Optimising Models. OMEGA International Journal of Management Science, Vol. 3, No. 5, 1975, pp. 583-594.

Publication of this paper sponsored by Committee on Energy Conservation and Transportation Demand.

Effect of Urban Development Patterns on Transportation Energy Use

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Many who have observed the large fraction of energy used in urban passenger transportation have suggested that this consumption could be reduced by encouraging higher densities and more compact settlements in urban areas. A study was carried out to investigate travel patterns and energy use in urban areas as determined by various descriptors of urban form. A statistical analysis of travel data from eight metropolitan areas found that energy use by urban passenger transportation is lower with some development patterns than with others. Some new neighborhoods would therefore be more energy efficient in their travel impacts than others. However, the transportation energy impacts of an extensive redevelopment (or growth) of an entire urban area would depend on the residential relocations that might occur with such drastic changes in overall housing availability. These were not examined. To calculate the energy use of various travel patterns, a simple direct approach developed at the General Motors Research Laboratories was used. This approach found that fuel consumption could be expressed as a linear function of a trip's travel time and travel distance, independent of complexities such as acceleration and deceleration rates or idle times.

Concern is now growing about the potential limits to the availability of petroleum fuel and the potential risks of our great dependence on the automobile for transportation. Even though many researchers are investigating alternative automobile fuels and energy sources that are not based on petroleum, others are concerned with additional courses of action. Increasing the efficiency of petroleum-based engines and vehicles is a major area of research that has been stimulated partly by federal legislation. In this area, making vehicles smaller, switching to lighter materials, and changing engine design are all receiving great attention.

Another approach to dealing with the potential fuel problem is to reduce our use of automobiles. Public transit, carpooling, and paratransit services are being considered as means of attracting drivers from their cars. In all of these cases, however, there is controversy over the extent to which energy use can actually be reduced (1). Part of the controversy is over the success levels attainable simply by promotion of the alternative modes. Some argue that automobile-restraint measures are necessary to get drivers out of their cars and that parking restraints, gasoline taxes, or road pricing must be used to coerce drivers to change modes. There is the additional question of whether the public transportation modes would actually save more energy than will the legislatively required efficient automobiles of the 1980s.

Other observers have suggested that the interrelated historical development of automobiles and cities during the last 50 years has led to a natural dependence on automobiles in low-density areas (2). This development has made public transportation noncompetitive in most urban areas for the majority of travelers who can afford their own automobiles. To reduce energy use, these observers suggest that we must change the structure of the cities to higher densities so that the resultant congestion would deter automobile use, and the higher densities would promote transit use as well as allow more walking. The remainder of this paper discusses this proposal to change urban form; the effectiveness of the approach is analyzed and various means for bringing it about are assessed.

Several analytical and simulation studies have been made of the relationship between urban form, transportation, and energy use. To understand their results, we must be clear about the possible ways in which urban form affects energy use. The next two sections set this background. First, the influence of travel patterns on energy use is discussed. This is followed by an analysis of the relationships between these travel characteristics and measures of urban form. The integration of these two pieces then provides the structure for the subsequent discussion.

ENERGY AND URBAN TRAVEL

The energy consumed by a single automobile trip depends on both travel time and travel distance. Research by Evans and others at the General Motors Research Laboratories has shown a simple linear relationship for a given vehicle for trip speeds less than about 35 mph (3-6):

$$F = a D + b T + c \qquad (1)$$

where a, b, and c are measured constants and

F = gallons per trip,
D = trip distance (miles), and
T = trip time (min).

The constant c represents the fuel required during cold starts compared to the use of an already warm engine and varies somewhat with ambient temperature.

Evans and others found that this relationship was a remarkably accurate representation of fuel use and that detailed trip characteristics such as acceleration and deceleration and idle times were not needed for the fuel estimate (4).

Based on the General Motors group's examination of 1973-1975 model cars, estimates of a, b, and c can be made for the fleet average. Also, Equation 1 can be written in terms of the distance and speed. The average fuel use per automobile then becomes

$$F = (0.039 + 0.078/v) D + 0.115 \qquad (2)$$

where v = average speed (mph), or

$$F = 0.039D [1 + (20/v)] + 0.115 \quad (2a)$$

Equation 2a shows that the variation in trip speed has a very important effect on fuel use and that simply relating fuel to distance traveled is insufficient. With a 25-mph average speed and a 6-mile average trip distance, efficiency in cities from Equation 2a is 11 miles/gal, lower than the national average of 14 miles/gal. The latter figure, of course, includes intercity highway travel.

By adding up all the automobile trips in an urban area, the results of Evans and others can be used to estimate total fuel use. If it can be assumed that their results can be used with system averages, then total fuel will be a function of trip frequency, average trip length, and average trip speed (5).

If a trip frequency that represents total person trips rather than automobile trips is used, the modal share for transit and the automobile load factor also affect fuel use. An equation that includes all of these factors can be derived for the systemwide fuel use:

$$F_t = 0.039\, ND\, [1 + (20/v)]\, (1/L)\, (1 - t - w) + 0.115\, (N/L)\, (1 - t - w) + Ntf \quad (3)$$

where

- f_t = systemwide fuel use per year;
- N = number of person trips per year;
- L = automobile load factor, normally 1.2 persons/car;
- t = fraction of trips by transit;
- f = transit fuel use per passenger trip; and
- w = fraction of trips by walking.

Most transportation studies in the United States do not determine the walking share (w) for travel, although a few have included it for trips to work. Hence, we will find later that the potential advantages of some urban forms to reduce energy use by making walking convenient cannot be estimated.

The fuel use per bus transit traveler is a value that is difficult to estimate because it depends greatly on the way the bus service is operated: the load factors, the handling of deadheading, and vehicle size. There has been a great amount of disagreement about what this value is in various cities and, more importantly, what it could be (1). Rail transit also has been controversial because of issues such as the energy use of access modes and the energy requirements for construction (1).

Another variable exists in Equation 3--automobile engineering characteristics. Chang and others found that the parameters a and b in Equation 1 are strongly related to engine size and vehicle weight (6). Hence, future changes in automobile design will change the parameter values used in Equation 3. With a mandated new-car efficiency of 27.5 miles/gal in 1985, the fleet average will be at that level by the 1990s; thus, the 14 miles/gal average of the mid-1970s will almost be doubled. This improvement in fuel efficiency will take place in the next 20 years without consideration of any changes in land use. Hence, any evaluation of policies to change either urban form or travel patterns should use the mandated improvement level as a base.

TRAVEL AND URBAN FORM

Most of the variables in Equation 3 are related to urban form and have values that can be changed by modifying the spatial relationship of urban activities. Exactly how urban structure affects the various travel characteristics has not been fully worked out, but a number of previous studies suggest that a strong relationship exists between urban land use arrangements and such travel characteristics as average vehicular trip length, trip duration, trip frequency, mode choice, and overall vehicle miles of travel.

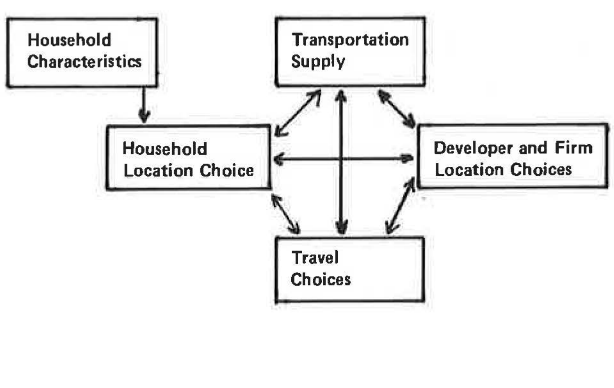
The relationships between urban development patterns and travel behavior can be considered by using the structure shown in Figure 1. One set of relationships in Figure 1 links development characteristics to transportation system characteristics, such as highway infrastructure and the availability of public transportation services. A second set links the characteristics of the households that choose to locate in a neighborhood to land use and transportation system characteristics, and the third set links neighborhood automobile ownership and travel to land use, transportation, and household characteristics.

The relationship between development patterns and transportation system characteristics is undoubtedly very complex. Public decisions to expand the transportation infrastructure influence decisions by developers and firms concerning the location and characteristics of housing, shopping, and industrial developments. The travel generated by these developments in turn influences new decisions on transportation infrastructure. These relationships are the outcome of a series of interrelated decisions made over a period of years.

A second set of relationships illustrated in Figure 1 shows the interaction between developer and transportation supply decisions on the one hand and neighborhood household characteristics and location choices on the other. Households make decisions about location based in large part on the land use and transportation characteristics of the neighborhoods available to them in a metropolitan area. Large households may tend to locate in low-density neighborhoods of single-family homes, for example, and plan on considerable automobile travel, and households that, for economic or other reasons, prefer not to rely on the private automobile may locate in neighborhoods that possess good public transportation. These decisions about household location in turn influence decisions about new land use developments and generate demand for transportation system changes, so that, as with the first set of relationships discussed above, questions of cause and effect become quite complex.

The third set of relationships shown in Figure 1 describes automobile ownership and travel behavior that result from the interaction of decisions made by households, firms, and public bodies and is the focus of most the analyses discussed in this paper. In effect, the analyses assume that public authorities have the power to alter land use and transportation system characteristics for different types of urban residents. It is emphasized, however, that

Figure 1. Structure of relationships between land use characteristics and household travel.



when policymakers actually set out to influence travel patterns through land use changes, they must consider the more complex interactions denoted at the top of Figure 1. Their problem is to take account of the second-round effects that always are present in private markets. Such matters as the prices of land, housing, and transportation will trigger population and other changes that may make it difficult to sustain any desired development pattern. These market influences on household locational choices and urban development patterns must be ignored here, but they may well be critical to any practical implementation of policies intended to influence travel behavior and energy use through alterations in the form of urban physical development.

A review of studies of transportation and land use interactions indicates that the aspect of urban form that most influences travel behavior is the separation between activities. Zahavi has found empirically, for several U.S. and foreign cities, that a measure of the separation between jobs and residences is highly related to the average trip length (7). This measure has been found by McLynn to be a function of the average distances to the urban center of jobs and residences as well as the two variances of these distances (8). Bellomo and others found by comparing data from Detroit for 1953 and 1965 that increases in the distance between residences and jobs increased the length of the work trip (9). They found a similar, but weaker, relationship for social trips and the distances between residences and social opportunities. Simulation studies that used traffic and land use models have also shown that trip lengths become longer as jobs and residences are separated (10).

All of these studies have provided support for the impression that trip lengths vary with the separation among activities. They also suggest that, for most U.S. cities, the average distance of the population or employment to the central business district (CBD) is often a good surrogate for the measure of activity separation.

Trip lengths also increase with metropolitan population, probably because the job-residence separation increases with urban size in the United States (9,11). Virtually all the metropolitan areas that have very long trip lengths are large urban centers where the population has decentralized more extensively than have job opportunities. Whether urban population size and the average separation of households from urban activities exert independent influences on travel lengths or whether population size merely serves as a surrogate for such distancing remains unclear at this point. What is clear is that average household distance from the downtown core and from other central points rises sharply with metropolitan population size. Urban size is probably important primarily as an indirect measure of origin-destination separation in explaining average trip lengths.

The average length of trips generated by residents in a specific neighborhood within an urban area is also related to activity separation (9,11). In this case, the average distance from the neighborhood to jobs or shopping opportunities is the relevant measure. It is not yet clear whether this neighborhood measure of activity separation is more or less important than the metropolitan average measure in explaining neighborhood patterns of trip lengths.

Trip length is also dependent on trip speed which, in turn, depends on the traffic volumes and capacities of the road segments being traversed. (Admittedly, this relationship between speeds and traffic volumes is somewhat circular and should be considered in an equilibrium analysis of supply and demand.) Both the capacities and flows will be related to the general intensity of surrounding land uses. Highway capacity will be easier to provide in outlying or low-density areas where land prices are lower and competing land uses are fewer. The density of traffic may be lower in these outlying areas where activities are farther apart and traffic flows are distributed more randomly.

The relationship between speed and land use measures has not been fully investigated, but the average trip speed is probably highly related, for most trips, to the local speeds at the trip ends. These latter factors appear to depend on the neighborhood density and the location of the trip ends (11). One locational measure that has been found significant is the distance to the CBD. Although this same measure has already been identified as having an important effect on trip length, in that case it was as a surrogate for separation between activities, whereas with speed it may be an indicator of traffic density.

The urban form measures that have now been described cover three different levels of geographic detail. At the highest level of aggregation, metropolitan population has been found to be important. This variable requires no knowledge about the inner structure of the urban area. The separation between activities, at the second level of aggregation, involves more detail about the urban structure and requires knowledge about the relative locations of many residential and industrial structures. The third measure is the neighborhood density--the population or employment density in a census tract or within walking distance. This last measure, like the first, requires no information about the complex interrelationships of activities, except at the geographic level of the individual household or firm and its immediate surroundings.

These three types of measures of urban form appear to be necessary and sufficient to describe the differences in metropolitan structure that affect vehicular travel patterns and, consequently, transportation energy use. The travel variables identified in Equation 3 have all been found to depend on these same measures of urban form (11,12). Although there has been little analysis of walking trips, the amount of land use mixing in a neighborhood (i.e., the close proximity of residences, jobs, and shopping) will likely promote the choice of this mode. The simple measures of employment or population density alone will not be highly related to walking. In fact, it has been found that the areas where walking has the highest fraction of commute trips are not the dense centers of large cities but medium-sized industrial or college towns (11,13).

The discussion now proceeds to analyze how the measures of urban form influence various travel characteristics. Since data are not available on walking trips or land use mixing, these characteristics will not be considered further, but this omission should not lead the reader to forget their potential importance as a means of reducing energy use.

MODEL OF THE EFFECTS OF URBAN FORM ON URBAN TRAVEL

The discussion in this section is based on analyses carried out by Cheslow and others that related land use measures and travel characteristics (11). The relationships should be viewed as preliminary due to the use of the distance-to-CBD measure as a surrogate for other, more complex, activity-separation measures.

The study by Cheslow and others examined actual travel characteristics derived from home interview surveys in eight standard metropolitan statistical areas (SMSAs). These cities, which are listed in Table 1, range in size from Los Angeles to Fresno and Youngstown. No cities that have rail transit were included in the sample. This study complements the simulation analyses carried out by others. It has more realism than simulation because actual trips are analyzed, but it is limited in the range of urban structures that can be examined to those that now exist.

The data set consisted of a pooled sample of neighborhoods drawn from the home interview surveys that were conducted between 1966 and 1971. Cross-sectional regression analysis was conducted at the level of the neighborhood, which was defined to consist of from two to four local traffic zones. The basic sample contained 234 neighborhoods drawn from the eight metropolitan areas. For each neighborhood, the individual responses to the home interview surveys were aggregated to form neighborhood means.

The several transportation characteristics that were examined are listed in Table 2 together with their mean values and standard deviations. These characteristics include all the variables in Equation 3 except transit fuel efficiency and the fraction of walking trips. The variables that describe urban structure included only neighborhood density and distance to the CBD. No employment-density values were available. Areawide characteristics, including urban population, urban density, and percentage of employment in the CBD, were also examined, but the small number of cities in the sample did not permit identification of the correct metropolitan-scale variable. These aggregate variables were highly correlated with each other in the data set.

To overcome this difficulty, dummy variables were used--one for each city. The analysis could then determine the relative importance of the metropolitan dummies and the local variables. For some travel characteristics (such as trip frequency), the dummies were not important, but for others (such as trip length), they dominated the other explanatory variables.

Household characteristics were also considered apart from the land use variables to determine the separate effects of changing densities and locations and those of changing the types of households. The land use and household characteristics are shown in Table 3.

The first aspect of urban travel characteristics to be dealt with concerns the characteristics of the urban transportation system. Equations were estimated by treating transit availability and automobile trip speed as if they were determined by the pattern of urban development. These results are shown in the following table.

Explanatory Variable	Coefficient	t-Statistic
Neighborhood transit availability		
Neighborhood density	0.000 246	7.78
Distance to the CBD	-0.155	-6.07
Metropolitan dummy variable	Varies	
Corrected R^2	0.60	
Automobile driver trip speed		
Neighborhood density	-0.029	-3.12
Distance to CBD	0.062	5.32
Metropolitan dummy variable	Varies	
Corrected R^2	0.81	

It is clear that these relationships are not supply functions in the usual sense of the term. Transit availability is the result of a long series of decisions made by public authorities over many decades. There is no reason to believe that the transit availability equation would adequately describe the type of transit service that would be provided in a newly built-up area. Problems also arise in determining the direction of causation between speed and the development pattern. Do low densities result in high automobile speeds, or does high speed

Table 1. Characteristics of the metropolitan areas.

	Urban Area			
City	Population	Density (people/mile^2)	Percentage of SMSA Employment in CBD	Density Gradient[a]
Dayton	685 942	3062	8.3	0.14
Denver	1 047 311	3574	9.3	0.14
Fresno	262 908	3328	6.5	0.09
Los Angeles	8 351 266	5313	4.0	0.08
Omaha	491 776	3257	13.7	0.22
Pittsburgh	1 846 042	3097	8.9	0.10
Washington	2 481 489	5013	11.8	0.13
Youngstown	395 540	3066	7.5	0.15

Note: All values are for 1970.
[a]Absolute value of the slope parameter of a negative exponential density function fitted to 1970 census tract data.

Table 2. Transportation variables used in the analysis.

Variable	Definition	Unit of Measurement	Mean Value in Sample	SD
Automobile				
Ownership	Average number of automobiles per family in neighborhood	Unit	1.22	0.42
Occupancy, journey-to-work	Average persons per automobile	Unit	1.20	0.16
Average trip duration	Average duration of automobile driver trips (vehicle time only, not door-to-door time)	Minutes	18.1	7.3
Average trip length	Average distance for automobile driver trips	Miles	7.4	4.7
Vehicle miles of travel	Average daily automobile driver vehicle miles traveled per family	Miles		
Transit				
Availability	Proportion of neighborhood within 0.25 mile of a transit line	Percent	59	36
Proportion of vehicle trips	Transit trips ÷ all vehicle trips	Decimal	0.048	0.085
Speed	Total automobile driver miles of travel by residents of neighborhood over total in-vehicle automobile driver minutes of travel	Miles per minute	0.41	
Vehicle trips per family	Average daily trip frequency per family (automobile driver or passenger and transit)	Unit	5.31	2.29

Note: Trips here refers to home-based trips internal to the study area.

Table 3. Land use and family characteristics used in the neighborhood analysis.

Variable	Mean Value in Sample	SD
Land use measure		
Distance from CBD (miles)	7.15	5.43
Neighborhood density[a] (persons/mile^2)	8026	7270
Urbanized area density (persons/mile^2)	3972	969
Urbanized area population (000 000s)	2.87	3.19
Employment in CBD (%)	5.30	1.96
Urbanized area density gradient (1/miles)	0.13	0.03
Household characteristic		
Family income ($)	9546	4485
Average family size (persons/household)	3.23	
Proportion of neighborhood that is black	0.148	0.295

[a]Equals persons per square mile of net area, where net area equals gross area minus recreational land minus the area of any bodies of water in the neighborhood. This measure does not exclude land devoted to industrial or commercial uses.

Table 4. Log-linear variables for automobile driver trip length.

Variable	All Purposes Coefficient	All Purposes t-Value	Work Coefficient	Work t-Value
Income	0.058	1.83	0.081	2.85
Neighborhood density	-0.024	-1.40	-0.049	-2.77
Average automobile driver speed	0.92	6.87	0.96	6.04
Distance to CBD	0.19	4.43	0.41	5.85
Metropolitan dummy variable	Varies		Varies	
Corrected R^2	0.92		0.91	

Table 5. Log-linear variables for home-based vehicle trips per household.

Variable	Coefficient	t-Value
Transit availability	0.051	1.38
Average automobile driver trip time	-0.121	-2.18
Household size	0.507	5.62
Average automobile ownership	0.584	9.11
Neighborhood density	-0.145	-4.03
Corrected R^2	0.68	

Note: Vehicle trips include trips made by automobile driver, automobile passenger, and transit passenger modes.

encourage a sprawling form of development in which residences and activities are far apart? In many cities bus lines follow the routes of the old streetcar lines, which at the time of their inception exerted a powerful influence on development.

Despite these difficulties of interpretation, it is probable that in some sense transportation supply functions do exist. Transit agencies do not make their decisions about construction and operations in a completely arbitrary manner. Transit service will attract more riders and generate more revenue in some situations than in others, and operators take this into account in making route extensions. Similarly, because automobile speed is partly determined by the level of road use and the resulting congestion, development characteristics probably exert some influence on this variable. Even public decisions about street widening and highway construction are influenced by congestion levels, the cost of land, and the amount of disruption that would be caused, all of which are partly dependent on land uses. These considerations suggest that, even though it is invalid to use these equations for making detailed predictions in a given metropolitan area, they may capture the average responsiveness in the past of urban areas to different development characteristics.

The main reason for including these equations in the current study was to clarify the role of land use characteristics in determining travel behavior. The observed relationship between neighborhood development traits and travel may be largely due to the intermediate association with transport supply. The direct effects of land use characteristics after supply variables are controlled may, in fact, be quite small.

Automobile ownership has been shown in many other studies to be an important factor in household travel decisions. Ownership rates in this analysis were estimated as a function of neighborhood development, household, and transportation system characteristics. Log-linear results are shown in the table below (note that "proximity to major center" is a dummy variable that has a value of 1 if the neighborhood is within 1 mile of the CBD or a major retail center).

Explanatory Variable	Coefficient	t-Statistic
Proximity to major center	-0.063	-1.48
Neighborhood density	-0.084	-2.88
Income	0.334	7.12
Average household size	0.524	7.42
Percentage black	-0.051	-5.55
Transit availability	-0.40	-1.28
Corrected R^2	0.69	

The set of travel choices was then assumed to be structured as follows. First, residents of a neighborhood choose an average trip length. This corresponds to the definition of an activity field within which people conduct most of their daily business. If a wide diversity of activities is located close to the neighborhood, this field may be relatively small. If average speeds are high, so that the time per unit of distance is small, the field will be correspondingly larger. Finally, certain types of households may have preferences for a larger- or smaller-than-average field. Trip duration, or travel time, is computed as the ratio of trip distance and trip speed. Vehicle trip frequency is then expressed as a function of travel time; household, neighborhood development, and transportation system characteristics; and automobile ownership. Mode choice is computed as a function of the same variables. These results are shown in Tables 4-7.

This formulation of the set of travel choices allows for the possibility of numerous indirect influences on household travel behavior. In principle, several of the travel choices (such as those regarding trip length and mode choice) would best be modeled as made simultaneously. However, as a first step in unraveling the way these relationships enter into travel choices, a simultaneous formulation was ignored.

Perhaps the best summary measure of differences in urban travel patterns is the total automobile miles traveled by households under different conditions. Traditionally, this measure has been called vehicle miles traveled (VMT), even though the sole vehicle involved is the automobile.

In this analysis, automobile VMT was derived indirectly from the other variables for which direct measurements are reported. In principle, automobile VMT is influenced by the number of vehicle trips, the transit share of such trips, average trip length, and the average ridership per automobile trip, or

$$\text{Vehicle miles traveled} = (\text{number of vehicle trips}) \times (1 - \text{transit share}) \times (\text{average trip length}) \div \text{average automobile occupancy} \quad (4)$$

In practice, trip frequency and average trip

Table 6. Mass transit use—all trips.

	Transit Proportion of All Vehicle Trips					
	1 (linear)		2 (linear)		3 (linear)	
Explanatory Variable	Coefficient	t-Value	Coefficient	t-Value	Coefficient	t-Value
Neighborhood density	0.001 36	1.6	0.002 12	2.5	0.0275	2.6
Distance to CBD	-0.005	2.0	-0.004 03	2.8	-0.066	2.9
Average automobile speed			-0.044	0.4	-2.71	1.4
Automobile ownership per family	-0.051	3.1	-0.029	1.9	-0.519	2.2
Proportion of population black	0.056	2.9	0.066	3.5	0.952	4.0
Average family income			0.000 075	0.05	-0.040	1.7
Transit coverage	0.002	0.3	0.025	1.3	0.426	1.6
Urban area population (000 000s)	0.061	3.3				
Metropolitan dummy variables[a]			0.054-0.152	0.83-2.6	-2.74-0.43	2.9-0.5
Corrected R^2	0.45		0.49		0.73	

[a]Fresno represents the bottom of the ranges and the Dayton the top.

Table 7. Mass transit and carpool use for work trips.

	Transit Proportion of Work Trips				Automobile Occupancy for Journey to Work	
	1		2			
Variable	Coefficient	t-Value	Coefficient	t-Value	Coefficient	t-Value
Neighborhood density	0.002 94	3.0	0.001 94	1.9	0.002 58	1.6
Distance to CBD	0.005	3.1	0.005 65	3.3		
Employment concentration at urban center (proportion of jobs in CBD)					1.40	3.7
Automobile ownership per family	-0.052	2.6	-0.038	2.1	-0.080	2.7
Proportion of population that is black	0.058	2.4	0.058	2.6	0.136	3.4
Transit coverage	0.008	0.9	0.021	0.9		
Urban area population (000 000s)	0.069	4.1				
Average automobile speed			-0.112	0.8		
Metropolitan dummy variables[a]			0.11-0.23	1.5-3.2		
Corrected R^2	0.47		0.49		0.30	

[a]Youngstown represents the bottom of the range and Dayton the top.

Table 8. Impacts on automobile vehicle miles of travel of a variation of 1 SD in density and distance to CBD.

Variable	Mean Value	SD	Path of Influence	Direction and Size of Effect on VMT[a] (%)
Density	8026 persons/mile^2	7270	Direct effect on vehicle trip frequency	-13
			Indirect effect on vehicle trips via automobile ownership	- 4
			Indirect effect on vehicle trips via average automobile speed	<0.5
			Direct effect on average trip length	-3
			Indirect effect on trip length via average automobile speed	-3
			All direct and indirect effects on transit share of trips	-1
Distance to CBD	7.2 miles	5.4	All direct and indirect effects on trip frequency	<0.5
			Direct effect on trip length	-14
			Indirect effect on trip length via average automobile speed	-4
Total			All direct and indirect effects	-33[b]

[a]Evaluated at mean VMT.
[b]Less than the sum of the individual effects, each of which is measured against the sample average VMT.

length are by far the most important contributors to variations in VMT. Transit shares are small enough that even substantial increases in ridership rates have little impact on total VMT. Average automobile occupancy does not show systematic variation with most other variables and fluctuates within a relatively small range and, therefore, exerts little influence on household VMT. (Keep in mind that these VMT estimates only cover home-based travel, i.e., trips that begin or end at home. These estimates understate total VMT by about 20 percent.)

Table 8 attempts to place in perspective the various lines of influence through which the two neighborhood urban development variables included in the analysis affect automobile VMT. The table shows the impact on household VMT of changes of one standard deviation in neighborhood density and neighborhood distance from the CBD. Such a shift would move the mean neighborhood in the sample into the top 16 percent with respect to the development characteristics that economize on automobile travel. Reference to a standardized change of this type makes it possible to compare the relative magnitude of the impacts of shifts in density and distance to the CBD.

A shift of one standard deviation may also be interpreted as a (rough) measure of the changes it is practicable to make in development patterns, at least in light of the current differences in development characteristics that are found in U.S. urban areas.

Table 8 demonstrates that neighborhood density produces its principal effect on vehicle trip frequency. As noted before, the major explanation for this impact seems to be the substitution at higher densities of walking trips for vehicle trips--a response that unfortunately could not be tested directly in our sample. Although the primary impact of density on trip frequency is a direct one, there is also an indirect effect through the lesser rates of automobile ownership that households choose when living in high-density conditions.

The direct and indirect effects of density on trip lengths are about one-third as important in their influence on automobile VMT as the impacts on trip frequency. The direct effects of density on trip length, through the clustering of destination points, are of roughly the same importance in reducing VMT as the indirect discouragement to longer trips through congestion or slower automobile speed.

The effects of density on transit ridership are conspicuous for their unimportance, at least as a means of discouraging automobile use. This suggests that the quest for high-density development and greater mass transit patronage may be relatively inefficient as a means of achieving most other urban goals.

Neighborhood proximity to the CBD has a very strong effect on automobile VMT through its effect on trip length. This influence is exerted both directly (by reducing the average distance to urban activities) and indirectly (by discouraging the long trips that greater congestion causes in trips from close-in neighborhoods).

All in all, a simultaneous shift of one standard deviation in both urban development characteristics has the effect of reducing average household VMT by approximately one-third--a substantial impact on urban automobile travel. This figure should be interpreted as an order-of-magnitude indicator of the sensitivity of automobile travel to urban development characteristics. The partially specified nature of most of the equations makes it impossible to read great accuracy into the results. In particular, the use of distance to the CBD as the only measure of job-residence separation is a practical compromise forced by data availability; the omission of other land use variables further restricts interpretation of the results. Nonetheless, Table 8 goes part of the way toward clarifying the complex interrelationships that link urban land use characteristics to travel choices and toward establishing at least a sense of the magnitude of the changes in travel behavior that can be accomplished from alterations in the urban development pattern.

To further indicate the relative importance of density and location, as well as of metropolitan variables, the range of values of the transportation characteristics is shown in Table 9 for neighborhoods in two of the metropolitan areas and in an average area. The demographic makeup in all the neighborhoods is assumed to be identical--average household income of $12 000, average household size of 3.5, and 10 percent black. Los Angeles, on the one hand, is a large, sprawling metropolis where activities are highly separated. Youngstown, on the other hand, is a much smaller and more compact area where activities are closer together. For many of the variables, there are greater variations between cities than between neighborhoods within the cities. This occurs even though the sample included no really high-density city, which indicates that large-scale activity separation is apparently more important than the local land use measures.

URBAN FORM AND TRANSPORTATION ENERGY USE

The variation in fuel use in the different neighborhoods and metropolitan areas can be derived by using Equation 3. The results are shown in Table 9. Again, there is greater variation between cities than within them. Because transit use is so low in the neighborhoods considered in Tables 9 and 10, assumptions about transit fuel use do not affect the energy calculations. At least among the neighborhoods in this sample, in no case does congestion appear to cause fuel use to increase with density. In the range of cities considered in Table 10, the more compact or dense an urban area is, the less fuel is used. The table also indicates an interesting phenomenon in which the fuel-efficiency level, measured in miles per gallon, is inversely related to fuel use. This occurs mainly because the shorter trips

Table 9. Representative travel measures for a high-income neighborhood.

Metropolitan Area	Inner High Density	Fringe High Density	Fringe Low Density
Automobile Driver Trip Length (miles)			
Los Angeles			
Work	16.4	19.3	26.3
All	12.7	14.6	17.2
Average area			
Work	7.4	8.6	11.4
All	5.8	6.6	7.7
Youngstown			
Work	3.9	4.1	5.6
All	3.3	3.5	4.1
Automobile Driver Trip Duration (min)			
Los Angeles	26.3	26.5	28.7
Average area	14.5	14.7	15.9
Youngstown	8.3	8.4	9.1
Vehicular Trip Frequency			
Los Angeles	6.2	5.9	9.1
Average area	6.7	6.7	10.4
Youngstown	7.1	7.1	11.3
Transit Use (%)			
Los Angeles	4.4	0.6	0.3
Average area	2.3	0.7	0.3
Youngstown	1.6	1.1	0.5
Automobile Vehicle Miles of Travel			
Los Angeles	49.7	56.5	103.0
Average area	24.8	28.7	52.2
Youngstown	14.7	15.6	29.3
Transit Availability			
Los Angeles	0.87	0.18	0.02
Average area	0.87	0.51	0.10
Youngstown	0.85	0.73	0.22
Automobile Driver Trip Speed (mph)			
Los Angeles	0.29	0.33	0.36
Average area	0.24	0.27	0.29
Youngstown	0.24	0.25	0.27
Automobile Ownership (cars/household)			
Los Angeles	1.8	1.9	2.6
Average area	1.8	1.9	2.5
Youngstown	1.8	1.8	2.4

Note: All figures refer to home-based internal travel only.

have a larger fraction of the travel that occurs with cold engines.

The analyses of Los Angeles and Youngstown do not give a complete picture of what happens in very dense neighborhoods in very compact cities. To give an indication of these situations, Table 11 shows the percentage changes in several travel characteristics if neighborhood land use variables were changed in different ways. One of these would have the urban area become compact, with a dense urban core--a city the size of Youngstown but with a large CBD employment such as in Washington, D.C.

Other alternatives include increasing the density by factors of three or five and placing the neighborhood one-quarter of the average distance to the CBD. (A density increase by a factor of five produces Manhattan-like concentrations.) Table 11 indicates much larger changes in the travel characteristics than those in Table 9. Now the local changes in land use have effects similar in magnitude to the areawide changes and, in the case of trip frequency, the impact is larger. One can surmise that this effect on trip frequency indicates a large switch to walking trips in the very high-density neighborhoods.

Even in these very high-density situations, transportation energy use appears always to decrease with more concentrated development. From Table 11, it appears that this result occurs because of the small changes estimated in automobile speed relative to those in trip length and frequency. One might have some doubts that speeds would remain so high because in Manhattan they are as low as 8-12 mph. These very low speeds represent a decrease from the average in the sample of more than 50 percent, much more than the model would estimate.

This observation of the possible errors in estimating speed change suggests that the analysis cannot be extrapolated accurately to these very high densities. We cannot yet be sure that a maximum density does not exist above which energy use would again start to rise.

Table 10. Representative daily energy use per household for a neighborhood.

Metropolitan Area	Inner High Density	Fringe High Density	Fringe Low Density
Daily Fuel Use (gal)			
Los Angeles	3.7	5.2	6.9
Average area	2.3	3.1	4.3
Youngstown	1.6	2.1	2.8
Average Miles per Gallon			
Los Angeles	13.3	14.2	14.8
Average area	11.0	11.7	12.4
Youngstown	9.4	9.7	10.4

CONCLUSIONS

How important are physical development characteristics in shaping urban travel behavior and energy use?

The analysis of neighborhood travel patterns presented here, coupled with previous studies, indicates that there is little uncertainty regarding the direction of effect of most urban development variables. High residential and employment densities are systematically linked with fewer vehicular trips and with greater rates of transit use. Large metropolitan populations and greater-than-average separation between residential and job locations are regularly associated with long average trip lengths. These qualitative conclusions regarding the determinants of travel behavior correspond with planners' perceptions, as reflected in planning proposals to alter travel patterns.

Previous studies have left unclear whether the physical development characteristics of cities shape transportation choices primarily at the neighborhood scale or primarily at the metropolitan scale. Of course, it is likely that both scales of influence are important. Nonetheless, it would be a much easier task to mold future urban transportation behavior if household travel choices were found to respond largely to the development characteristics of their own neighborhood and its environs. Even drastic changes in the physical planning of new developments can be contemplated without great difficulty. Transformation of the configuration of an entire metropolis is another matter. Nothing short of physical destruction or a total reversal of economic markets is likely to convert San Diego or Tucson into an exemplar of compact development.

The empirical analysis presented here has shown the impact of neighborhood development characteristics to be substantial, though frequently less important than household demographic characteristics and automobile ownership rates in influencing travel choices. The representative development scenarios used to illustrate the findings of the regression analysis involved savings of more than 40 percent in annual transportation energy use per household, when relatively high-density, centrally located development was compared to low-density fringe development in the same metropolitan region, after control for household and other characteristics.

The data set assembled for this study was not the ideal one with which to examine influences on a metropolitan scale. In the majority of instances, the regressions indicated important differences between metropolitan areas. Unfortunately, because so few metropolitan areas were included in the sample, it was impossible to pinpoint the urban-scale char-

Table 11. Changes in neighborhood travel characteristics due to modification of urban structure.

Travel Variable	Mean Value	Change SMSA to Medium Size and Compact (%)	Neighborhood Density Increase (%): Factor of Three	Neighborhood Density Increase (%): Factor of Five	Neighborhood One-Quarter of Average Distance to CBD (%)	Combination of Two Preceding Modifications (%)
Automobile trip frequency	5.1	-13	-21	-31	-9	-44
Vehicular trip frequency	5.3	+7	-18	-25	-5	-29
Automobile trip distance	7.4	-43	-5	-8	-19	-34
Automobile trip speed	24.5	-21	-3	-5	-8	-12
Percentage transit	4.8	+370	+72	+170	+80	+354
Automobile ownership	1.2	0	-11	-15	-6	-20
Automobile occupancy	1.2	-6	+1	+1	-1	0
Fuel use	2.7	-35	-24	-35	-28	-56

acteristics that distinguished the different metropolitan regions. The analysis, however, is consistent with earlier studies that have reported that metropolitan population size, central employment concentration, and work-residence separation (for which the other two variables may be proxies) dominate travel choices at the metropolitan scale.

A word needs to be said regarding the desirability of alternative urban travel patterns. Because public costs are associated with automobile travel, many land use planners have taken the position that urban development patterns that reduce automobile travel are superior.

A careful analysis of the relative advantages of alternative development patterns must first investigate the ability of citizens to reach desired destination points and then examine both the private and public costs in doing so. There are two basic design options for providing accessibility. One is to endow the individual or the household with its own means of travel and to design urban areas to facilitate individual travel. This transportation strategy relies on personal mobility. Since World War II, this has been the overwhelmingly dominant approach to urban transportation in the United States, as embodied in the automobile and in ambitious urban road construction programs.

An alternative strategy would be to design cities so that households and destinations are in close proximity to each other, with the result that many trips can be made on foot or by mass transit. Until part way through this century, the shape of urban areas was in fact constrained by the structure of mass transportation routes and by the walking radiuses around transit stations. The availability of automobiles has freed urban development from this constraint, but one of the most common planning recommendations is to return to an urban design that would facilitate, or even require, greater use of mass transportation while diminishing use of the automobile.

A full comparison of the transportation costs associated with alternative development patterns is beyond the scope of empirical analysis at this stage of our understanding. Private costs would have to include dollar outlays, time consumed in travel, and the inconvenience of travel to the user. Public costs take the form of public capital investment, operating subsidies for mass transit systems, air pollution and other externalities generated by automobile use, and any social costs associated with gasoline consumption beyond those reflected in its price. This analysis, taken as a whole, goes some distance toward identifying and measuring these social costs. It does not, however, settle on a prescription of the optimal development pattern or attempt a cost-benefit comparison of alternative urban designs.

In this paper we limit ourselves to examining the trade-off in travel patterns and energy use associated with alternative urban development forms. It is intended to cast light on the question, "How greatly could urban transportation patterns and energy use be modified through urban land use alterations?" The related, and ultimately more important question, "Is it economically and socially desirable to rearrange urban development patterns in order to alter travel behavior?", is not answered.

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Publication of this paper sponsored by Committee on Traveler Behavior and Values.