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The Effect of Added Transportation Capacity on Travel: A Review of Theoretical and Empirical Results

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1. Introduction

The addition of transportation capacity affects potentially all attributes of trips made by urban residents—frequency, time of day, destination, mode, route, and linking of trips. The impact could be more pronounced if unsatisfied or latent demand exists due to congestion (Cambridge Systematics, Inc. (CSI) and JHK & Associates (JHK), 1979). In the long-run, added capacity may influence households' automobile ownership decision, and residence and job location choice. Firms' location decision will also be affected. Sooner or later, waves of development start filling the fringe area. It appears almost certain that, as long as the urban area continues to grow, fringe land with good transportation access will be converted to residential and commercial use. The addition of transportation capacity is one of the key contributors to urban growth.[1]

Perhaps the most fundamental impact of added capacity is attributable to urban growth which stems from the ability that transportation capacity offers in supporting a larger urban population and more extensive non-residential activities. Obviously this growth has immediate impact on travel demand; an X% increase in an area's work-force would most probability lead to an

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[1] This is not to say that transportation capacity alone can induce growth in an urban area. The extensive discussions on the subject of transportation investment and urban growth found in the literature (e.g., Bone and Wohl, 1959; Levitan, 1976) suggest that transportation capacity is just one of the factors that jointly contribute to growth and development (Deakin, 1991).

increase in work trip generation by approximately X%. Possible increases due to changes in departure times, destinations, modes, routes, or even "induced trips," appear minute when compared with this primary growth effect.

However, if growth were controlled by strict land use measures, or if growth in an urban area were supported by its political constituencies, then the secondary impacts of added capacity would no longer be a trivial issue. One would need to address the question, "What is the trip inducing effect of added capacity?" If highways were not congested, would people go out more often and drive farther? Can we reduce air pollution and other external costs of congestion by adding capacity? One may also be concerned with long-term effects of added capacity upon the evolution of urban area. Would people own fewer automobiles and use public transit more if the capacity of the transit system is increased? Would radial expansion of the highway system merely contribute to ever increasing trip lengths?

Neither primary growth effects nor the secondary trip effects of added capacity are thoroughly understood. The growth effects are not incorporated in the standard urban passenger travel demand forecasting procedure in the sense that future land use is pre-determined, essentially independent of the future travel demand and supply. Nor are the effects of improved accessibility on trip generation, trip chaining and trip timing represented in the procedure. This is partly due to the lack of theory. Economic theory is often too simplistic to account for the complexity of travel behavior with the multitude of potential behavioral adjustments (e.g., one can change any, or combinations, of trip frequency, destinations, modes, routes, trip timing, and linkages).[2] Attempts have been made to construct travel behavior models that draw on broader theoretical bases (e.g., Bhat, 1991; Koppelman and Townsend, 1987; Pas and Harvey, 1991). Yet many steps need to be taken before these efforts can be reflected in the practice of travel demand forecasting.

Furthermore, determining the effect of added capacity is not at all a trivial task because it is concerned with intricately and dynamically inter-related system components: transportation supply system, land use, accessibility, and travel demand. Transportation supply system affects land use, as evidenced by land use development that seems to inevitably follow the construction of new facilities. Transportation supply system, demand, and land use together define accessibility. "Induced trips" represent the effect of accessibility on trip generation. Travel demand in turn affects transportation supply system through the planning process. These interrelationships, with time lags built in, imply an urban system which may be viewed as a labyrinthine "ecological system." Consequently an attempt to model one variable, say travel demand, as a function of the rest encounters highly multicollinear "explanatory" variables, making the identification of each contributing factor's effect impractical.

This paper presents a review of theoretical and empirical results in the literature that shed light on the effect of added transportation capacity. The purpose of the effort is to establish a base from which future research effort can depart. The review of theoretical studies is limited only to those aspects of daily travel behavior for which empirical observations are available. Studies

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[2] Perhaps most realistic cases are analyses of the shopping trip frequency and destination choice (e.g., Narula, et al., 1983; Thill, 1985). But even they are extremely simplistic.

on network assignment and departure time choice are outside the scope of this study. Theories and empirical evidence on long-term impacts of added capacity are also outside the scope, except for a review of disaggregate choice models on household auto ownership.

This paper is organized as follows. In Section 2, several theoretical models and paradigms of urban travel behavior are discussed. Section 3 offers a review of empirical studies that examine the impact of highways on travel. Studies on the impacts of public transit capacity and HOV lanes are reviewed in Sections 4 and 5, respectively. Section 6 addresses the limitations of the current demand forecasting procedure, and Section 7 presents conclusions and future research directions. (This draft does not include Sections 4 through 6.)

2. Theoretical Approaches

A comprehensive theory of urban travel behavior is difficult to establish, perhaps because travel is such a fundamental element of life. Individuals travel for economic, social, psychological and physiological reasons. Although some aspects of travel behavior (e.g., travel mode choice) may be well described using theories scattered in these academic disciplines, constructing an embracing theory of urban travel and formulating a system of quantitative models, has not been accomplished yet.

To examine the impact of added capacity would require a more fundamental understanding of why people travel. It would also require the accumulation of empirical evidence that is based on exact measurement of each factor's effect. As a precursor of such an endeavor, the discussions in this section focus on: micro-economic formulations of travel behavior; the paradigm of constancy in travel time budgets; evidence offered by what may be called the "ecological approach"; the effect of accessibility as a general measure of the generalized cost of travel; and some of the difficulties associated with the identification of the effect of generalized travel cost on travel (which is a function of the capacity the supply system offers, the spatial distribution of opportunities, and travel demand).

Economic Theory

The cost of transporting goods and passengers plays critical roles in theories of land use and urban development. Theoretical models have been constructed to explain a firm's decision as to where to locate its plant, a household's choice of where to reside, or a retailer's selection of store locations. For example, a household may be willing to live farther away from the city center and spend more time to commute if that will allow it to consume more residential space. The rent per unit space, then, must decrease as the distance from the city center increases. Empirical observations often agree with such relations theoretically derived for highly hypothetical and abstract models of urban area (for a recent review, see Berechman and Small, 1988).

A very fundamental relationship in economics is the one between supply and demand; the demand for a good will increase as its price decreases, while its supply will increase as the price increases, and an equilibrium will be attained in the market where the demand equals the supply with the good priced at an equilibrium price. This can be applied to urban travel by viewing transportation as a commodity to be consumed (e.g., see Wohl, 1962). For illustrative simplicity, let the time cost of travel be the only cost and let this cost be proportional to the inverse of the average travel speed in a hypothetical urban area. Then the demand for travel will increase as travel speed increases and travel cost decreases. But as demand increases (therefore as traffic volume increases), speed declines and travel cost increases. The former relation constitutes a demand curve and the latter a supply curve. The intersection of these two curves indicates an equilibrium volume and speed. An improvement to the roadway infrastructure—or, increased capacity—would lower the supply curve (a larger volume can be carried at the same speed) and the equilibrium point would shift to the right to a larger equilibrium volume, a higher speed and a lower cost. The message is quite clear; added capacity will lead to an increase in travel, with the volume added after the improvement representing "travelers diverted from other facilities, those making more frequent trips, those switching from other modes of travel, or those making entirely new trips" (op. cit., pp. 52-53). This, however, represents a highly simplistic and aggregate approach to travel behavior. Besides, people make trips to engage in activities at different locations; the demand for travel is a derived demand and should be treated as such.

In their micro-economic derivation of a gravity model of trip distribution, Niedercorn and Bechdolt (1969) depict trip making as a resource allocation behavior. A visit by a trip maker situated at i to a destination zone j, is assumed to produce a positive amount of utility, with repeated T_{ij} visits collectively yielding utility, $U_j(T_{ij})$. Function U is assumed to be strictly concave, i.e., $dU_j(T_{ij})/dT_{ij} > 0$ and $d^2U_j(T_{ij})/dT_{ij}^2 < 0$ for $0 \leq Tij < \infty$. A fixed amount of travel resources, M_i is allocated to trips to visit available destination zones. With M_i measured in monetary terms, and with the assumption that U_j can be expressed in terms of a measure of the attractiveness of destination zone j, P_j, and a function $f(T_{ij})$, the optimum frequencies of visits are obtained by:

$$\text{maximize } U_i = \sum U_j(T_{ij}) = \sum P_j f(T_{ij})$$

$$\text{subject to } r\sum d_{ij}T_{ij} \leq M_i \quad .$$

where d_{ij} is the distance between i and j, r is the cost per unit distance of travel and the summation is over all j. If a logarithmic function is assumed for f, the optimum frequencies to the respective destination zones are found to be

- directly proportional to M_i/r,
- directly proportional to $P_j/\sum P_j$, and
- inversely proportional to d_{ij}.

This analytical framework is immediately applicable with M_i defined to be a travel time budget, i.e., a maximum amount of total travel time that can be expended. Since U_j is increasing for $0 \leq Tij < \infty$, this budget is always used up when trip frequencies are optimized. Then, improvements in travel speed will always result in additional trips, additional vehicle-miles traveled (VMT), and, if improvements are not uniform over the network, shifts in trip distribution. For example, a uniform improvement in travel speed by 10% will result in an increase by 11.1% (= 1/0.90) of both trip frequency and VMT. (Different relationships can be obtained by assuming different functional forms for the utility function; see Niedercorn and Bechdolt, 1969.)

Similar approaches are taken by Beckmann and Golob (1972) who examined a wider range of behavioral formulations including

$$\text{maximize } U(T_{i1}, \ldots, T_{ij}, \ldots, T_{in}) - \sum C_{ij}T_{ij}$$

where C_{ij} is the generalized cost of a round trip from i to j. In this formulation, the total net benefit to a household derived from travel is maximized. Beckmann and Golob also adopt depictions of trip making as a resource allocation behavior, and briefly discuss the case where both monetary and time budget constraints exist.e[3] The conclusions of their analysis are similar to those discussed above; trip frequencies will increase as the generalized cost of travel decreases.[4]

Travel Time Budgets

When trip making is viewed as a resource allocation behavior, then the total travel resource that can be allocated becomes a primal driving factor. Zahavi proposes an alternative travel demand forecasting procedure which explicitly incorporates time and monetary budgets for travel. Zahavi's paradigm of constant travel time budgets and empirical observations on which it is based (Zahavi and Talvitie; 1980; Zahavi and Ryan, 1980) have led to extensive debates (e.g., Downes and Emmerson, 1983; Supernak, 1982, 1984; Zahavi, 1982; van der Hoorn, et al., 1983). Zahavi's approach is one of a few principles of travel behavior that have been developed into operational forecasting systems. Its use has been alluded to recently by Stopher (Applied Management & Planning Group, 1990) as a possible approach to accounting for the travel impact of added capacities. A close review of the approach appears to be warranted.

The UMOT (Unified Mechanism of Travel) model is proposed as an alternative to traditional approaches to urban passenger travel and demand-supply relationships (see Zahavi and McLynn, 1983). The backbone of the UMOT model is the hypothesis of the constancy in household travel budgets: The "UMOT model maximizes the daily spatial and economic opportunities per household, represented by the daily travel distance, under explicit constraints. The constraints are the daily travel time and money expenditures per traveler and per household, respectively. These travel budgets have been found to display consistent regularities and to be transferable both spatially and over time" (op. cit., p. 137). This formulation of trip making as a travel distance maximization process is based on the viewpoint that travel itself produces utility, therefore savings in travel time and costs will be used for more travel. (It is however noted without further clarification that "both the travel time and money budgets are state variables that change during each iteration"; op. cit., p. 138).

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[3] This work is said to be the basis of Zahavi's UMOT model system discussed next (Zahavi and McLynn, 1983).

[4] These approaches do not consider the consolidation of several visits to several destinations into one trip chain (e.g., a trip to work and a trip to shop combined to form a chain of work trip, shopping trip and home trip), or consolidation of several visits made to the same destination into one visit (e.g., one weekly shopping trip instead of seven daily trips). Another weakness is that no attention is given to how a time or monetary budget for travel is established.

These assumptions underlying UMOT yield many interesting insights, e.g., households respond to an increase in auto monetary travel cost not by reducing the level of auto ownership but by choosing to hold automobiles of lesser quality, or of lower "car factor" values (the car factor represents the quality of the vehicles that tend to be owned by households in each income group, or "the type of car associated with each income group, namely above or below a standard car, where the value of 1 ... signifies a standard car" (op. cit., p. 144).

These assumptions, at the same time, seem to produce counter-intuitive indications. For example, Zahavi and McLynn report that higher-income households are able to satisfy their travel needs by increasing vehicle ownership levels, but "Low-income households, on the other hand, cannot satisfy the demand for car travel to all their travelers. Furthermore, since the increasing number of travelers have to be satisfied by other modes than car, say buses, all which require travel expenditures, car ownership levels actually decrease with increasing household size" (op. cit., P. 145). Or, "gasoline consumption may increase, not necessarily decrease, at some point along the increases in car unit costs ... The reason for this somewhat unexpected result is that decreases in the Car Factor (namely, increasing the average age of cars) result in increases in gasoline consumption" (op. cit., p. 149). Perhaps the most paradoxical is the result, "a reduction of bus fares ... may allow low-income travelers the transfer of the freed bus fares to car travel" (op. cit., p. 151); "conventional wisdom tells us that bus fare reductions should attract car travel to bus travel, while the UMOT model predicts otherwise" (op. cit., p. 151). While Zahavi and McLynn maintain that this is an example of the Giffen effect with bus trips being an "inferior good," no empirical evidence is offered in support of the result.

It is not difficult to imagine that the UMOT model system is at best controversial. Downes and Emmerson (1983) note that "the effects of trip characteristics on trip rates is not fully understood" and present a study that examines the effect of improved travel speeds on the trip length and frequency. They use 1976 large-scale household interview survey results from 12 municipalities of varying populations and sizes. The study separately analyzes a subsample of those some 32,000 individuals who "only travelled internally" within study areas (op. cit., p. 174) and concludes that the total travel expenditure decreases as travel speed increases for those internal travelers, while it increases with speed if external travel is included. The results thus cast doubt on the assumption of constant travel time expenditure. The study, however, does not explicitly state how the average speed was defined for each traveler. If the average speed is defined as the total distance traveled by a traveler divided by the total time it took (which is suggested by the discussion on p. 176), then this variable is endogenous and the results by Downes and Emmerson could be seriously biased.

Van der Hoorn et al. (1983) acknowledge that the UMOT approach is "very appealing to policy makers and researchers because it is conceptually simple and robust, the data requirements are low and the model is easy to compute on a micro computer" (op. cit., p. 156). However, their effort to implement the model for the Netherlands has led to: the identification of several limitations in the model, questionable mode use elasticities with respect to their costs, and a finding that the auto ownership component is "too simplistic" (op. cit., p. 168; In his comments to van der Hoorn et al., Zahavi notes that most of the limitations are accounted for in the latest version of the UMOT model).

Supernak (1982) points out the inconsistency that exists among various measures of travel budgets (or, expenditures) and cites empirical observations that contradict the hypothesis of constant travel budgets. In particular, Supernak reports that trip rates are "more regular and stable" than travel time budgets, supporting the conventional sequential approach that starts with trip generation analysis.

It is indeed unfortunate that Zahavi passed away before he was able to complete the UMOT model. It is yet to be determined whether the above counter-intuitive indications from the UMOT model are logical consequences of the assumption of constant travel budgets, or mere aberrations resulting from a forecasting system yet to be completed.

Accessibility and Added Capacity

An accessibility measure, representing the relative ease of reaching to opportunities in an urban area from a specific area within it, may be interpreted as a general indicator of the cost of travel. Then, applying the economic principle discussed earlier, residents in a high-accessibility area should tend to travel more, not necessarily in terms of travel time or cost, but in terms of trip rates or VMT. Theoretically it is expected that trip generation is positively correlated with accessibility.

Added transportation capacity, whether by means of additional freeway lanes, HOV lanes, or public transit lines, implies increased accessibility in impacted areas. The effect of added capacity, then, can be examined by testing the relationship between accessibility and travel, in particular trip rates. Note that trip generation analysis as they are practiced now typically does not incorporate accessibility measures. Trip production and attraction are assumed to be functions of socio-demographic and land use variables, but not accessibility. Added capacity is not viewed as a factor that cause changes in trip generation.[5]

Since accessibility measures will vary within an urban area, cross-sectional data suffice in the test; longitudinal data, although more desirable, may not be necessary. This approach is more attractive than the comparison of changes in travel patterns before and after a capacity improvement. The main advantage is the availability of needed data in practically every metropolitan area. There is no need to wait for a capital project in order to obtain before-and-after observation, or to establish a control group in order to capture time effects.

Attempts to establish positive links between accessibility and trip generation, however, have not been successful. The most frequently referenced study is by Nakkash and Grecco (1972). Their results exhibit statistically significant effects of accessibility only on school trip production and attraction; accessibility measures are not significant in most trip generation equations. Taken literary, the results lend support to the current practice of trip generation analysis by showing the absence of capacity effects on trip rates with the only exception of school trips. Before drawing on any conclusion, however, it is necessary to review the relationship among the key contributing factors of urban trip making.

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[5] A notable exception is MTCFCAST, a model system developed for the Metropolitan Transportation Commission (MTC). This model system is discussed later in this paper.

Ecological Correlations

Urbanization is a result of the benefit of clustering; "To achieve most of the goals that human beings have, 'cluster' is more efficient than 'scatter'" (Smith, 1975, p. 26). Although the preference for isolation may exist, it may be preferred to surrender "isolation or control over space in the interest of conserving transportation resources" (op cit., p. 27). This is especially the case for production due to both internal and external economies of scale. Transportation cost, then, explains the intensity of land use, population density and rent (land value) that decline with the distance from the urban center (Alonso, Beckmann, etc.). Because the city center represents a concentration of opportunities, accessibility in general decreases with the distance from the city center.

The observation that certain levels of residential density is needed for public transit to be viable (Pushkarev and Zupan, 1976) implies that public transit either offers limited service or is not available at all in low density areas. Residents in these areas are then required to have automobiles to gain mobility. This is well supported by empirical observation (e.g., Mogridge, 1986). For data from Portland (OR) and Vancouver (WA), Shindler and Ferreri (1967) derive bivariate correlation coefficients among the logarithm of net residential density, transit-to-auto accessibility ratio, and the number of automobiles per dwelling unit as shown in the table below.

	a.	b.	c.
a. Net Residential Density (logarithm)	1.000	0.703	-0.691
b. Accessibility Ratio (transit to auto)		1.000	-0.652
c. Number of Autos per Dwelling Unit			1.000

Source: Shindler and Ferreri (1967)

It is also well established that auto ownership is most significantly associated with transit use. Shindler and Ferreri (1967) summarize: The relationship between auto ownership and transit use "was so strong, that auto ownership dominated all other factors in explaining the trip-making split between auto and transit travel. Thus for any given level of auto ownership in an area, transit use was, in a sense, predetermined regardless of the quality of service" (op. cit., p. 24).

Additional variables that may enter the picture here is household size and income. These variables are both correlated positively with auto ownership and negatively with residential density and accessibility ratio. This may be explained in part by the tendency that households with children prefer single-family housings and suburban life-styles. Thus an urban area exhibits intricate correlations among variables that are closely related to household travel behavior. These correlations, which may be called "ecological correlations," are results of decisions made by households and firms and actions taken by public agencies over time.[6]

Effects of Added Capacity?

A direct consequence of such strong and clear relationships among residential density, household size, income, and auto ownership, is the multicollinearity that exists among these variables that have traditionally been considered to influence household trip generation most strongly. Being defined as a function of land use and inter-zonal travel time variables, accessibility measures are also multicollinear with the other contributing factors. As a result, it is extremely difficult to determine the independent effect of each contributing factor.[7] Consequently it has not been possible to produce definitive answers to such seemingly rudimentary questions as: "Does an increase in capacity induce trips?" or "Can we decrease automobile ownership and increase transit use by increasing residential density?"

The problem is further compounded due to the endogeneity of these "explanatory" variables. Although variables representing land use, auto ownership and accessibility have traditionally been treated as exogenous variables that are determined outside the system, they actually not only feed into each other but also are influenced by travel demand over time. Residential and commercial land use and transportation networks together define accessibility and travel demand. Travel demand and transportation supply characteristics determine the levels of service available on networks. Levels of service in turn lead to the enhancement of network characteristics through planning actions, which lead to further residential and commercial land use development. As this cycle repeats itself over time, it creates an evolving system in which all pertinent variables are endogenously determined within the system. The effect of capacity increase has not been examined in this dynamic context.[8]

Summarizing the discussion of this section, economic formulations of trip making offer unambiguous indications that added capacity, which implies decreased cost of travel, would lead to more trip and VMT. Furthermore, they have shown that travel time or monetary budgets play important roles. Travel budgets, or travel expenditures to be more precise, are clearly determined by households, although no models reviewed here attempt to model the process of determining a travel budget endogenously. The most desirable level of travel expenditure, of

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[6] However, note that ecological correlations are consequences; they are not causes that will lead to changes in the future.

[7] The approach frequently taken when multicollinearity is present is to eliminate some of the multicollinear variables to produce a set of relatively independent explanatory variables. It is not surprising if accessibility measures tend to be the first to be eliminated because, unlike household size, car ownership or income, they are aggregate measures defined for traffic zones. As such, they are subject to measurement errors and exhibit smaller variations (see, e.g., McCarthy, 1969; Fleet and Robertson, 1968) and are likely to have less significant coefficients associated with them.

[8] The problem is even more complex when regional demographic and economic growth is taken into account. This leads to another issue of whether transportation capacity leads to regional growth. As noted earlier, the extensive discussions on this subject found in the literature suggest that transportation capacity is just one of the contributing factors.

either time or money, will vary from household to household or from situation to situation. The notion of forecasting future travel demand based on the assumption that the travel expenditure of a household remains constant over time, is not well founded and appears to produce results that cannot be theoretically supported. Then how does a travel expenditure, or trip making in general, change in response to changes in capacity and resulting changes in generalized travel costs? No definite answer to this question appears to be available. The discussion here pointed out the multicollinearity among the factors that contribute to trip making, which is a consequence of ecological correlation that prevails in an urban area. In the sections that follow, pieces of empirical evidence are put together to form empirical conclusions on the impact of added capacity.

3. Impacts of New Highways

The literature on the impacts of new highways appears to be dominated by cost-benefit analyses of highway investment. For example, a sample of articles in *Transportation Research Record* includes economic impact analyses by Batchelor, et al. (1975), Gaegler, et al. (1979), and Mahady and Tsitsos (1981); those emphasizing property values as a major element in the cost-benefit analysis (e.g., Gamble, et al., 1974; Langley, 1976); and those focusing on community values (e.g., Ellis, 1968; Falk, 1968). Empirical studies of the impact of new roadways on travel behavior, however, are surprisingly few and far apart[9]

A report by U.S. Department of Transportation (1981) concludes:

> "It seems clear from the studies which have been conducted over many years that highway service level improvements do induce increases in VMT. However, the magnitude of induced traffic is thought by some to be quite small and, by others, to be significant in certain circumstances" (op. cit., p. 22).

On the other hand, Smith and Schoener (1978) maintain

> "A frequent statement advanced by transportation professionals is that highway improvements, by inducing travel, create more congestion than they eliminate. Although few data exist to support this statement, it has gained legitimacy by sheer repetition."

This view is repeated in a *Research Results Digest* issue (Transportation Research Board, 1980).

In this section, available evidence is reviewed to assess the effect of new highways on travel, especially on induced trips.

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[9] A very recent, notable exception is a study of a new ring road in Amsterdam, the Netherlands, to be presented at the forthcoming 1992 TRB Annual Meeting. Unfortunately written documents are not available in time for this presentation.

Taxonomies

Many highways have been built during the periods when urban areas underwent demographic and economic growth. Urban growth has been accompanied by new highways, and new highways were sooner or later surrounded by growing suburbs. In this sense new highways have been synonymous with urban growth and growing travel demand. The first step in the effort to reveal structural relationships between added capacity and travel demand would be to define different elements of the traffic that seemingly fills up a new highway almost immediately.

Zimmerman et al. (1974) propose that traffic on a (new or capacity-improved) highway be classified into:

existing traffic,
development traffic (due to land-use changes),
natural growth (demographic and socio-economic changes),
diverted (from other streets or highways),
induced (new trips made because of the new highway),
transferred (from other modes), and
shifted (to new destinations).

The last four categories are consequences of a new highway of which induced traffic is a part. Holder and Stover (1972) propose to distinguish between "apparent induced traffic" and "true induced traffic" (read in CSI and JHK, 1979, p. E-1). Similar to Zimmerman, et al. (1974), Holder and Stover also attribute changes in traffic counts to "cultural traffic" due to sifts in demographic or socioeconomic characteristics; "'converted traffic' (from other modes); 'developed traffic' (resulting from land use change); and 'diverted traffic' (from other streets and highways)" (op. cit., p. E-1).

The "development" traffic and "natural growth" traffic as defined by Zimmerman, et al. represent increases in trip generation that are accounted for in the land use model that provides input to the trip generation models in the sequential demand forecasting procedure. Similarly, "diverted" traffic, "transferred" traffic and "shifted" traffic are in principle accounted for by the trip distribution, modal split and network assignment phases of the procedure (although actual practice may be less than ideal; see Harvey, 1991; Applied Management & Planning Group, 1990). This leaves induced traffic unaccounted for in the sequential demand forecasting procedure. Also unaccounted for is the effect of a new highway on the temporal distribution of traffic, which is not considered in these classification schemes of traffic.

The review of empirical evidence in the literature presented below indicates that new highways do have impact on VMT, presumably due to a large extent to shifted traffic. This impact is well represented by the demand forecasting procedure. The impact of a new facility on induced traffic, however, is not evident.

Impact on VMT

The average trip length appears to increase with the construction of new highways. Voorhees, Barnes and Coleman (1962) cite that the average work trip length in Baltimore increased from 2.6 miles in 1926 to 4 miles in 1946, and to over 5 miles as of the writing of the paper.

Bellomo, et al. (1970) also note similar historical increases in trip lengths. For example, "In Detroit the mean auto driver work trip length in miles increased by 18% as the area increased in population by 14%, and the average speed of network increased by 12%" between 1953 and 1965" (op. cit., p. 1). Presumably this is to a large extent due to the geographical and demographic expansion of the area, leading to substantial development and natural growth traffic, and probably to a lesser extent, shifted traffic.

Voorhees, et al. (1966) offer quantitative indications of the effect of population and network speed on trip length. Based on aggregate data (average trip duration, etc.) from 23 cities, they developed a model,

$$L = 0.003P^{0.20}S^{1.49}$$

where L is the average trip length in miles, P is the urban area population, and S is the average network speed in mph (op. cit., p. 31). The positive effect of network speed on trip length is evident. The effects of the "physical structure of an urban area" on the trip duration and distance are also noted in the study. The distribution of opportunities is not considered in the study.

Accounting for three factors—the size and physical structure of an urban area, network speed, and socio-economic factors—is considered crucial in forecasting future trip length (op. cit., p. 36). Based largely on simulation results, the effects of network speed are summarized as:

> "(a) change in the average trip length (miles) for uniform density cities will probably be directly proportional to the square root of changes in network speed; and (b) change in the average trip length (minutes) will probably be inversely proportional to the square root of changes in network speed—experience, however, has shown that peak hour speeds have not greatly changed in large metropolitan areas" (op. cit., p. 36).

Then, an addition of capacity, which would lead to a higher highway speed, would also lead to an increase in VMT.

The results reported by Frye (1963) also indicate that a capacity increase has a direct impact on traffic beyond development and natural growth traffic. The opening of the Congress Expressway in a 16-square-mile area in the western suburbs of Chicago led to an increase in the total VMT in the area by 21% between 1959 (before opening) and 1961. An increase of 7% could be expected in the area due to natural growth. Frye's findings are summarized in U.S.D.O.T. (1981, pp. 20-21) as: "About half the total increase (10.5%) was due to diversion of traffic from areas outside the study area." "The other 3.5 percent is attributed to induced traffic (i.e., new or longer trips) and adverse travel (the extra VMT generated by travelers going out of their way to use the new facility ...)."[10]

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[10] The term, induced traffic, is used in a broader sense to include both induced and shifted traffic as defined by Zimmerman, et al. (1974).

Induced Trips

Unlike the other types of traffic on a new highway, induced traffic must be captured in the trip generation phase of the sequential forecasting procedure. Trip generation models typically use demographic and socio-economic variables for residential trip generation (e.g., household size and auto ownership) and land-use variables (e.g., zonal employment, retail and floor area) for non-residential trip generation. It is not a common practice to use variables that represent transportation supply characteristics. In fact the current practice of trip generation analysis appears to be based on the premise that there exist constant household trip rates that do not change over time, do not vary within or across metropolitan areas, and are unaffected by the levels of service on transportation networks. Typical examples can be found in the Institute of Transportation Engineers (ITE) trip rates (ITE, 1979) and "quick response" demand forecasting procedures and computer program packages (e.g., Sosslau, et al., 1978). Empirical evidence to the contrary does exists. For example, Goulias, et al. (1990) in their analysis of 1980 Detroit home interview travel survey results find that dummy variables representing the county of residence are significant in many of the household trip generation models by purpose estimated in the study. Yet, no compelling indicator of trip-inducing effect of added capacity appears to be offered in the studies reviewed below.

As noted earlier, Nakkash and Grecco (1972) present formal statistical tests of the significance of accessibility measures in trip generation equations. They argue: "Conceptually, there is not strong basis for assuming that trip-making is independent of the transportation system" (op. cit., p. 99). The issue addressed here is precisely that of induced trips in the narrow sense as defined by Zimmerman, et al. (1974). If, as economic theory implies, a decrease in the generalized cost of travel leads to an increase in trip making, then those households residing in zones with high accessibility would exhibit higher trip rates. Nakkash and Grecco examine this hypothesis by testing the statistical significance of accessibility measures in trip generation models.

The method used is straightforward. A "relative accessibility measure" is defined by trip purpose using destination "mass" terms and friction factors (based on auto travel times; op. cit., p. 102) and normalizing it as

$$A_{ik(l)} = \sum_{j=1}^{n} S_{jk} F_{ij(l)}$$

$$RA_{ik(l)} = A_{ik(l)} / \sum_{i=1}^{n} A_{ik(l)}$$

where S_{jk} is the size of activity k in zone j, $F_{ij(l)}$ is the friction factor corresponding to the travel time from zone i to zone j for purpose l, $A_{ik(l)}$ is the accessibility of zone i to activity k for purpose l, and $RA_{ik(l)}$ is the relative accessibility. This measure is introduced into trip production and attraction models by purpose that were developed in the Indianapolis Regional Transportation and Development Study (altogether 13 models are defined). The models are estimated with and without stratification which divided the study area into central and non-central areas (the former comprises 105 zones out of the 395 in the study area; op. cit., p. 103).

The results of this analysis are, unfortunately, inconclusive. Presumably due to the multicollinearity problem discussed earlier, Nakkash and Grecco report that often "no satisfactory models were developed," or "models were developed but no statistical testing was possible" (op. cit., p. 107). Only two pairs of trip production models and two pairs of trip attraction models are successfully estimated that can be legitimately used to test the significance of the accessibility measure. Of these, only one production model and one attraction model (both for home-based school trips) offer significant results (the results are quite counter-intuitive as school trips are of mandatory nature and should be least influenced by accessibility. This may have been caused by the practice of excluding non-mortorized trips from trip diaries that were prevalent at the time their data were collected).

It is entirely possible that trip generation is in fact largely unaffected by accessibility, as suggested by the study by Nakkash and Grecco. However, it is also possible that, as noted repeatedly in this paper, likely multicollinearity among the explanatory variables may have led to the insignificant accessibility coefficients. The models may have been subject to specification errors; introducing the accessibility measure as a linear additive term may not have been appropriate. Another potential problem is with accessibility measures themselves. These zonal variables tend to exhibit small variations across zones, and erroneously represent the true accessibility available to each household. Finally, the aggregate, zone-based analysis may have been too insensitive to detect the effect of accessibility.

Kannel and Heathington (1974) examines a panel of households which were interviewed in both 1964 and 1971. The same panel of households is used in their 1973 study of the stability in trip generation analysis. The objective of this 1974 study is to examine the hypothesis that "the trip production from households is affected by the accessibility of the household to major activity centers within the urban area" (op. cit., p. 78). The accessibility measures developed by Nakkash (see Nakkash and Grecco, 1972), are used in the study.

Kannel and Heathington use causal models to examine cause-effect relationships among several endogenous variables, including accessibility, auto ownership, and mobility. The indicator of mobility is the number of home-based (presumably motorized) trips. Two alternative model structures are examined (each structure is applied to the 1964 and 1971 data and leads to very stable sets of coefficients). In the first structure, accessibility affects both auto ownership and trip generation negatively. In the second model, which is preferred to the first by the authors, the direct link from accessibility to trip generation is eliminated. Thus, accessibility affects mobility, but only indirectly through automobile ownership.

Smith and Schoener (1978) examine the impact of I-95 based on "data from origin-destination travel surveys conducted by the Rhode Island Department of Transportation in Providence for the years 1961 (before construction of I-95) and 1971 (after I-95)" (op. cit., p. 152). Households are cross-classified according to household size and auto ownership. The dependent variables are VMT per household, vehicle-hours of travel (VHT) per household, and auto driver trips per household.

Repeated cross-sectional data are used to address these issues. The 1961 sample contains 11,467 households, but the 1971 sample contains only 855. The study concentrates on vehicular trips; "all trips that were not auto driver trips" were eliminated from the data set (op. cit., p. 154). The study area is divided into two, the portion inside the influence of the new highway and the portion outside it.

Smith and Schoener (1978) correctly point out that "Many previous studies have shown that a correlation exists between aggregate highway supply per capita and VKMT per capita. The existence of such a correlation, however, does not guarantee the existence of a causal relationship between the two variables" (op. cit., p. 153). Their analysis based on household data accounts for this problem and offers extremely interesting statistics. They conclude:

> "The comparison of the resulting matrixes revealed that the highway did not increase trips or VHT, but it did increase VKMT. This allows the tentative conclusion that travelers increase their VKMT until they use up a given amount of travel time. This conclusion supports the standard system-insensitive approach to trip generation as well as the use of travel time as an impedance in trip distribution" (op. cit., p. 152).

The study, however, is subject to limitations. Firstly, the sample size for the "after" period is extremely small, probably producing the tendency of accepting null hypotheses of no change. Secondly, the method used to test the statistical significance of change is less than ideal. Instead of examining the number of significant pairwise t-statistics in before-and-after cross-classification tables, the analysis of variance should have been used.

The concurrent processes of the proliferation of automotive transportation and the decline of urban public transit are well documented by aggregate historical data. The impacts of individual highway projects on transit use are less frequently documented. An interesting exception is a study by Richards and Beimborn (1973), which, based on longitudinal transit ridership records before and after the opening of a highway route, indicates that transit ridership started to decline before the highway opening due to residential and commercial relocation, and that opening itself had only limited impact on ridership.

The very question of induced traffic is addressed in NCHRP Project 8-19 (CSI and JHK, 1979; TRB, 1980). The study is admittedly "inconclusive," reflecting the complex nature of trip making, presence of a wide range of contributing factors, and resulting difficulties associated with its investigation. Several observations are made in the study. Whether person trips will increase or not is said to depend on the characteristics of the transportation system such as the reduction of off-peak travel times and costs, or the level of congestion before the system change (op. cit., p. 2-5). "The increase in person trips produced by a supply increase may or may not result in an increase in the number of vehicle miles travelled, depending upon the nature of the supply change" (op. cit., p. 2-6). VMT may decrease if the supply change decreases the distance between prominent origins and destinations, or if it encourages multiple occupancy vehicles.

Importantly, "A congested facility generally reflects the presence of unsatisfied or latent demand for trip making that may be satisfied if travel conditions are improved by the construction of new transportation facilities" (op. cit., p. 2-5). It is noted that non-work trips are more sensitive to supply characteristics, and "the supply change must affect the off-peak travel conditions within the corridor" to have impact on the volume of person trips (op. cit., p. 2-5).

These, and the number of other observations made in the report suggest difficulties involved in stating the effect of added capacity in general terms. Whether a capacity addition leads induce trips or not needs to be determined case by case while considering all the supply characteristics and other contributing factors.

4. Impact of New Transit Lines

5. Impacts of HOV Lanes and Other TSM Measures

6. Limitations of Current Forecasting Procedures

7. Conclusions

Assessing the impact of added capacity is a complex task because of the intricate causal relationships among transportation supply, land use, accessibility, and travel demand. The resulting simultaneity and endogeneity make the use of complex analytical methods inevitable; it is unreasonable to expect that simplistic analyses based on limited data bases will be able to properly address the issue.

At the same time, changes in travel demand are difficult and time consuming to measure precisely. Although carefully designed evaluation studies may offer valuable insights, the case-specific nature of impacts as discussed in CSI and JHK (1979) suggests that generalization of their results may be difficult.

One conclusion that can be drawn from this literature review is that only limited utilization has been made of existing travel survey results. Only few studies have used accessibility measures; no studies have attempted to examine the interaction between land use and travel. It is quite likely that this is due to unavailability of suitable data, despite the many origin-destination surveys.

Traditional origin-destination surveys have been conducted in practically every metropolitan areas, quite often at up to three time points that are approximately 10 years apart. Usually metropolitan planning organizations (MPO's) prepare network and land use data that accompany origin-destination trip records. These data files, however, do not seem to be well archived, well documented, or easily available for research purposes. If complete trip, network, and land use data sets can be made available from selected metropolitan areas of different sizes and densities, they will form a powerful data base that will facilitate many analyses that will extend beyond the many limitations discussed in this study. The use of existing origin-destination data appears to be a very cost-effective and expeditious approach in addressing the added capacity issue. This, and other points are itemized in the following tentative summary of this study.

- There is no empirical indication that added capacity generates a significant volume of induced traffic.

- The standard sequential procedure is capable of forecasting diverted, transferred and shifted traffic.
- Abbreviated application of the procedure, unwarranted attempts to transfer models and extrapolation of the models to inapplicable options, are unfortunately present.
- A better understanding of trip timing decision is necessary, especially for non-work trips.
- A better understanding of trip chaining behavior is also needed.
- Impacts on auto ownership, residential and job location choice, and land use, need to be better understood and incorporated into the forecasting procedure.
- Existing data can be better utilized with more elaborate statistical methods to test behavioral theories.
- Existing data can be utilized in multi-regional and multi-period comparative analyses of trip timing decision, trip chaining behavior, and the issue of suppressed trips.
- Likewise existing data can be utilized to examine the effect of congestion on mode and destination choice.
- Improving the conventional forecasting procedure can be best achieved through analysis of cross-sectional data because dynamic models derived from longitudinal (especially panel) data may not be compatible with cross-sectional models.
- More widespread use of panel surveys is encouraged for project evaluation.

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