance between jobs and housing within different commuter catchment areas of a metropolis will reduce traffic congestion (Sultana, 2005). The idea is intuitively appealing: workers who live near their jobs have shorter commutes.

The large-scale entrance of married women into the labor force since the early 1970s poses a potential obstacle to the goals of a jobs-housing balance: two workers, with two commutes, cannot minimize both commutes. They may be able to minimize the sum of their commutes, but most research on the topic suggests that two-worker households do not. Perhaps because of the constraint imposed by two commutes, some studies also find that two-worker households' travel behavior is less influenced by the built environment—such as residential density at the trip origin—than single-worker households.

Other studies suggest that minimizing commutes does not appear to be an important determinant of household residential location choices. Instead, other factors, such as housing costs and childcare amenities dominate households' choice of residential location.

Key Findings

- The entry of women into the workforce is one of the most significant changes in the labor force in the last century. Gender and marital status have declined significantly in importance in explaining who works and does not work.
- From 1970 to 2004, the labor force participation of married women has increased from 41 to 61 percent, resulting in a growing number of dual-earner households. The rapid rise of dual-earner couples has created a growing complexity in household arrangements.
- Dual-worker households have additional constraints that single-worker households do not face that may lead to excess commuting. These households are more constrained in their ability to choose a residential location because they often must coordinate commute times for two workplaces. The travel choices of dual-worker households, especially those with children, are also less responsive to built-environment characteristics than single-worker households.
- Further research on differences in travel behavior between dual-worker and single-worker households is needed. Future research should account for the complex interaction of gender, income, and the presence of children on residential location and commute. In addition, the conflicting findings between Sultana (2005) and other researchers on whether dual-worker households are more likely to engage in excess commuting than other households should be further examined.

Trends in Labor Force Participation in Households

The share of households with two or more workers is hard to identify from the literature. Trends in the *average* number of workers per household differ based on the source of the data, with one source showing modest growth in the average, and the other showing the average has remained constant over the last several decades. These data also obscure the *distribution* of the number of workers per household

Hu and Reuscher (2004), using 2001 National Household Travel Survey data, find an increase in the average number of workers per household from 1969 to 2001 of about 12 percent (from 1.21 to 1.35). McGuckin and Srinivasan (2003) use decennial census data, and find that the average number of workers per household remained fairly constant from 1960 to 2000, at roughly 1.2. Over the same period, the average number of people per household declined from 3.3 to 2.6, indicating an increase in the average *share* of household members who are working of about 30 percent.

Two trends are likely at work: a sharp increase in the labor force participation of married women that is partially offset by a drop in the number of married couple households. Although the drop in the share of married couple households has been notable, falling by 20 percentage points between 1970 and 2006 from 70.8 percent to 50.8 percent of all households (U.S. Census Bureau, 2007), the trend toward increasing labor force participation of married women is more significant. Indeed, Fischer and Hout (2006) describe the entrance of the American woman into the labor force as one of the defining changes in workplace in the last century. In 1900, gender and marital status heavily determined who worked: 88 percent of the employed were either men or unmarried women; in 2000 only 61 percent were. Over the course of the century, women entered the workforce, while the ban on child labor and the widespread growth of retirement meant that young teenagers and seniors left it. By the end of the century, differences by age were far greater than those by gender. In 2000, the percentage of women at work or seeking work was just 13 points below that of men their same age. Unlike in earlier generations, most married women and mothers worked.

Over the past several decades, the increasing size of the female labor force continues to be one of the most notable changes in the U.S. economy. In 1970, the labor force participation rate of married women was 41 percent; by 2004, it was 61 percent, resulting in a growing number of dual-earner households (U.S. Bureau of Labor Statistics). Consequently, the traditional American model of husband as breadwinner and wife as homemaker has been replaced by dual-earner couples. The rapid rise of dual-earner couples has created a growing complexity in household arrangements.

Residential Location Choices of Dual-Worker Households

In a two-earner household, the two wage-earners share a dwelling but typically have separate working places, adding to the complexity of their spatial location decision. Workers in a two-earner household have constrained ability to choose a residential location near both workplaces. Housing search theory indicates that these workers cannot freely choose the optimal residence and job combination due to the presence of moving costs and imperfect information about jobs and residences (Deding *et al.*, 2009). As a result, workers are not always in their optimal labor-housing market situation, but attempt to improve their current position over time through spatial job and residential moves. One of the implications of this sub-optimal labor-housing market situation that workers do not minimize their

commuting costs given the spatial configuration of jobs and housing, referred to in the literature as "excess commuting."

In their literature review on excess commuting, Ma and Banister (2006) identify the increasing prevalence of two-worker households as a key reason for excess commuting. Excess commuting is defined as the additional journey-to-work travel represented by the difference between the actual average commute and the smallest possible average commute, given the spatial configuration of workplace and residential sites. Two-worker households are recognized to have more constraints than single-worker households.

Supporting this idea, Kim (1995, cited in Ma and Banister, 2006) included controls for the constraints on the mobility of two-worker households, and found less excess commuting. That is, two-worker households are more likely to minimize their commutes than is demonstrated by models without these controls. As another example, controlling for the constraints on the mobility of multiple worker households significantly reduced the amount of excess commuting found from 65 to 15 percent in the Greater Toronto, Canada area (Buliung and Kanaroglou, 2002, cited in Ma and Banister, 2006).

A study conducted by Deding et al. (2009) supports the association between two-worker households and excess commuting in Denmark. Using national register data, the study examines the effects of the spatial configuration of workers' residence and workplace location on intraregional residential and job moving decisions of workers belonging to two-earner households. It focuses on how commuting distance, the distance between the workplaces, and commuting distance of the spouse affect residence as well as job mobility.

The likelihood of moving is positively affected by the commuting distances of both spouses, and negatively affected by the distance between the workplaces. In contrast, workers are more likely to change jobs when they have longer commuting distances, greater distances between the two workplaces, and are less likely to change jobs when the spouse has a shorter commuting distance. These study's estimates were not only significant, but were large.

Differences in Travel Patterns between Single- and Dual-Worker Households

In addition to the increased likelihood of excess commuting identified by the studies reviewed above, the travel choices of single- and dual-worker households differ in other ways as well. Maat and Timmermans (2009) find that dual-worker households are more sensitive to characteristics of work location than single-worker households, and single-worker households are more sensitive to built environment characteristics of residential areas. Their study used a targeted survey of a Dutch area to analyze whether the decision to commute by car is influenced by built environment characteristics of residential neighborhoods and work locations, taking into account the interdependencies between household partners. The study found that residential environment—specifically, higher residential densities and shorter distances between home and a railway station—only increases the probability of commuting via transit among single-earner households. No effects were found for dual-worker households. In contrast, higher density of the work location reduces the probability that dual-worker household members commute by car, even in dual-earner households with two cars.

Purvis *et al.* (1996) also find differences in travel patterns between single- and dual-worker households. For example, they find that dual-worker households are more likely to reduce non-work trips in response to longer work trips than single-worker households.

Factors Affecting Residential Location Decisions

In contrast to Deding *et al.*'s (2009) Danish study and Ma and Bannister's (2006) literature review, Sultana (2005) uses Atlanta as a case study to dispute the idea that married-couple, dual-earner households are prone to excess commuting. Controlling for socioeconomic status and individual characteristics of workers, the study uses the Public-Use Microdata Samples (PUMS) dataset from the 2000 Census to examine whether the average travel time from home to work varies by households with single- or dual-earners.

In comparing commute times by household types, after controlling for matched household characteristics, including residential and work place location s as well as occupational status and work hours, there were either no significant differences between single- and dual-earner households, or the average commutes of single-earner households actually turned out to be longer. These results do not support the assumption that dual-earner households are more constrained in balancing home and work locations and therefore contribute to longer aggregate commutes for the entire metropolitan area. In fact, these results suggest that dual-earner households are more prone to reduce their commuting time compared to single-earner households, despite the fact that they purportedly face problems in balancing home and work locations.

Instead, Sultana suggests that households are not able to economize on commuting times when housing prices do not match their affordability levels, an essential requirement for the job-housing balance concept. As reflected by the observed relationships between commuting time and housing value, Sultana suggests that dual-earner households choose to trade off their housing cost and commuting burden, because they have a wider array of affordable housing choices given their dual incomes. She posits that commuting costs are simply overshadowed in importance by housing costs.

The Influence of Gender and Children on Dual-Worker Households' Residential Location

Mok (2007) uses household census data from Toronto, Canada to understand the interplay between the presence of children and housing location. Mok finds that dual-worker households with children make different residential location choices than dual-worker households without children. When children are present, the two earners tend to live further away from their work, whereas childless couples tend to stay closer to where they work. One explanation for this result is that households with children factor in the availability of good quality schools and other childcare amenities in making residential location choices.

In their study of two-worker households in San Francisco, Sermons and Koppelman (2001) finds that presence of children is an important determinant of female and male commuting. They find that men's commutes are generally longer than those of women, and use data from a 1990 household travel survey to identify household characteristics that account for this difference. The difference between men and women's commute times are larger in households with children than those without

children. This supports the household responsibility hypothesis, which asserts that women commute less than men because women tend to perform more of the household maintenance and child-rearing responsibilities.

4.5. The Influence of Income and Demographic Characteristics on Travel Behavior

A number of socioeconomic characteristics are thought to influence travel behavior, and are studied extensively in the literature, including income, age, gender, race/ethnicity, immigrant status, and household structure. The characteristics of neighborhood residents may influence the degree to which changes in the built environment – such as increases in residential density – affect travel behavior. In other words, the same policy may be less effective in one location than in another because of differences in the characteristics of neighborhood residents. A more recent addition to the literature is the study of personality or attitudes and how they influence travel behavior. A few researchers are finding that variables that measure personality and attitudes are powerful additions to variables that capture socioeconomic characteristics in explaining travel behavior.

The most findings about income and demographics in relation to the climate are that these factors are important in explaining travel behavior, and that a rich set of socioeconomic variables reduces – and may even eliminate – self -selection bias (Brownstone, 2009). The following subsections on each of these characteristics reviews primarily studies that focus on the influence of socioeconomic variables on travel behavior. Literature that is primarily concerned with the influence of the built environment on travel behavior also provides insights into the role of socioeconomic variables on travel behavior. Both types of studies are included in this section, although the latter are discussed in far more detail in other sections of this literature review. In general, models of travel behavior have far more explanatory power when both characteristics of the built environment and socioeconomics are included.

The independent effects of different demographic characteristics are sometimes difficult to isolate. Sometimes the interaction between two socioeconomic variables better explains variation in travel behavior. In general, race and income appear to be more important than gender, consistently indicating that lower-income, minority household have lower mobility than higher-income, white households. Studies also show that mobility decreases with age, but the findings are mixed on how age affects mode choice. The impact of household structure on travel behavior is also mixed. Finally, personal attitudes and lifestyle play an important role in explaining travel behavior, though the inclusion of these variables is a relatively new strategy among travel behavior researchers.

Key Findings

- Socioeconomic characteristics of neighborhood residents are important in explaining travel behavior. This suggests that policies designed to reduce VMT may be less effective in one location than in another because of differences in the characteristics of neighborhood residents.

- Several studies show that characteristics of the built environment are less important in explaining travel behavior than personality and attitude and socioeconomic characteristics.
- Including a rich set of socioeconomic variables in models of travel behavior reduces – and may even eliminate – self -selection bias.
- In general, mobility increases with income, evidenced by an increase in the number of trips taken and higher levels of auto ownership among high-income households. While low-income households are more likely to use transit, the relationship is confounded by the influences of other variables such as car ownership and race.
- Mobility decreases as people age: commute times and the number of trips taken both decrease with age. The research is mixed on the impact of age on driving and transit use.
- Overall, men travel further and longer than women, especially when commuting to work. While some conclude that this gap in travel behavior is closing, further analysis reveals mixed conclusions. Women make more daily trips than men but the research is mixed on the relationship between gender and mode choice. The effect of gender is complicated by overlapping effects of other characteristics such as race and ethnicity, household responsibilities, and residential location.
- Minorities travel shorter distances, have longer commutes, use transit more, and have lower rates of car ownership, similar to the findings associated with low-income households.
- Foreign-born residents are less likely to drive than U.S.-born residents, but their likelihood of driving increases the longer they live in the U.S. Little research has been done on the travel behavior of foreign-born residents. Given their increasing presence in the U.S. population and their travel needs, more research on the relationship between immigrant status and travel behavior would be useful.
- Household structure impacts travel behavior but the findings vary with the number of people and the age of children in the household. In general, households with more children take more household trips and drive more.

Income

Income affects the resources a household has to spend on traveling, as well as its access to different travel options. In general, mobility increases with income. Increases in income are associated with increased travel distances and increased time spent traveling for all travel purposes (Giuliano, 2003; Van Acker, *et al.*, 2007). More specifically, household income is positively associated with the distance and time spent commuting to work (Crane, 2007). A number of studies also find that as income increases, so do the number of trips a household takes (Krizek, 2003; Noland and Thomas, 2007; Shay and Khattak, 2007; Sun, *et al*., 1998; Van Acker, *et al.*, 2007). Exhibit 4.5-1 provides further detail on the findings of research on the relationships between travel behavior and income.

Not reflected in Exhibit 4.5-1, several of these studies also show that as income rises, so does auto ownership (Cao, *et al.*, 2007; Chen, *et al.*, 2008; Kockelman, 1996; Giuliano, 2003) and the number of vehicles owned per household (Holtzclaw, 2002; Schimek, 1996).[129]

Exhibit 4.5-1. Findings of Studies on the Relationship between Travel Behavior and Income

Author, Year	Trip Purpose	Trip Type	Est. Assoc. with Income	
1-A: Income and Travel Distance/Time				
Crane, 2007	Work	Auto	+	Log of HH income
Giuliano, 2003	All	All	+	HH income >$75k
			-	HH income <$75k
Van Acker, et al., 2007	All	All	+	Social Status (including income)
1-B: Income and # Trips				
Cao et al., 2009	All	Auto	+	Income
Doyle and Taylor, 2000	All	Auto	+	Income
Krizek, 2003	All	All	+	Income
Noland and Thomas, 2007	All	All	+	HH income
Schimek, 1996	All	Auto	+	Ln income
Shay and Khattak, 2007	All	All	+	Middle Income High Income
		Auto	+	Middle Income High Income
		Walk	NS	Middle Income High Income
Sun et al., 1998	All	All	+	Income
Van Acker, et al., 2007	All	All	+	Social Status (including income)
1-C: Income and VMT				
Chatman, 2003	Personal commercial[a]	Auto	+	HH income
Kockelman, 1996	All	Auto	+	Income per HH member
	Non-work	Auto	+	Income per HH member
Krizek, 2003	All	Auto	+	Income
Schimek, 1996	All	Auto	+	Ln income
Sun et al., 1998	All	Auto	+	Income

[a] Personal commercial travel includes trips made for shopping, medical/dental, going out to eat, and other social/recreational trips.

[129] Holtzclaw (2002) also finds that the number of miles traveled per vehicle decreases with income, indicating that the more vehicles a households has, the more of them it uses.

Based on differences in travel behavior between high- and low-income people, Deka (2002) goes so far as to suggest that transit services be directed to the poor – which is the segment of the population most likely to use the services. She argues that the likelihood of coaxing moderate- and high-income individuals from the suburbs out of their cars is low, so resources are better used in central cities where the poor are likely to be concentrated.

With access to more vehicles, higher-income households are likely to drive more. A number of studies show that higher-income households make more driving trips overall (Cao, *et al.*, 2009; Doyle and Taylor, 2000; Schimek, 1996; Shay and Khattak, 2007). In addition, as income rises, so do the number of vehicle miles traveled (Chatman, 2003; Kockelman, 1996; Krizek, 2003; Schimek, 1996; and Sun, *et al.*, 1998).

One explanation for the increased travel time and distance among higher-income households is that they live further away from the city center, while poverty tends to be centralized in the inner city. The traditional explanation for centralization of poverty, which assumes that cities are monocentric, is that wealthy people want to buy more land, and therefore live where land is cheap. Glaeser, *et al.*, (2008), disagree. They use data from the 2001 National Household Transportation Survey to examine the reasons for centralized poverty. They estimate the time costs of taking public transportation and driving, as well as the demand for land relative to income, and find that the poor locate in central cities mainly because of better access to public transportation in urban centers. Auto ownership has high financial costs, making it unappealing to the poor, while public transportation is inexpensive (but time-intensive), making it relatively attractive to the poor.

A variety of other researchers also find that income affects the choice between driving and taking other modes of transport. Giuliano (2001) uses the 1995 Nationwide Personal Transportation Survey and finds that low-income households are more likely to use public transit than higher-income households. However, because the poor are less likely to be employed, they are less likely to use transit for work trips than higher-income people. The use of transit for work trips increases as income increases.

Giuliano also models the probability of being a regular transit user, and finds that once car ownership, race/ethnicity, being employed or not, access to transit, and other variables are controlled for, low income does not have an independent effect on the probability of using transit regularly. She hypothesizes that this is because of the correlation between car ownership and income. In general, car ownership is by far the strongest predictor of regular transit use.

Last, Giuliano tests the joint effect of poverty on each independent variable in the model and finds that the interaction of poverty and race results in a higher likelihood of transit use for blacks and Hispanics. She concludes that it is the interaction of race and poverty that drives transit use patterns rather than income on its own.

Several other researchers also find that income affects the likelihood of using alternative travel modes to driving. Chatman (2003) finds that higher-income households are more likely to choose to drive for their commutes than lower-income households. Cervero and Kockelman (1997) find that having a higher income decreases the likelihood of making trips with any non-single-occupant-vehicle or non-

personal-vehicle (shared ride, transit, and non-motorized) travel mode. Others find that having a higher income decreases the likelihood of taking non-motorized modes of transportation specifically (i.e., walking or biking) (Bhat, *et al.*, 2009; Guo, *et al.*, 2007).

A few studies demonstrate that the relationship between income and travel behavior is not linear. Increases in income up to a threshold of about $50,000 result in households driving less, while households with incomes above $50,000 drive more as their income rises (Rajamani, *et al.*, 2003). On the other hand, Kitamura, *et al.*, (1997) finds that increasing income has a positive effect on the number of trips taken up to an annual income threshold of $90,000, at which point the number of trips decreases with increasing income. Differences such as these observed at different income levels may imply that having a higher income gives households more choice to base their travel behavior on preference or convenience.

Age

Age affects travel behavior because of the changes in physical mobility, work schedules, and household responsibilities that are associated with age. Trend data show that as people age they have lower mobility and take fewer and shorter trips (Pucher and Renne, 2003; Collia, *et al.*, 2003). Giuliano (2003) finds that as age increases total travel time decreases, while Doyle and Taylor (2000) examine commuting behavior specifically, and find that as age increases commute times decrease.

Projections about future driving patterns are strongly influenced by the aging of the baby boom generation over the next several decades. The Transportation Research Board's (2009) projection notes that by 2010, growth of the population ages 65+ will substantially exceed that of younger adults. Based on Pitkin and Myers (2008), the scenario assumes that boomers will begin to sell their largely suburban homes and move to smaller units that are more likely to be located in more densely developed environments such as retirement communities. It is not clear, however, whether baby boomers will move in large numbers to central cities. Regardless of the location of their retirement, the evidence, as discussed in this section, strongly suggests that baby boomers will begin to travel less.

Exhibit 4.5-2 provides further detail on the findings of studies of the relationship between age and travel behavior in both base and expanded models (described below). As shown in the exhibit, the models used in the research on the relationship between age and travel behavior varies greatly in terms of how age is measured and the different trip purposes the authors examine. The variety among the models makes it difficult to compare their findings. For example, some researchers measure age with a continuous variables while others divide age into categories (e.g., less than or greater than 65 years old).

A number of these studies indicate that people become less mobile as they age, evidenced by the decreasing number of trips that people take as their age increases (Boarnet and Sarmiento, 1998; Cao, *et al.*, 2009; Guo, *et al.*, 2007). However, this trend differs by age category, trip purpose, and travel mode, with the results of some scenarios showing an opposite trend (Guo, *et al.*, 2007) (see Exhibit 4.5-2).

Because older persons tend to be less physically mobile and tend to travel during off-peak times, they rely more on the flexibility and accommodation of personal vehicles than the rest of the population. Therefore, it makes sense that research would show that car ownership and the number of vehicles per household increase with age (Chen, *et al.*, 2008; Schimek, 1996). But findings on the effect of age on the choice to drive are mixed. Several studies find that as age increases driving decreases (Cao, *et al.*, 2009; Chatman, 2003; Kim and Ulfarsson, 2004; Rajamani, *et al.*, 2003; Schimek, 1996), while others find that increasing age increases the likelihood of driving (Chen, *et al.*, 2008; Cervero and Kockelman, 1997, Doyle and Taylor, 2000). Cao *et al.* and Kim and Ulfarsson both attribute the decrease in driving as people age to mobility limitations or cognitive deterioration among older drivers. On the other hand, Chen *et al.* and Cervero and Kockelman attribute the increase in driving with age to the finding that older households tend to own more personal vehicles and therefore are able to drive more.

Age also affects the choice between driving and alternative modes of transportation, likely because of the reduced physical mobility of older persons. Researchers have found that as people age, they are less likely to take public transit for all trip purposes (Doyle and Taylor, 2000, Giuliano, 2001, Handy and Tal, 2005) and for non-work travel (Polzin, *et al.*, 1999). However, Giuliano finds that the relationship between age and transit use is insignificant for commuting, a finding that is generally inconsistent with the rest of the literature (Giuliano, 2001). She attributes this finding to the fact that the elderly are less likely to travel by any mode, so isolating one mode of transportation (in this case transit) would have the same results.

Exhibit 4.5-2. Findings of Studies on the Relationship between Travel Behavior and Age

Author, Year	Trip Purpose	Travel Mode	Est. Assoc. with Age
2-A: Age and # Trips			
Boarnet and Sarmiento, 1998	Non-work	Auto	- Continuum
Cao, *et al.,* 2009	Non-work	Auto	- Continuum
		Non-motorized	- Continuum
Guo, *et al.,* 2007	Maintenance[a]	Auto	- Young Adult 18-30 + Senior over 65
		Non-motorized	- Young Adult 18-30 NS Senior over 65
	Discretionary[b]	Auto	NS Young adult 18-30 and Senior over 65
		Non-motorized	NS Young adult 18-30 - Senior over 65
Doyle and Taylor, 2000	All	All	NS Continuum
	Errands	All	+ Continuum
	Work	All	+ Continuum
Schimek, 1996	Personal	Auto	+ Young under 35
			- Old over 64
2-B: Age and Travel Distance/Time			
Bagley and Mokhtarian, 2002	Work	All	+ Continuum
Chatman, 2003	Personal commercial[c]	Auto	- Continuum
Crane, 2007	Work	Auto	+ Continuum
Doyle and Taylor, 2000	Work	All	- Continuum
Giuliano, 2003	All	All	- Child < 17
			- Senior adult 65+
Schimek, 1996	All	Auto	+ Young under 35
			- Old over 64

[a] For example: errands, health visits, personal trips, etc.

[b] For example: social, recreational.

[c] Personal commercial travel includes trips made for shopping, medical/dental, going out to eat, and other social/recreational trips.

The research on the influence of age on travel mode choice is mixed, and may depend primarily on how age is measured. Rajamani, *et al.*, (2003), Cao, *et al.*, (2009), and Cao, *et al.*, (2007) all find a negative relationship between age and all mode types, supporting the idea that mobility decreases with age. Likewise, as age increases some studies find that the likelihood of walking or biking decreases (Cao, *et al.*, 2009; Kockelman, 1996; Rajamani, *et al.*, 2003). However, using age

categories,[130] Bhat, *et al.*, (2009) find that persons between age 31 and 45 and persons over age 45 are more likely to use non-motorized transportation compared with those age 30 or under.

Research has also found that as age increases, the likelihood of taking public transportation decreases for all trip purposes (Rajamani, *et al.*, 2003; Zhang, 2004). Rajamani, *et al.*, (2003) finds that as age increases, transit use decreases, while Zhang finds that those under 30 are more likely to use rail and bus for work and non-work trips compared with those over 30. Pucher, *et al.*, (1998) find that children and the elderly are more likely to take transit than adults under 65.

Gender

A number of studies have documented differences between men and women's travel behavior. A number of researchers find evidence that men travel further and longer than women. Giuliano (2003) finds this to be true for all travel. Crane (2007) looks specifically at personal vehicle commutes and finds that on average men commute farther than women, and that the gender commute gap persists across multiple demographic variables, including income, marital status, age, housing tenure, parenthood, and location within a metropolitan area. However, Doyle and Taylor (2000) find that when looking at gender alone, men commute for shorter amounts of time than women, but that this effect varies with characteristics such as race, urban verses suburban location, and mode choice.

Historical data shows that males commute further and longer than females, but many researchers hypothesize that this gap is shrinking due to changes in women's role in the labor market and the household in recent decades. Recent studies look more closely at the gender "commuting gap" to better understand these trends, and find that the gap may be converging at the aggregate level but is diverging along certain dimensions (Crane, 2007, Crane and Takahashi, 2009, Rosenbloom, 2006). Crane and Takahashi find that over the last 20 years (1985 through 2005) the gender gap in commute length has widened for older workers but narrowed for younger workers. In another study, Crane finds that trends in the commuting gap vary with the measure of commute length: men and women's commute distances are converging slowly but their commute times are diverging (Crane 2007).

In general, it is likely that the influences of gender on travel behavior have more to do with other socioeconomic characteristics, such as age, life cycle, race, ethnicity, household responsibility, and income, than with any innate differences between men and women (Crane and Takahashi, 2009; Rosenbloom, 2006).

A growing body of research using empirical models to measure the effect of gender on travel behavior remains inconclusive. In theory, because women often take care of more household responsibilities during the day than men, they are likely to take more household trips instead of, or perhaps in addition to, their daily commute. Doyle and Taylor's (2000) research supports this theory in several different models, finding that women do take more daily trips, take more daily trips with a child, and take more daily trips in trip chains (single trips involving multiple destinations). Many other studies also show that women take more trips than men (Boarnet and Crane, 2001; Boarnet and Sarmiento, 1997; Guo, *et al.*, 2007) and drive more miles for non-work purposes (Chatman, 2003), although men drive more miles overall (Bagley and Mokhtarian, 2002; Handy, *et al.*, 2005).

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[130] The other papers revised in the paragraph define age as a continuous variable.

Findings in the literature on mode choice are also mixed. Some research shows that women are less likely to drive than men (Bagley and Mokhtarian, 2002; Cervero and Kockelman, 1997; Chatman, 2003). However, in a study of mode choice using data from Montgomery County, MD, Cervero (2002) finds that women are more likely to drive and less likely to take transit, and attributes women's car dependence to their increased likelihood of trip-chaining between work, shopping, and child care.

In contrast to Cervero, Doyle and Taylor (2000), based on national data, find that women are more likely to take transit, and drive for a smaller proportion of their trips than men. Bagley and Mokhtarian (2002), using data from the San Francisco Bay Area, also find that women are more likely to use transit than men, but travel fewer miles on transit because they travel shorter distances on it than men who use transit. Several studies show that men are more likely to walk or bike than women (Bagley and Mokhtarian, 2002; Kockelman, 1996). The difference in findings between Cervero, Doyle and Taylor, and Bagley and Mokhtarian may result from the differences in geographies studied.

Meanwhile, Giuliano (2001) finds that the effect of gender on transit use is only significant when measured jointly with race. When she estimated models with separate variables for gender and race, the coefficient for gender was not significant. However, with gender and race measured jointly, black males and females and Hispanic females are more likely to take transit and Hispanic males are less likely to take transit. Exhibit 4.5-3 illustrates the differences by trip purpose and travel mode in the findings discussed above.

Exhibit 4.5-3. Findings of Studies on the Relationship between Gender and Travel Mode

Author, Year	Trip Purpose	Travel Mode	Direction (+/-)
Female			
Bagley and Mokhtarian, 2002	All	Auto	-
		Transit	-
		Walk/Bike	-
Cervero, 2002	All	Transit	-
		Drive-alone	+
		Group-ride	+
Chatman, 2003	Work	Auto	-
Male			
Cervero and Kockelman, 1997	Non-work	Non-SOV	-
	Personal business	Non-personal vehicle	-
	Work	Non-personal vehicle	-
Doyle and Taylor, 2000	All	Auto	+
		Transit	-
Kockelman, 1996	All	Auto	-
		Walk/Bike	+

Race/Ethnicity

Trends in travel behavior by race and ethnicity indicate a similar pattern to that of income, suggesting that race/ethnicity can act as a proxy for income. Trend data show that in general, minorities have lower mobility and tend to use transit more than whites (Pucher and Renne, 2003). Empirical research supports this trend, but the definition of minority varies among different studies. Doyle and Taylor (2000) find that blacks take fewer trips than whites, but trip making by Latinos and other racial/ethnic groups is not significantly different from whites. Giuliano (2003) finds that blacks and Hispanics travel shorter distances than whites overall, but that distance traveled by Asians is not significantly different. Guo *et al.* (2007) find that the effect of race and ethnicity varies by race/ethnic group, trip type, and trip purpose, but that where race/ethnicity is significant, minorities (African-Americans, Hispanics, or Asians) take fewer trips than whites (see Exhibit 4.5-4).

Looking specifically at differences in commuting patterns, Taylor and Ong (1995) find that in general, in 1985 white commuters had longer average commute times than those of blacks or Hispanics. They examine trends over time using data from the American Housing Survey in 1977, 1978, and 1985, and also find that the commutes of whites, blacks, and Hispanics appear to be converging. Despite shorter commute distances, Taylor and Ong observe *longer* commute travel times among minority central city residents than others, and demonstrate that this is a result of their lower rates of car ownership and greater use of relatively slow public transit (see also Johnston-Anumonwo, 1995. Shen (2000) also finds that commute time tends to be longer for low-income minorities than for other residents of the central city).

Taylor and Ong's findings fail to support the spatial mismatch theory that there is a growing separation of the primarily minority residents of inner-city areas from jobs, which are increasingly located in the suburbs (Holzer, 1991; Kain, 1992). Based on these findings, they argue that policies that expand public transit to the suburbs in order to improve employment outcomes for minority workers will be unsuccessful. Rather than a spatial mismatch, Taylor and Ong assert that there is a mismatch in commute modes, resulting in slower commutes for transit-dependent minority workers compared with white workers.

Ong and Blumenberg (1998), on the other hand, offer evidence to support spatial mismatch, finding that welfare recipients who live in job-rich neighborhoods are more likely to find work near their home than those who live in job-poor neighborhoods. Doyle and Taylor (2000) also find that minorities have longer commute times than those of non-minorities.

Exhibit 4.5-4. Findings of Studies on the Relationship between Race/Ethnicity and Travel Behavior

Author, Year	Trip Purpose	Travel Mode	Est. Assoc. with Race/Ethnicity
4-A: Race/Ethnicity and # Trips			
Doyle and Taylor, 2000	All	All	- Black NS Latin NS Asian NS Other
Guo, *et al.,* 2007	Non-work, maintenance	Auto	NS African American Hispanic Asian
		Non-motorized	- African American NS Hispanic NS Asian
	Non-work discretionary	Auto	- African American NS Hispanic - Asian
		Non-motorized	- African American - Hispanic - Asian
4-B: Race/Ethnicity and Travel Distance			
Giuliano 2003	All	All	- Black - Hispanic NS Asian NS Other
Taylor and Ong, 1995	Work	All	NS Black NS Hispanic
3-C: Race/Ethnicity and Travel Time			
Doyle and Taylor, 2000	Work	All	+ Black + Latin - Asian NS Other
Giuliano, 2003	All	All	NS Black + Hispanic NS Asian + Other
Taylor and Ong, 1995	Work	All	+ Black NS Hispanic

Findings on the travel mode choices of different race and ethnic groups are mixed. Minorities (mainly blacks and Hispanics) are more likely to use transit for all trips (Giuliano, 2001) and for non-work travel than non-minorities (Polzin, *et al.*, 1999). In addition, Giuliano (2001) finds that when race is measured jointly with income, the likelihood of using transit is much higher. This finding indicates that it is the interaction of poverty and race that drives the higher likelihood of transit use for blacks and Hispanics, rather than either of these characteristics in isolation. Doyle and Taylor (2000)

also find that minorities are less likely to drive but more likely to carpool. Exhibit 4.5-5 shows the findings of studies of mode choice by race and ethnicity.

Exhibit 4.5-5. Findings of Studies on the Relationship between Race/Ethnicity and Mode Choice

Author, Year	Trip Purpose	Travel Mode	Est. Assoc. with Race/Ethnicity
Bhat, *et al.,* 2009	All	Non-motorized	NS African American NS Hispanic NS Asian NS Other
Chatman, 2003	Work	Auto	NS African American NS Asian NS Other
Doyle and Taylor, 2000	All	Drive	- Black - Latin NS Asian - Other
		Transit	NS Black NS Latin - Asian - Other
		Carpool	+ Black) + Latin NS Asian + Other
Giuliano 2001	All	Transit	+ Black Female + Black Male + Hispanic Female Depends on model: Hispanic Male
Polzin, *et al.,* 1999	Non-work	Transit	+ African American NS Hispanic NS Asian NS Others
Rajamani, *et al.,* 2003	Non-work	Drive-alone	NS White
		Transit	NS White
		Walk	- White
		Bike	NS White

Rajamani, *et al*., (2003) finds that minorities are more likely to walk than whites, perhaps reflecting lower car ownership rates among minorities. However, several researchers have found no significant relationship between certain race/ethnic groups and various mode choices. Bhat, *et al.* (2009) find no significant relationship between race and the use of non-motorized transportation and Rajamani, *et al.* (2003) find no significant relationship between race/ethnicity and choosing to drive-alone, take transit, or bike.

Immigrant Status

With an increasing proportion of immigrants making up the United States' population, the travel patterns of the foreign born will have an increasing impact on the transportation needs of U.S. residents. However, there is a much thinner literature examining this issue. Data trends show that recent immigrants are less likely to drive alone for their commute, and more likely to use alternative modes of transportation including carpooling, public transit, or walking or biking (Chatman and Klein, 2009).

However, the travel behavior of immigrants appears to change over time. Handy and Tal (2005) find that the longer immigrants live in the U.S., the more miles they drive and the less likely they are to choose public transportation over a private vehicle for getting around. The rate of convergence to average travel behavior of U.S. residents varies for different ethnicities. Hispanic immigrants tend to use transit more than native-born commuters even after 20 years in the U.S. In comparison, Asian immigrants switch more rapidly to automobile use (Blumenberg and Shiki, 2007).

The Transportation Research Board's (2009) study notes that immigrants are younger than the average population, and are the primary source of U.S. population growth. Their propensity to locate in central cities and to live in multifamily housing (Pitkin and Myers, 2008) also provides an opportunity for denser development patterns in the future. Given the increasing presence of immigrants in the U.S. population, more research on the relationship between immigrant status and travel behavior would be useful.

Household Structure

Household structure can affect travel behavior because of the increasing transportation needs of households with multiple people, especially among households with children. As discussed in the previous section, dual-worker households with children make different residential location choices than dual-worker households without children (Mok, 2007). When children are present, the two earners tend to live further away from their work, whereas childless couples tend to live closer to where they work. This suggests that the presence of children has a strong influence – although indirect – relationship on travel behavior and may weaken the relationship between density and travel behavior.

The presence of children is found to be an important determinant of female and male commuting in other studies as well. Sermons and Koppelman (2001), studying two-worker families in San Francisco, find that the difference between men and women's commute times is larger in households with children than those without children. This supports the household responsibility hypothesis, which asserts that women commute less than men because women tend to perform more of the household maintenance and child-rearing responsibilities.

Not surprisingly, many researchers find that auto ownership increases with household size (Chen, *et al.*, 2008; Holtzclaw, 2002; Schimek, 1996). Conceptually, a car is more economical when there are more people in a household to transport, more trips to make, and possibly more drivers. Perhaps counter intuitively, Shay and Khattak (2007) find that auto ownership decreases with the number of children in the household. The authors speculate that the unexpected negative influence of children

on auto ownership is due to the fact that children increase household size without adding drivers and also affect the travel of adults in the household. Chen, *et al.*, (2008) find that the number of young children has a negative but insignificant effect on car ownership.

Exhibit 4.5-6. Relationship between Household Structure and Travel Behavior

Author, Year	Trip Purpose	Travel Mode	Est. Assoc. with Subject
6-A: Household Structure and # Trips			
Kitamura, *et al.,* 1997	All	All	+ HH size - Adults (>16)
Sun, *et al.*, 1998	All	All	+ HH Size
6-B: Household Structure and Mode Choice			
Bagley and Mokhtarian, 2002	All	Auto	NS HH size # children (<16)
		Transit	NS HH size # children (<16)
		Walk/bike	NS HH size # children (<16)
Cao, *et al.,* 2009	Non-work	Auto	- # of children (<6)
		Transit	NS # of children (<6)
		Walk/bike	NS # of children (<6)
Cervero and Kockelman, 1997	Non-work	Non-SOV	+ # Children (<5)
		Personal Vehicle	- # Children (<5)
Chatman, 2003	Work	Auto	NS Single adult HH Children (1/0)
			NS Single adult HH Children (1/0)
Chen et al., 2008	All	Auto	NS # children (<6)
Handy et al., 2005	All	Auto	+ # Children
Kitamura et al., 1997	All	Transit	NS HH size
		Walk/bike	NS HH size
Rajamani et al. 2003	All	Drive alone	- # children
		Transit	- # children
		Walk	- # children
		Bike	- # children
Sun, *et al.*, 1998	All	VMT	+ HH Size
Handy and Tal, 2005	All	Transit	- HH Size
		Walk	- HH Size

Crane (2007) finds that household structure is associated with auto commute distance. He measures both household size and children as a percentage of the household separately and finds opposite relationships with auto commute distance. Crane finds that larger households have shorter commute distances by auto. However, commute distance by auto for men increases as children as a percentage

of the household increases. It has no significant impact on women's commute distances. Crane suggests that this finding could indicate that parenting responsibility plays little role in determining women's journeys to work.

Although the literature is consistent in finding that households with children and larger households take more household trips, findings vary on trip purpose, mode choice, and age (Kitamura, *et al.,* 1997; Sun, *et al.,* 1998). As the number of children increases, the likelihood of driving alone decreases for all trips (Rajamani, *et al.,* 2003) and for non-work trips (Cervero and Kockelman, 1997). Having more children also increases the likelihood of driving for non-work trips (Cervero and Kockelman, 1997) or for all trips (Handy, *et al.,* 2005).[131] In addition, Sun, *et al.,* (1998) finds that increases in household size are associated with increases in the number of vehicle miles traveled. However, when looking specifically at the effect of having young children (under the age of five) Cao, *et al.,* (2009) finds that as the number of young children in a household increases, the number of household auto trips decreases. The authors attribute this finding to the time constraints placed on parents of young children or to the inconvenience of taking children on trips. The differences in trip making and mode choice by household structure are detailed in Exhibit 4.5-6.

Many studies find that household structure also affects mode choice. As the number of children in a household increases, the likelihood of taking transit and the likelihood of walking or biking decreases (Rajamani, *et al.,* 2003; Tal and Handy, 2005). The likelihood of taking transit and walking also decreases as household size increases (Handy and Tal, 2005). In addition, single adult households are more likely to use public transit for non-work purposes (Polzin, *et al.,* 1999).

However, a number of studies find no significant relationship between household structure and mode choice, including walk/bike trips, transit trips (Bagley and Mokhtarian, 2002; Cao, *et al.,* 2009; Kitamura, *et al.,* 1997), and auto use (Bagley and Mokhtarian, 2002, Chatman, 2003; Chen, *et al.,* 2008).

Personality and Attitudes

As Van Acker *et al.* (2007) acknowledge in their literature review, much of the research on travel behavior considers three categories of variables: land use variables (such as density and diversity of land use), socioeconomic variables, and personality or attitudinal variables (such as being pro-driving or pro-transit). The latter is a recent addition to the literature and is still being refined as researchers search for appropriate data. Studies that compare the relative importance of each of these explanatory variable types are described below.

Van Acker *et al.* find that socio-economic characteristics are more important in explaining travel behavior than land use. In the authors' model, socio-economic characteristics are measured by a series of "social status" variables (e.g., employment status, car ownership, education level, income level) that are associated with more trips, longer travel distances, and longer travel times. Their

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[131] Cervero and Kockelman note the contradictions in their research by explaining that parents of young children are likely to bring their children along with them on non-work trips which makes them more likely to take multiple-occupant automobile trips (i.e., non-SOV), but also more likely to use a personal vehicle when making those trips.

preliminary analysis using Flemish data[132] suggest that people with a higher social status travel longer distances, longer times, and make more trips per day. They also live in more urban environments. They find that the impact of land-use—rural, urban, or neither urban nor rural environment; location inside or outside a metropolitan center; and distance to public transit—on travel behavior is limited.

Kitamura *et al.* (1997) include a variety of attitude variables in their research, all related to opinions about urban life, including the environment, using transit, suburban living, automotive mobility, time pressure, urban living, congestion, carpooling, smog, and being a workaholic. The authors find that attitude factors, socioeconomic characteristics, and neighborhood descriptors are all significant as a group in explaining travel demand. However, the explanatory power of the neighborhood descriptors is relatively small. Socioeconomic variables account for a larger fraction of variation in travel behavior than neighborhood descriptors. In addition, attitude factors are more strongly associated with travel behavior than neighborhood characteristics. Based on this, the authors conclude that land –use policies promoting higher densities and mixed uses may have modest impacts on travel demand unless residents' attitudes are also affected.

Cao *et al.* (2009) also incorporate the three categories of explanatory variables to predict the frequency of trips by three different mode types: driving, using transit, and walking/biking. The authors do not compare the magnitude of the impact of each group, but they do find that both preferences and attitudes for travel and the built environment play an important role in explaining mode choice, and that both categories better explain the variation in non-motorized travel than in auto or transit travel.

Bagley and Mokhtarian (2002) incorporate attitudinal, lifestyle, and demographic variables to examine the relationship between residential neighborhood type and travel behavior. They find that attitude and lifestyle choices related to travel have the greatest impact on travel behavior compared with sociodemographic and residential location characteristics. In fact, the authors find that residential location has little impact on travel behavior when sociodemographic, attitudinal, and lifestyle variables are accounted for.

[132] Analysis is considered preliminary because there is limited information on land-use and much of the data is categorical in nature.

5. Conclusions and Areas for Further Research

The consensus of the scientific community about the human contributions to climate change and its possible impacts indicates that significant action is warranted to avoid the worst possible consequences. One proposed course of action is to increase residential density, primarily on the grounds that it will reduce vehicle miles traveled, a measure that is closely related to the climate impacts of housing.

A vast volume of research has been conducted on the relationship between residential density and VMT, as well as other types of travel behavior such as the number of vehicle trips, auto ownership, and mode choice. The consensus of this literature is that large increases in residential density – a doubling of current levels of density – do reduce VMT, vehicle trips, auto ownership, and the likelihood of commuting to work by car by modest amounts (roughly 5 percent reductions in VMT and vehicle trips). Research suggests that doubling density *in combination with* other policies including those that affect land-use diversity, neighborhood design, access to transit, and destination accessibility could have more significant impacts on travel behavior – such as reductions in VMT on the order of 25 to 30 percent. Other factors, such as employment density, appear to be more important in some aspects of travel behavior, such as mode choice, than residential density.

An important unresolved question is the extent to which estimates of impacts on travel behavior are affected by self selection, or people's tendency to choose to live in walkable, transit-oriented neighborhoods because they prefer not to drive. Importantly, it is not clear whether there is unmet demand for the high-density, walkable neighborhoods that are associated with lower auto ownership and VMT. If there is – perhaps because of local zoning restrictions that tend to encourage low density residential development – then neighborhood choices that better match consumers' preferences could indeed result in sizeable (e.g., 25 to 30 percent) reductions in VMT. If not, then projections of the impact of residential density on travel behavior are overestimated, and actual reductions in VMT, vehicle trips, and auto ownership may be much smaller.

Other aspects of people's characteristics, demographics (such as income and immigrant status), personality, and attitudes also affect the degree to which residential density influences travel behavior. The local context – such as the local economy and geography – also affects the relationship between residential density and travel behavior. It is clear that there is no one-size-fits-all strategy for changing travel behavior.

There are a number of other factors that affect the relationship between residential density and the climate (via travel behavior). One of these is the increasing number of households with two workers – who often commute to different locations – and appear to make residential location decisions based on factors primarily other than the distance to work. A second is the trend toward decentralization of employment from city centers. The trend, which started over half a century ago, weakens the ability of public transit – particularly fixed rail systems – to meet travel needs, and reinforces the need for auto ownership and neighborhoods that accommodate autos. Third, the recent increase in non-work trips may reduce the importance of access to public transit, because non-work trips often involve multiple destinations and are thus less well suited to public transit than work trips.

In addition to unresolved questions about the role of self selection, other important questions are left unanswered by the current research on the connection between residential density and the climate. Among others, how difficult would it be to achieve residential densities that are double their current levels across a metro area – that make Atlanta look more like Boston? Experience from Portland, Oregon, an area known for its urban growth boundary suggests that sizeable increases in density takes decades – at least 30 years. Given that the built environment is long lived, this result is not surprising.

Few studies include the impact of travel cost—either in terms of time or money—on travel behavior, but those that do conclude that pricing may play a more important role in explaining travel behavior than characteristics of the built environment. They conclude that changes in policies that affect the monetary or time cost of car ownership and use—such as increases in gas taxes or the price or availability of parking and the supply of roads—are more effective in changing travel behavior than any other policy. If policy makers find these types of economic incentives to be unpalatable, policies that lead to large-scale changes in land-use are a distant second-best alternative.

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Attachment. Definitions of Mixed-Use Development Variables by Author (From Section 2.2. The Influence of Mixed-Use Development on Travel Behavior)

Author, Year	Mixed Use Variable Name	Mixed Use Variable Description
Bailey *et al.* 2008	Land use mix	Mix of residents and jobs by Census tract
Boarnet and Crane 2001	Retail density Service density % Residential % Commercial	Retail employment/land area Service employment/land area % of land in the household's census tract in residential use % of land in the household's census tract in commercial use
Boarnet and Sarmiento 1998	Retail density Service density	Retail employment/land area Service employment/land area
Cao *et al.* 2009	Land use variables:	# Business types within 400 meters # Business types within 800 meters # Institutional businesses within 800 meters Distance to nearest library Distance to nearest theater Distance to nearest post office
Cervero 1996	Land use variables:	Having commercial or non-residential buildings within 300 feet of unit Having grocery or drug stores between 300 feet and 1 mile of unit
Cervero 2002	Land-use diversity at origin Land-use diversity at destination	Retail employment and population relative to countywide ratio Retail employment and population relative to countywide ratio
Cervero and Duncan 2003	Employment accessibility Retail/service density Land-use diversity at origin/destination factor	# Jobs within 1 mile of trip origin # Retail/service jobs per net commercial acre within 1 mile of trip origin Developed through factor analysis, with mixed use entropy, employed residents-to-jobs balance, employed residents-to-retail/services balance, and "residentialness" scored high on these factors
Cervero and Duncan 2006	Job accessibility Retail/service accessibility	Jobs with 4 miles of residence Retail and service jobs within 4 miles of residence

Author, Year	Mixed Use Variable Name	Mixed Use Variable Description
Cervero and Kockelman 1997	Dissimilarity index	Proportion of dissimilar land uses among hectare grid cells within a tract
	Vertical mix	Proportions of parcels with more than one land use category on site
	Intensity factor	Based on the density/intensity of non-residential uses including retail stores, activity center, parks as well as population density and walking accessibility
Chatman 2003	Mixed-use development – workplace	Employment share retail at workplace tract
	Mixed-use development – residence	Employment share retail at residence tract
Dargay and Hanley 2004	Amenities short walk	Walking distance to amenities is on average in lowest third of index
	Amenities long walk	Walking distance to amenities is on average in highest third of index
Frank and Pivo 1994	Entropy index	Index of land use mix at origin and destination, based on single-family and multi-family units, retail and services, office, entertainment, institutional, and industrial/manufacturing.
Guo *et al.* 2007	Land use variables	Land use mix within a .25 mile radius Land use mix within a 1 mile radius Fraction of residential land use within a 1 mile radius Fraction of commercial land use within a 1 mile radius
Kockelman 1996	General mix	Dissimilarity index
	Tract entropy	Balance across six distinct land use categories using proportions of each category found with each census tract boundary
	Mean entropy	Average of entropies computed for ½ mile radius around a tract, based on six land use types
	Mean non-work entropy	Average of non-work entropies ½ mile radius around tract, based on four land use types
Leck 2006	Land use mix	Based on meta-analysis of studies on the relationship between land use mix and travel variables
Rajamani *et al.* 2003	Land-use mix diversity index	Index based on proportion of acres in residential, commercial, industrial, and other land uses
Sun *et al.* 1998	Entropy	Formula based on the # different land use developments and proportion of land development

Author, Year	Mixed Use Variable Name	Mixed Use Variable Description
Vance and Hedel 2007	Commercial density	# commercial outlets (retail, service, entertainment) in zip code/zip code area
	Commercial diversity	Index that accounts for the # and proportion of retail, service, and entertainment outlets in a zip code