UC Berkeley
Berkeley Planning Journal

Title

The Impact of Urban Form on Travel Behavior: A Meta-Analysis

Permalink

https://escholarship.org/uc/item/20s78772

Journal

Berkeley Planning Journal, 19(1)

Author

Leck, Eran

Publication Date

2006

DOI

10.5070/BP319111488

Copyright Information

Peer reviewed

The Impact of Urban Form on Travel Behavior: A Meta-Analysis

Eran Leck

Abstract

A common viewpoint held by many New-Urbanist and Neo-Traditional planners is that characteristics of the built environment, such as population density, mixed land use settings and street configuration, exert a strong influence on travel behavior. The empirical evidence for this relation, however, as portrayed in many primary studies, is somewhat mixed. This paper offers an application of statistical meta-analysis in an attempt to settle the contradictory findings reported in the single studies. The findings reaffirm the role of residential density as the most important built environment element influencing travel choice. The findings also reinforce the land use mixing component of the built environment as being a strong predictor of travel behavior. The findings do not, however, support the most controversial claim of the New Urbanism regarding the role of street pattern configuration in influencing travel behavior.

Introduction: The Built Environment–Travel Connection

Over the past two decades, many communities, cities and metropolitan areas across North America have embraced new design approaches [New Urbanism (Katz 1994), Neo-Traditional Development (Duany and Plater-Zyberk 1992), and Transit Oriented Development (Calthorpe 1993)] in an attempt to reduce the negative social, economic, and environmental impacts of urban sprawl. These planning concepts can be summed up as an effort of reorienting fringe development toward patterns reminiscent of U.S. communities prior to World War II (Ryan and McNally 1995). The key design strategies employed by the Neo-Traditional, New Urbanism and Transit Oriented Development (TOD) approaches include:

- Compact and dense residential and employment development.
- Diverse mix of activities and housing options.
- Concentration of residences and jobs in proximity to transit stations and commercial businesses.

- Design of smaller buildings, blocks and narrower roads at the neighborhood scale.
- Highly connected roads (grid layout), sidewalks and paths, allowing relatively direct travel by motorized and non-motorized modes.
- A clearly defined center with public space, public buildings, a transit stop, and retail businesses.
- Public open spaces in accessible locations (Calthrope 1993; Katz 1994; Bernick and Cervero 1997; Niles and Nelson 1999; Lund 2003).

The main argument put forward by the proponents of these design approaches is that the characteristics of the built environment have a direct impact on the scope of travel (e.g. vehicle miles traveled, vehicle hours traveled, travel frequency) and on mode choice (walking, cycling, using the private car, or riding transit).

Past Research on the Impacts of Urban Form on Travel

A considerable body of literature now exists on the impacts of urban form on travel behavior. Crane (1996) argues that creating a typology of the impact of the built environment on travel could be useful in understanding the subject. According to Crane, studies on the influence of urban form on travel behavior can be usefully organized by:

- Compact and dense residential and employment development.
- Travel purpose (journey-to-work, shopping, trip chaining, etc.)
- Analytical method (simulations, regressions, etc.)
- Choice of explanatory variables (travel costs, travel opportunities, socio-economic characteristics, etc.)
- Nature and level of detail in the data (aggregated, disaggregated).
- Characterization and measures of urban form (street layout, composite measures of density, mixed use, pedestrian features, etc.)

The typology presented below, follows Crane's latter proposal. This type of classification is especially suitable for the empirical method chosen in this paper (meta-analysis), since it provides a simple framework for identifying and understanding the relationship between the various components of the built environment (independent variables) and travel behavior.

Residential and Employment Densities

The significance of population and employment densities as predictors of travel behavior is almost undisputable. Many studies dealing with the

impact of urban form on travel have found the density measure to be, by far, the strongest predictor of travel behavior amongst all of the other built environment measures. One of the earliest studies on the effects of urban form on travel was conducted by Levinson and Wynn (1963), who find that neighborhood density substantially reduces vehicle trip frequency. Pushkarev and Zupan (1977) confirm that population density is a decisive factor in justifying investments in heavy rail transit systems. To support high-frequency light rail service, for instance, Pushkarev and Zupan conclude that densities of at least nine dwelling units per acre within a 15 mile radius of a downtown would be required (Cervero and Radisch 1996). A study in Portland by 1000 Friends of Oregon estimates that an increase in 20,000 jobs within a 20-minute commuting distance by car will reduce daily household vehicle miles traveled (VMT) by half a mile while increasing the number of daily auto trips by one-tenth of a trip. The same increase in jobs within a 30-minute commuting distance by transit was estimated to reduce daily VMT a bit more, to six-tenths of a mile, and the number of daily car trips by one-tenth of a trip (1000 Friends of Oregon 1993). A similar study to that of the 1000 Friends of Oregon report was conducted by Holtzclaw (1994). Using the 1990 U.S. Census of Population and Housing for 28 communities in California, Holtzclaw measures the influence of neighborhood characteristics on auto use. The reported regression coefficient on density in his study was 0.25, suggesting that doubling the density will reduce both the number of cars per household and the VMT per household by about 25 percent.

A small number of studies, however, find the impact of density on travel to be fairly weak. A study by Schimek (1996), which used data from the 1990 Nationwide Personal Transportation Survey, finds that density matters, but not by much. A 10 percent increase in density was projected to lead to only a 0.7 percent reduction in household automobile travel. By comparison, a 10 percent increase in household income was projected to contribute to a 3 percent increase in automobile travel. Studies conducted at the neighborhood level by Cervero and Kockelman (1997) in San Francisco and by Greenwald and Boarnet (2001) Portland find that density has a modest and only a local effect on travel. Higher densities only marginally reduced the probability for commuting by car and slightly increased the probability for walking and riding transit.

Land Use Mix

The assertion that land-use mixture, that is the intermingling of offices, shops, public open spaces, and other consumer amenities amongst one another, yields some transportation benefits is almost undisputable in the literature. The assumption is that in mixed used settings people will be less likely to drive and more likely to walk to their destinations. This behavior

presumably should be reflected in lower vehicular trip generation rates and higher non-motorized modal splits.

Many studies show that mixed land use settings have a significant impact on the travel choices of individuals. However, the nature of this relationship is much more complex than other urban form factors, such as population or employment densities, and the results reported in various studies with regard to the influence of land use mix on travel tend to be subject to much larger variation. The main reason for this variation is that there is neither a simple way to define what a "mixed environment" is nor a clear-cut method of how to quantify it. Although some progress has been made in recent years to address this issue [see for example the dissimilarity index proposed by Kockelman (1997)], the inherent subjectivity of what represents mixed land use will likely result in continued variation in approaches to its quantification.

Recent research by Cervero (2002), conducted in Montgomery County, Maryland, finds that mixed land use settings exert a strong influence on travel behavior. His study shows that intensities and mixtures of land use significantly influence decisions to drive-alone, share a ride, or patronize transit. A previous study, also by Cervero (1996), which examined the impact of mixed land use on travel choices at a more aggregated level (i.e., the 44 largest U.S. metropolitan areas), finds that having grocery stores and other consumer services within 300 feet of one's residence tends to encourage commuting by mass transit, walking and bicycling, while controlling for such factors as residential density and vehicle ownership. Contrary to these findings, Crane and Crepeau (1998) find little role for land use mixture in explaining travel behavior. Mixed use settings were not found to be significantly correlated with fewer car trips or lower car mode splits.

The unanswered question in the built environment - travel studies (as in any other statistical study investigating the relationship between independent and dependent variables) is that of causation. Although many studies show strong correlations between the two elements, it is not clear whether attributes of the built environment, such as high residential densities and mixed land use settings actually contribute to lower VMT and higher slow mode and transit shares. It is possible that this relationship is due to the fact that people choose to reside in high density and mixed environments because they prefer to drive less.

Street Pattern

The street pattern plays a key role in many of Neo-Traditional and Transit-Oriented Development plans. The assumption is that designing smaller

blocks, continuous sidewalks and highly connected roads (grid layout) will reduce automobile trips, automobile frequencies and VMT, and will generate greater pedestrian traffic (Crane 1996; Ryan and McNally 1995; Plaut and Boarnet 2003). This assumption however is probably the most controversial and highly debated hypothesis of the urban form-transportation connection. The empirical evidence collected from many studies draws indecisive conclusions with regard to the impact of street pattern designs on travel behavior.

Perhaps the most typical transportation feature of Neo-Traditional and New Urbanist plans is a grid street layout, in contrast to the looped cul-de-sac pattern. Calthorpe's (1993) assertions about the transportation benefits of his suburban designs depend heavily on the study of Kulash et al. (1990) that traditional grid circulation patterns reduce VMT by 57 percent as compared to VMT in other street networks. The more complex simulation studies of McNally and Ryan (1992) similarly report less driving in a rectilinear grid street system (Crane 1996). A simulation study conducted by Gat et al. (2005), in a highly auto dependent urban district near Tel Aviv, Israel, has predicted that a "pre-emptive TOD styled design initiative," characterized by a highly connected grid network and mixed land usage, could shift slow mode splits to a 40 percent share, as compared to a 5 percent share in the "business as usual" alternative.

The results of the simulation studies conducted by Kulash et al. (1990) and McNally and Ryan (1992) have come under sharp criticism. Crane (1996) claims that the evidence concerning the transportation benefits of the grid pattern is weak at best, and contradictory at worst. He argues that those studies supportive of the proposition that "grid patterns reduce car use" tend to have serious flaws, such as assuming that trip frequencies do not vary from one design to another, or failing to isolate the independent influence of the street pattern on travel behavior.

Other commonly investigated features of the street pattern include sidewalk and cycling path ratios. The assumption is that higher shares of these indicators will contribute to higher rates of slow mode trips. Cervero (2002), in a study conducted in Montgomery County, Maryland, finds that neighborhoods with fairly well developed sidewalk infrastructure appear to have influenced mode choice to some degree, seemingly by providing more attractive settings for taking a bus or joining a vanpool. Contrary to these findings, a study by Rodriguez and Joo (2004), which examined the relationship between travel mode choice and the attributes of the street pattern (sidewalk availability, presence of walking and cycling paths) in areas which were in close proximity to the University of North Carolina at Chapel Hill, finds the influence of these attributes on mode choice to be fairly weak.

The empirical evidence on the impact of urban form on travel is mixed. Although a considerable consensus has been reached with regard to the impact of population and employment densities on trip generation and mode choice, a great deal of ambiguity is still left concerning the influence of street pattern characteristics and land use mix on travel behavior. This issue of inconclusive and inconsistent studies is problematic, but solvable. In the past three decades, a number of statistical techniques have been formulated in order to resolve the apparent contradictions in research findings. The best known technique was developed by Glass (1976), who introduced a method of translating results from different studies to a common metric. He coined the term "meta-analysis" and distinguished it from primary analysis and secondary analysis.

Meta-analysis: Main Principles and Procedures

Meta-analysis is a package of statistical procedures designed to accumulate and integrate experimental results across independent studies that address a related set of research questions. Unlike traditional research methods, meta-analysis uses the summary statistics (correlation coefficients, P values, Z Scores, t values, sample size, etc.) from individual primary studies as the data points. These procedures allow one to determine the strength and direction of associations between the independent and dependent variables. Meta-analysis is particularly suitable in cases where research outcomes are to be judged or compared (Lyons 2003; Hunter and Schmidt 1990; Hedges and Olkin 1985). In this context, standard regression methods or, in the case of categorical data, discrete choice methods are often employed (Nijkamp and Pepping 1998).

There are two main methods for conducting a meta-analysis. The first method involves the combination of probability values, Z scores or correlations. In this procedure the correlation coefficients are either combined by the use of simple average, or by "weighted" average according to the sample size of each primary study (Lyons 2003). An alternative approach for this method is Fisher's transformation. In this statistical procedure, the correlation coefficients are first transformed to Z scores. This step ensures the normality of the distribution sample.

Glass (1976) and Cohen (1977) have developed a second method of meta-analysis that does not rely on the combination of Z-scores or probability values as the common metric. Instead, this method uses standardized differences between mean scores (effect size – d) as the combinatorial statistic. The effect size is a quantitative index, equivalent to the difference between means, used to measure the magnitude and direction of relations between independent and dependent variables.

The Application of Meta-analysis in Transportation and Urban Planning

Over the span of three decades, meta-analysis has grown from a fairly unknown statistical method, used only in few research fields (e.g. education, clinical psychology, medical sciences), to a very common technique for conducting empirical research in many of the social science disciplines.

In recent years, more than a dozen studies have applied meta-analytical methods in an attempt to settle contradictory findings in the urban and transportation planning fields. Nijkamp and Pepping (1998) have offered an application of meta-analysis for analyzing the critical success factors of urban energy policies and sustainable city initiatives. Debrezion et al. (2003) have used the method in an attempt to measure the aggregated impact of railway stations on residential and commercial property values. The database for their research was based upon 70 underlying cross-sectional studies that varied in their geographical settings (United States, Canada, and Europe), and time scale (early 1970s through 2002). Results of the meta-analysis show that commuter railway stations have a consistently higher positive impact on property values than light and heavy railway/metro stations. Other applications of meta-analysis in regional science and urban and environmental economics can be found in Van den Bergh and Button (1997), Button and Kerr (1996), and Button and Nijkamp (1997).

It appears that only two studies have used meta-analysis in an attempt to reach a more clear-cut conclusion regarding the built environment–travel connection. In a form of meta-analysis, Ewing and Cervero (2001) estimated elasticities for VMT and vehicle trips based on the results of published studies. Four measures of the built environment were used: density, diversity, design and regional accessibility. The results of the meta-analysis showed a statistically significant, but rather weak connection between urban form variables and travel behavior. A 10 percent increase in local density and local design, for example, was associated with a 0.5 percent decline in vehicle trips, and a 10 percent increase in local diversity was associated with a 0.3 percent fall in vehicle trips and a 0.5 percent decrease in VMT. The authors note that although these elasticity values are not large in absolute terms, they are significantly different from zero, and the cumulative effects of regional accessibility, density, diversity, and design are actually quite large.

Ewing (2005) examines the effect of the built environment on physical activity levels and health related issues (e.g. Body Mass Index, obesity). His research investigated the association between compact development patterns and the use of active travel modes such as walking and transit, after controlling for the amount of reported leisure time walking. In the final stage of his research, Ewing conducted a meta-analysis of travel

elasticities with respect to land use density, diversity, and design. The elasticities derived suggest that for every 1 percent increase of measures of density or design, the percentage of trips made on foot rises by approximately 0.45 percent.

Potentials and Pitfalls of Meta-analysis

One of the great advantages of meta-analysis is that it provides the opportunity to view the 'whole picture' in a research enterprise. It keeps the researcher from relying on the results of a single study in attempting to understand a phenomenon. Meta-analysis allows a more objective appraisal of the evidence than traditional narrative reviews and may explain heterogeneity or the similarities and differences among the methodologies and the results of various individual studies (Egger and Smith 1997).

Another major benefit of meta-analysis is that by accumulating results across studies, one can enlarge the sample size of the research, gain a more accurate representation of the population relationship and a higher statistical significance than one achieved in a single underlying study. In this context, Rosenthal and DiMatteo (2001) argue that pulling together the results of only two studies, even if they are less statistically significant, provide much more powerful evidence against the null hypothesis than the results of a single study that is more statistically significant. Meta-analysis thus provides the opportunity for even smaller and less significant effects to contribute to the 'overall picture' of the research.

Meta-analysis has been criticized in a number of ways. First, it has been argued that published findings are highly selective and do not represent the "state of the art" accurately. Researchers are inclined to report findings that are statistically significant and to neglect those that are not. Journal editors tend to reject submitted manuscripts which do not include statistically significant findings due to the high competition for journal space. Second, meta-analysis has been criticized for "garbage in and garbage out," that is the mixing together of "good" and "bad" studies (Hunt 1997). Third, meta-analysis has been reproached for mixing "apples and oranges." This claim is due to the fact that the procedure involves summarizing results from studies that vary in their modeling techniques, in the measurement of independent and dependent variables, and that employ very different types of sampling units to achieve answers to questions that are similar, though often not identical (Schwarzer 1989; Hunt 1997).

Research Design

In light of the problem of mixed empirical evidence, this research attempts to settle the contradictory findings reported in the single studies and reach

more robust conclusions with regard to the outstanding questions of the effects of density, land use mix and street pattern configuration on travel behavior.

The Application of Meta-analysis in Light of the Main Critiques

Before specifying the research approach, it is appropriate to explain the justification of using meta-analysis in this research in light of the three main critiques of the method. The first criticism suggests that meta-analysis is prone to publication bias either because journal editors tend to reject insignificant results or since authors are likely to report only significant findings. This constraint, known as the "file drawer problem," has much more to do with publication ethics than with the actual "problematic nature" of the procedure itself. Any evaluation tool, be it meta-analysis or a different method, can only make inference on what is known and reported. The "file drawer problem" is even less relevant within the particular context of the land use–travel connection due to the raging debate within the planning community regarding the impact of the built environment on travel behavior. As can be seen from the literature review section, highly critical studies, which show insignificant relationship between built environment characteristics and travel behavior indicators, are almost as abundant as studies that show strong and robust connection between the two elements.

The second critique contends that meta-analysis mixes together "good" and "bad" quality studies. This criticism is more relevant to medical or clinical studies, where the methodological quality of the study is determined by the method of allocating the population to treatment or control groups (random allocation is considered to be of high quality and non-random allocation of low quality). Glass, McGaw, and Smith strongly disagree with the "garbage in, garbage out" critique and argue that proper meta-analytic procedures do not prejudge the quality of studies for selection purposes: "The influence of study quality on findings should be regarded as an empirical a posteriori question, not an a priori matter of opinion or judgment used to exclude large numbers of studies from consideration" (Glass, et al. 1981). This meta-analysis research has avoided the use of simulation studies, which were often criticized for exaggerating the effect of built environments characteristics on travel behavior. Concurrently, studies which did not control for socio-demographic effects were also excluded from the meta-analysis.

The third main critique of meta-analysis is that the procedure "mixes apples and oranges." This claim is true in a sense because the various primary studies used in the meta-analysis often employ different statistical procedures and measure their independent and dependent variables in a

dissimilar manner. In many of the meta-analyses conducted in the social sciences, as in the case of this particular research, the underlying studies are also drawn from different populations and vary in their geographical settings and scale. An answer to the "apples and oranges" criticism can be quite simple. It can be argued, as Rosenthal and DiMatteo (2001) correctly note, that it is a good thing to mix apples and oranges, particularly if one wants to generalize about fruit (density, land use mix and street pattern configuration), and that studies that are exactly the same in all respects are actually limited in generalizability.

Any statistical procedure can be misused, and meta-analysis is no exception. Today there is no longer serious criticism that rejects meta-analysis methodology. In the context of the transportation and urban planning fields, Nijkamp and Pepping (1998) note that "meta-analysis has clearly demonstrated its validity and usefulness as a methodological tool for comparative study in the field of transport science and environmental science."

Research Approach

This meta-analysis research aggregates the findings of various primary studies in an attempt to estimate the overall impact of built environment characteristics on travel behavior. Five urban form variables (residential density, employment density, land use mix, sidewalk ratio, and grid percentage) and seven travel variables (VMT, VHT, vehicle trips, non-work vehicle trips, probability of commuting by automobile, transit, or by walking) were included in the meta-analysis.

The main problem encountered in the design of the research involved the characterization of the independent variables. Many of the built environment variables used in the various primary studies were defined and quantified in a dissimilar manner. Some studies, for example, have defined density as "the number of households per acre," and others have defined it as "the number of residents per squared mile." The variation in the measurement of the land use mix was even greater, since every study used a different index to measure it. Due to the fact that there is no simple way to overcome this problem, the decision was made to focus only on the nature and direction of the relationship (significance and coefficient sign). The treatment of the dependent (travel) variables was easier since all of the studies have used common measurements such as vehicle trip frequency, or VHT. Other travel variables such as VMT and VKT (both of which denote travel distance) and the probability of commuting by a certain mode and the percent of trips made by a certain mode (both of which represent mode choice) were pooled together in order increase the sample size.

The meta-analysis method used in this research to estimate the combined effect of the various urban form components on travel behavior involved the aggregation of probabilities according to the weight (sample size) of each underlying study. Summary statistics, containing data such as correlation coefficients, P values, Z values, t values and sample sizes were collected from each primary study. The reported Z (probit models) and t values (OLS multiple regression, logit models) in each study were used to calculate normal distribution probabilities. In some cases, the Fisher's r to Z transformation was used in order to translate the correlations coefficients into Z scores and obtain the normal distribution probability.

Research Data

The research is composed of 17 different primary studies, which supplied a total of 32 unweighted data points to the meta-analysis, as shown in Table 1. It is important to note that preliminary search revealed over 40 published studies on the impact of urban form on travel behavior, but because of statistical and methodological constraints only half of them were used in the final analysis. This paring was primarily due to the exclusion of key summary data (which serve as inputs for the meta-analysis) and socio-demographic factors used as control variables in the underlying studies.

Most of the primary studies were located using electronic databases. The very thorough and comprehensive synthesis study by Ewing and Cervero (2001), which explored the effects of the built environment on key transportation outcomes, has also aided in identifying relevant data. Studies were included in the meta-analysis if they were published in the last fifteen years in the United States and assessed any of the three characteristics of the built environment (density, land use mix, and street pattern configuration) in relation to travel behavior. The original seventeen studies were carried out at the neighborhood, urban or regional levels, and their statistical information was drawn from census tract data (CT), transportation/traffic analysis zone data (TAZs), or from specifically-tailored surveys. Although the various primary studies differ from each other in many respects, there is still considerable logic in combining their results. Cervero and Ewing (2001) supply this rational in their synthesis study. They report that built environment–travel elasticities obtained from studies conducted by "different methodologies in different geographic areas for different time periods" tend to cluster around common values.

Table 1: Summary of the Primary Studies Used in the Meta-Analysis

Author(s)	Study Area	Estimation Method	Sample Size	Dependent Variable	Independent Variables
Cervero, 1994a	San Francisco	OLS regression	27	Percent of trips by rail transit (mode split)	Station distance (feet), density (DU per acre), land use mix, continuous sidewalks
Cervero and Gorham, 1995	Los Angeles	OLS regression	1,636	Percent of work trips by transit (mode split)	Gross residential density (HH per acre)
Cervero, 2002	Montgomery County, Maryland	Binomial logit	427	Mode choice: drive alone, work trips	Gross density (squared miles) origin and destination, land use diversity - origin and destination, ratio of sidewalks - origin and destination
" "	" "	" "	1,960	Mode choice: transit, all trips	" "
Frank et al., 2000	Seattle	OLS regression	1,700	Vehicle miles traveled	Gross residential density origin (HH per acre)
" "	" "	" "	" "	Vehicle hours traveled	" "
" "	" "	" "	" "	Vehicle trip frequency	" "
Ewing, 1995	Palm Beach County	OLS regression	548	Vehicle hours traveled	Gross residential density origin (HH per acre), gross employment density (jobs per acre), origin and destination
Schimek, 1996	Different US cities	OLS regression	15,916	Vehicle trip frequency	Gross population density (persons/sq km)
" "	" "	" "	" "	Vehicle miles traveled	" "
Cervero, 1991	Different US cities	OLS regression	52	Percentage of work trips by private car	Mixed use
" "	" "	" "	39	Percentage of work trips by mass transit	" "
" "	" "	" "	" "	Percentage of work trips by walking	" "
Kockelman, 1997	San Francisco	OLS regression	8,050	Total vehicle kilometers traveled	General mixed use
" "	" "	" "	6,311	Non-work VKT	" "
" "	" "	MNL	52,650	Mode choice: personal vehicle choice	Gross residential density (HH per acre) - origin and destination, gross employment density (employees per acre) - origin and destination
Boarnet and Sarmiento, 1998	Southern California	Ordered probit	432	Number of non-work automobile trips	Percent grid, population density (1,000 persons/sq mile), retail density (retail jobs/sq mile), service density (service jobs/sq mile)

Table 1: Summary of the Primary Studies Used in the Meta-Analysis (cont'd)

Author(s)	Study Area	Estimation Method	Sample Size	Dependent Variable	Independent Variables
Sun et al., 1998	Portland	OLS regression	300	Trip frequency	Employment density
" "	" "	" "	" "	Vehicle miles traveled	Land use balance
1000 Friends of Oregon, 1993	Oregon	OLS regression	2,223	Vehicle miles traveled	Number of households per zonal acre, employment per zonal acre, percent of commercial buildings
Crane and Crepeau, 1998	San Diego	Ordered logit	1,336	Household car trip frequency	Connected street pattern (grid), mixed street pattern (grid + cul de sac)
" "	" "	Ordered probit	" "	Car mode choice	" "
Greenwald and Boarnet, 2001	Portland	Ordered probit	1,083	Non-work walking trips	Zip population density per square mile, zip retail employment density
" "	" "	OLS regression	1,089	Non-work walking trips	Block population density, percent grid, census tract retail employment density
Cervero, 1994b	Different cities in California	OLS regression	17	Percent of work trips by rail	Employment density
Frank and Pivo, 1995	Washing-ton state	OLS regression	1,000	Percent of trips by private car	Employment density, population density, mixing of uses
" "	" "	" "	" "	Percent of trips by transit	Employment density, population density, mixing of uses
" "	" "	" "	" "	Percent of trips by private car	Employment density, population density, mixing of uses
Cervero, 1996	11 US metropoli-tan areas	Binomial logit	9,823	Probability of commuting by auto-mobile	Residential density, mixed land use
" "	" "	" "	15,258	Probability of com-muting by public transit	" "
" "	" "	" "	9,805	Probability of com-muting by walking or bicycling	" "
Cervero and Duncan, 2002	San Francisco	Nested logit	7,836	Probability that a trip will be made by walking	Land use diversity, origin and destination

Research Findings

The results of 18 meta-analysis tests, sorted according to the three main built environment characteristics discussed in the literature review section, are summarized in Tables 2 through 4. Each column represents an explanatory built environment variable and each row represents a dependent travel variable. Four summary statistics are presented for each of the 18 meta-analyses. They include the number of primary studies used in each test (# Studies), the total sample size (N), the coefficient sign (Sign), and the significance (Sig.) of the association between the urban form and travel variables. The number of primary research projects used in each meta-analysis ranges between two to six studies. Although this number seems to be quite small, it is important to remember that the combination of only two studies in the meta-analysis procedure provides much more powerful evidence against the null hypothesis than the results of a single study (see Rosenthal and DiMatteo 2001). A final comment is related to the question of causation. The conclusions in this section follow the supposition made in all primary studies, assuming that the characteristics of the built environment influence travel behavior and not vice-versa.

Residential and Employment Densities

Table 2 presents the meta-analysis results for the linkage between densities and travel behavior. The reported findings reaffirm the role of residential density as being the most important built environment element which influences travel choices. Residential densities were found to be overwhelmingly significantly and negatively correlated with VMT/VKT, VHT, total vehicle trips, and with the probability of commuting to work by automobile. The density element was also found to be statistically significant and positively correlated with the probability of commuting to work by transit, or by walking and cycling.

Employment density was found to exert a strong influence on travel behavior. Higher employment densities were found to be significantly connected with fewer VMT/VKT and total vehicle trips, and with a lower probability of commuting to work by automobile. Higher employment densities were not, however, found to be significantly linked with lower Vehicle Hours Traveled. This may be due to the fact that VHT is a more sensitive variable, in a sense that it does only reflect traveled distance, but also takes into account travel time or congestion conditions. Thus, in highly congested regions, the linkage between density (at trip end) and VHT may be less clear.

High employment densities were found to be significantly associated with higher probabilities of commuting to work by transit or by slow modes.

The main reason for the strong influence that employment density has on mode choice is due to the fact that the clustering of jobs, especially in close vicinity to bus or rail stations, allows people to either use transit or car pool to work. In areas which are characterized by high employment densities as well as by other mixed land uses (especially residential use), there is also a much greater chance for commuting by slow modes of walking and cycling.

Table 2. Meta-Analysis Results for the Relationship between Density and Travel Variables

	Gross Residential/Population Density (Origin)		Gross Employment Density (Destination)	
VMT/VKT	N	#Studies	N	#Studies
	19839	3	3923	2
	Sig.	Sign	Sig.	Sign
	P<0.001	-	P<0.001	-
VHT	N	#Studies	N	#Studies
	2248	2	2248	2
	Sig.	Sign	Sig.	Sign
	P<0.001	-	NS	-
Vehicle Trips	N	#Studies	N	#Studies
	17616	2	2000	2
	Sig.	Sign	Sig.	Sign
	P<0.001	-	P<0.05	-
Vehicle Trips (non work)			N	#Studies
			864	2
			Sig.	Sign
			NS	-
Probability of Commuting by Automobile / Percent of Trips by Automobile	N	#Studies	N	#Studies
	73296	4	53650	2
	Sig.	Sign	Sig.	Sign
	P<0.001	-	P<0.001	-
Probability of Commuting by Transit / Percent of Trips by Transit	N	#Studies	N	#Studies
	35139	6	1017	2
	Sig.	Sign	Sig.	Sign
	P<0.001	+	P<0.001	+
Probability of Commuting by Walking / Percent of Trips by Walking	N	#Studies	N	#Studies
	21693	4	2083	2
	Sig.	Sign	Sig.	Sign
	P<0.001	+	P<0.01	+

NS – not significant at the 5 percent level

Mixed Land Use

If any doubts exist with regard to the influence of land use mixing on travel behavior, they are repudiated in this study. As can be seen from Table 3, the influence of mixed land use on travel was found to be overwhelmingly significant.

Table 3. Meta-Analysis Results for the Relationship between Land Use Mix and Travel Variables

	Land Use Mix	
	N	#Studies
VMT/VKT	10573	3
	Sig.	Sign
	P<0.001	-
	N	#Studies
Probability of Commuting by Automobile/ Percent of Trips by Automobile	10875	3
	Sig.	Sign
	P<0.001	-
	N	#Studies
Probability of Commuting by Transit/ Percent of Trips by Transit	18284	5
	Sig.	Sign
	P<0.001	+
	N	#Studies
Probability of Commuting by Walking/Percent of Trips by Walking	18641	3
	Sig.	Sign
	P<0.001	+

NS – not significant at the 5 percent level

Land use mix is negatively associated with VMT and with the chance of commuting by automobile, and positively linked with the probability of commuting to work by transit or by slow modes. This finding is mainly due to the fact that the intermingling of residences, jobs, shops, and recreational facilities in a compact urban environment induces people to carry out their daily activities within a much smaller geographical area, thus on the one hand reducing VMT while on the other hand increasing the probability of traveling by slow modes.

Street Pattern

Table 4 shows the relationship between two street pattern elements (grid percent coverage and sidewalk ratio) and travel behavior. It is important to note that relatively few non-simulation studies have investigated the

impact of street pattern configuration on travel behavior. The linkage between these two elements was found to be insignificant.

Table 4. Meta-Analysis Results for the Relationship between Street Network Configuration and Travel Variables

	Ratio of Sidewalks		Percent Grid	
			N	#Studies
Probability of Commuting by Automobile/ Percent of Trips by Automobile			3025	3
			Sig.	Sign
			NS	+
	N	#Studies		
Probability of Commuting by Transit/ Percent of Trips by Transit	1987	2		
	Sig.	Sign		
	NS	+		

NS – not significant at the 5 percent level

The existence of a higher sidewalk ratio in an urban environment was not found to be related to higher probability of commuting by transit. The New Urbanist assumption that a larger sidewalk ratio will encourage walking to transit stations and thus boost transit use does not seem to hold water. The effect of grid percent coverage on the probability of commuting by automobile, although not significant at the 5 percent level, was somewhat surprising. The coefficient is positive, suggesting that higher grid percent coverage raises the probability for commuting by car, and does not lower it. This finding clearly contradicts the results of few simulation studies (e.g. Kulash et al. 1990; McNally and Ryan 1992), showing significant and negative association between the two elements.

Conclusions

This paper has analyzed the impact of urban form on travel behavior by the use of meta-analysis statistics. Several important lessons can be learned from this investigation. First, it is clear that two elements of the built environment, population density and employment density exert a strong influence on travel behavior, even when controlling for socio-demographic variables such as income or age. Second, the effect of land-use diversity on travel turned out to be even stronger than expected. The mix of offices, shops, and public facilities in urban settings does exert a

particularly strong influence on mode choice. Residents who live in more diverse urban environments are more likely to commute to work by transit or by slow modes. Third, the claim of many New Urbainsts and Neo-Traditional planners concerning the advantages of a grid layout and continuous sidewalks design does not seem to have merit. The impact of these design features on travel behavior was found to be not significant. In the case of the grid network design, it may well be that the superior accessibility created by this type of network actually works in the opposite direction — that is, it might be actually contributing to a higher probability of commuting by car.

The results of this meta-analysis research have clarified some of the outstanding questions dealing with the effects of density, land use mix and street pattern configuration on travel behavior. The main shortcoming of the study is its inability to account, as Ewing and Cervero (2001) did in their synthesis study, for urban form-travel elasticities. This dearth is mainly due to the dissimilar definition and quantification of the explanatory variables in the various underlying studies. Deriving elasticities under these constraints could have led to biased and skewed results.

One of the main strengths of this particular study is the inclusion of seven travel variables in the meta-analysis. As a comparison, Ewing and Cervero (2001) included only two travel variables (vehicle trips and Vehicle Miles Traveled) in their analysis. They have also made quite a hard supposition in the estimation of vehicle trips and VMT, assuming overall trip rates to be constant (slow modes and transit trips were substituted for auto trips). This meta-analysis study has taken a much more cautious approach. It has avoided the generalization of travel variables, and separately investigated the relationship between urban form variables and various travel measures, including VHT, non work vehicle trips and mode choice. This caution, however, came at the expense of obtaining smaller sample sizes for each of the meta-analyses. Future meta-analysis research on the built environment-travel connection could incorporate some elements from the two methodologies. Prospective synthesis research should account for elasticities that represent relationships between built environment and travel measures beyond vehicle trips and VMT (e.g. VHT, mode choice). Concurrently, the validity of the explanatory built environment variables should be enhanced in order to avoid biased elasticities. This enhancement can be achieved by constructing a normalized index for the density, diversity and design attributes used to measure the built environment that is aimed at narrowing the discrepancies caused by the different methodologies and quantification methods used in the various primary studies.

Acknowledgments

References

Bernick, Michael, and Robert Cervero. 1997. Transit Villages in the 21st Century. New York: McGraw-Hill.

Boarnet, Marlon, and Sharon Sarmiento. 1998. Can Land-use Policy Really Affect Travel Behaviour? A Study of the Link between Non-work Travel and Land–use Characteristics. Urban Studies 35 (7):1155–1169.

Button, Kenneth, and Jonathan Kerr. 1996. Effectiveness of Traffic Restraint Policies: A Simple Meta-regression Analysis. International Journal of Transport 23:214–225.

Button, Kenneth, and Peter Nijkamp. 1997. Environmental Policy Assessment and the Usefulness of Meta-analysis. Socio-Economic Planning Sciences 31 (3):231–240.

Calthorpe, Peter. 1993. The Next American Metropolis: Ecology, Community and the American Dream. New York: Princeton Architectural Press.

Cervero, Robert. 1991. Land Uses and Travel at Suburban Activity Centers. Transportation Quarterly 45 (4):479–491.

———. 1994a. Transit Based Housing in California: Evidence on Ridership. Transport Policy 1 (3):174–183.

———. 1994b. Rail Oriented Office Development in California: How Successful? Transportation Quarterly 48 (1):33–44.

———. 1996. Mixed Land-uses and Commuting: Evidence from the American Housing Survey. Transportation Research Part A –Policy and Practice 30 (5):361–377.

———. 2002. Built Environments and Mode Choice: Toward a Normative Framework. Transportation Research Record Part D 7:265–284.

Cervero, Robert, and Michael Duncan. 2002. Transit's Value Added: Effects of Light and Commuter Rail Services on Commercial Land Values. Paper read at Transportation Research Board, 81st Annual Meeting.

Cervero, Robert, and Roger Gorham. 1995. Commuting in Transit versus Automobile Neighborhoods. Journal of the American Planning Association 61 (2):210–225.

Cervero, Robert, and Kara Kockelman. 1997. Travel Demand and the 3Ds: Density, Diversity and Design. Transportation Research Part D 2 (3):199–219.

Cervero, Robert, and Carolyn Radisch. 1996. Travel Choices in Pedestrian versus Automobile Oriented Neighborhoods. Transport Policy 3 (3):127–141.

Cohen, Jacob. 1977. Statistical Power Analysis for the Behavioral Sciences. Rev. ed. New York: Academic Press.

Crane, Randall. 1996. Cars and Drivers in the New Suburbs: Linking Access to Travel in Neotraditional Planning. Journal of the American Planning Association 62 (1):51–65.

Crane, Randall, and Richard Crepeau. 1998. Does Neighborhood Design Influence Travel? A Behavioral Analysis of Travel Diary and GIS Data. Transport Research Part D 3 (4):225–238.

Deberzion, Ghebreegziabiher, Eric Pels, and Piet Rietveld. 2003. The Impact of Railway Stations on Residential and Commercial Property Value: A Meta Analysis. Tinbergen Institute Discussion Paper No. TI–2004–023/3.

Duany, Andres, and Elizabeth Plater–Zyberk. 1992. The Second Coming of the American small Town. Wilson Quarterly Winter 19–50.

Egger, Matthias, and George Smith. 1997. Meta-analysis — Potentials and Promise. British Medical Journal 315 (7119):1371–1374.

Ewing, Reid. 1995. Beyond Density, Mode Choice, and Single Purpose Trips. Transportation Quarterly 49 (4):15–24.

———. 2005. Can the Physical Environment Determine Physical Activity Levels? Exercise and Sport Sciences Reviews 33 (2):69–75.

Ewing, Reid, and Robert Cervero. 2001. Travel and the Built Environment. Transportation Research Record 1780:87–114.

Frank, Lawrence, and Gary Pivo. 1995. Impacts of Mixed Use and Density on Utilization of Three Modes of Travel: Single-Occupant Vehicle, Transit and Walking. Transportation Research Record 1466:45–52.

Frank, Lawrence, Brian Stone, and William Bachman. 2000. Linking Land Use with Household Vehicle Emissions in the Central Puget Sound: Methodological Framework and Findings. Transportation Research Part D 5:173–196.

Gat, Daniel, Yaacov Mamane, Pnina Plaut, Eran Leck and Shlomo Bekhor. 2005. Planning a Sustainable Urban District: Urban Design, Transportation, Environment. Planning — Journal of the Israel Association of Planners 2 (1):3–8. (in Hebrew, English abstract).

Glass, Gene V. 1976. Primary, Secondary and Meta-Analysis Research. Educational Researcher 10:3–8.

Glass, Gene V., Barry McGaw, and Mary Lee Smith. 1981. Meta-analysis in Social Research. Beverly Hills, Calif.: Sage Publications.

Greenwald, Michael, and Marlon Boarnet. 2001. Built Environment as Determinant of Walking Behavior: Analyzing Non-work Pedestrian Travel in Portland, Oregon. Transportation Research Record 1780:33–42.

Hedges, Larry V., and Ingram Olkin. 1985. Statistical Methods for Meta-analysis. Orlando: Academic Press.

Holtzclaw, John. 1994. Using Residential Patterns and Transit to Decrease Auto Dependence and Costs: Natural Resources Defense Council.

Hunt, Morton. 1997. How Science Takes Stock: The Story of Meta-Analysis. New York: Russell Sage Foundation.

Hunter, John E., and Frank L. Schmidt. 1990. Methods of Meta-analysis: Correcting Error and Bias in Research Findings. Newbury Park: Sage Publications.

Katz, Peter. 1994. The New Urbanism: Toward an Architecture of Community. New York: McGraw–Hill.

Kockelman, Kara. 1997. Travel Behavior as a Function of Accessibility, Land Use Mixing and Land Use Balance. Transportation Research Record 1607:117–125.

Kulash, Walter, Joe Anglin, and David Marks. 1990. Traditional Neighborhood Development: Will the Traffic Work? Development 21:4–21.

Levinson, Herbert, and F. Houston Wynn. 1963. Effects of Density on Urban Transportation Requirements. Highway Research Record 2:38–64.

Lund, Hollie. 2003. Testing the Claims of New Urbanism: Local Access, Pedestrian Travel, and Neighboring Behaviors. Journal of the American Planning Association 69 (4): 414–429.

Lyons, Larry. Meta – Analysis: Methods of Accumulating Results Across Research Domains. 2003 [cited. Available from http://www.lyonsmorris.com/MetaA].

McNally, Michael, and Sherry Ryan. 1992. A Comparative Assessment of Travel: Characteristics of Neotraditional Developments. Irvine, CA: Institute of Transportation Studies, University of California.

Nijkamp, Peter, and Gerard Pepping. 1998. A Meta-analytical Evaluation of Sustainable City Initiatives. Urban Studies 35 (9):1481–1500.

Niles, John, and Dick Nelson. 1999. Measuring the Success of Transit Oriented Development: Retail Market Dynamics and Other Key determinants. Paper read at American Planning Association National Planning Conference, at Seattle, Washington.

Plaut, Pnina, and Marlon Boarnet. 2003. New Urbanism and the Value of Neighborhood Design. Journal of Architectural and Planning Research 20 (3):254–265.

Pushkarev, Boris, and Jeffrey Zupan. 1977. Public Transportation and Land Use Policy. Bloomington, IN: Indiana University Press.

Rodriguez, Daniel, and Joonwon Joo. 2004. The Relationship between Non-motorized Mode Choice and the Local Physical Environment. Transportation Research Part D 9:151–173.

Rosenthal, Robert, and Robin DiMatteo. 2001. Meta-analysis: Recent Developments in Quantitative Methods for Literature Reviews. Annual Review of Psychology 52:59–82.

Ryan, Sherry, and Michael McNally. 1995. Accessibility of Neotraditional Neighborhoods: A Review of Design Concepts, Policies, and Recent Literature. Transportation Research Part A 29 (2):87–105.

Schimek, Paul. 1996. Household Motor Vehicle Ownership and Use: How Much Does Residential Density Matter? Transportation Research Record 1552:120–125.

Schwarzer, Ralf. Meta-Analysis Programs 1989 [cited. Available from http://userpage.fu–berlin.de/~health/meta_e.htm].

Sun, Xiaoduan, Wilmot Chester, and Tejonath Kasturi. 1998. Household Travel, Household Characteristics, and Land Use: An Empirical Study from the 1994 Portland Travel Survey: Working Paper, University of Southwestern Louisiana and Louisiana State University.

VandenBergh, Jeroen, and Kenneth Button. 1997. Meta-analysis of Environmental Issues in Regional, Urban and Transport Economics. Urban Studies 34 (5–6):927–944.

1000 Friends of Oregon. 1993. Making the Land Use, Transportation, Air Quality Connection. The Pedestrian Environment 4A.

Eran Leck is a doctoral candidate in Urban and Regional Planning at the Technion–Israel Institute of Technology. His main research interests include transportation and land-use planning, efficiency and equity impacts of transportation improvements, and core-periphery relations in Israel. He is currently writing his dissertation which investigates the effect of transportation and human capital improvements on regional economic growth.