Demand for Urban Goods Vehicle Trips

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This paper describes the results of the first of several investigations that have explored the relationship between the generation and distribution of intraurban goods vehicle trips and the spatial structure of the Boston metropolitan region. An aggregate trip-end generation model is presented that illustrates that zonal trip-end generation rates vary systematically with the density and mix of socioeconomic activities, the usage of vehicles of different sizes, and the location from the center of the region. An industry-specific direct demand model is employed to analyze the generation and distribution of trips in delivery routes as a function of the supply of transportation and activity systems variables. The linked nature of goods vehicle trips is found to require modifications in the formulation of planning models and to give rise to the differential contribution of goods-producing and goods-consuming activities to levels of goods vehicle traffic.

A well-recognized need exists for improved models of urban goods vehicle movements (1, 2, 3). This need stems from the practical requirements of urban planning for goods and passengers as well as from the substantial potential of quantitative models for increasing our understanding of urban goods transportation and its relationship to the spatial structure of metropolitan areas.

There are two basic analytical approaches to investigating the short-term relationship between the transport of goods and urban spatial structure (4). In the first approach, the demand for urban goods vehicle trips is viewed as a direct function of the location, intensity, and mix of socioeconomic activities. In the second approach, the demand for goods vehicle trips is a function of trade in commodities, which is, in turn, a function of the spatial pattern of activities and their production and consumption of goods. Each of these approaches has been explored in empirical research conducted by me at the Centre for Land Use and Built Form Studies, University of Cambridge, and the Transportation Systems Center, U.S. Department of Transportation. The first approach, the implementation of which is described here, has the virtue of requiring only available survey data, is most relevant to obtaining near-term improvements in existing planning models, and provides a natural format for testing hypotheses that pertain to vehicular trips.

In this paper, trip generation and attraction and trip distribution have been analyzed with two empirical models as a function of the spatial patterns of socioeconomic activity and the supply of transport. First, a trip-end generation model was used to test alternate functional forms and to explore the differential impacts of groups of activities on levels of trip making. Second, trip generation and distribution were modeled simultaneously with a direct demand construct that was used to assess the influence of transport supply and the effect of route choice behavior on goods vehicle traffic.

Each of these models was estimated by using data collected during 1963 and 1964 as part of the Eastern Massachusetts Regional Planning Project, a comprehensive transportation and land use planning study (5). These data, graciously made available by the Massachusetts Department of Public Works, consisted of measures of industrial and residential activity in each of the 626 traffic zones that cover the region, a matrix of interzonal travel times, and the results of an origin-destination survey of goods vehicle movements (6).

PREVIOUS RESEARCH

Analytical consideration of the relationship between the transport of goods and urban spatial structure dates from the earliest metropolitan transport studies undertaken following World War II. The first explorations of this relationship were largely confined to simple tabulations, but, in the Detroit study (7), and subsequently in the Chicago Area Transportation Study (8), zonal goods vehicle trip generation for specific land uses was assumed to be proportional to person trip generation. The alternative and now dominant approach, that urban traffic be viewed as a function of activities (or land use), was most prominently articulated by Mitchell and Rapkin (9). They submitted that this now familiar proposition was equally applicable to both truck and passenger trips.

In 1965, Hill (10) formally proposed the sequence of models for predicting truck traffic that is in widespread

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use today. This method, identical to that employed at the time in the analysis of passenger travel, entailed the estimation of goods vehicle trip generation equations and the use of gravity models for predicting trip distribution.

Studies of establishment truck trip generation have been conducted by Starkie (11); Bates (12); Christie, Prudhoe, and Cundill (13); and Hutchinson (14). Aggregate zonal trip generation models have been constructed by Peat, Marwick, Mitchell and Company (15) for the data employed in this study and by Saunders (16), among others.

The models that have been employed to estimate the relationship between goods transport and metropolitan spatial structure are open to criticism on several grounds. They are, for the most part, characterized by the absence of a strong theoretical base specifying either the choice explanatory variables or the functional form of the relationship. As a result, model forms have frequently been dictated by ad hoc specification marked by the omission of important variables such as measures of transport supply or cost or, in aggregate (over industries) models, measures of activity in freight transport and warehousing. Further, Starkie (3), Saunders (16), and Slavin (4) have shown that, in addition to failing to achieve acceptable levels of statistical explanation, estimates of existing planning models may frequently fail to conform to the assumptions that underlie least squares estimation.

Finally, existing models that relate goods transport and urban spatial structure have not taken account of a fundamental feature of intrametropolitan freight transport and urban truck trips—urban goods vehicle trips are organized in routes composed of multiple numbers of trips. As will become evident, this fact strongly influences the demand for intraurban truck trips. Because of all these deficiencies, the nature of the relationship between goods transport and urban spatial structure remains an important research topic.

GENERATION OF GOODS VEHICLE TRAFFIC

The formulation of the model for analyzing zonal trip generation was guided by a number of hypotheses concerning the determinants of urban goods vehicle trips. These determinants included the mix of zonal activities and their intensities, the intraregional location of activities, patterns of intraregional and interregional trade, and the technology of urban goods transport.

As evidenced in Figures 1 and 2, substantial variation exists in both the percentage of urban truck trips made by various activity groups and their trip generation rates. For this reason, the choice of activity variables is of the greatest importance in the specification of aggregate zonal trip generation models. For this analysis, the choice of the activity variables was based on distinguishing between those activities that both receive and ship goods and those that primarily receive shipments but do not produce output transported by motor freight modes. Production and distribution activities fall in the former category and households and services fall in the latter. Services also generate goods vehicle trips for business purposes although households, in general, do not. Based on this classification of activities, residential population and employment in manufacturing, wholesale and retail trade, motor freight transport and warehousing, and all other activities combined were selected as initial variables. Extensive examination of correlation matrices and preliminary equations suggested that the best results were to be obtained with these variables. However, the residuals from preliminary model estimates were found to be correlated with zonal intensities of development and location.

Figure 1. Percentage of total goods vehicle trips by activity.

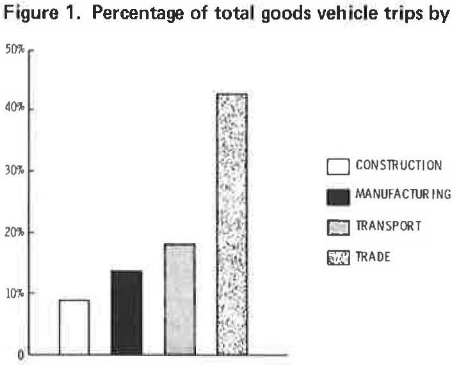
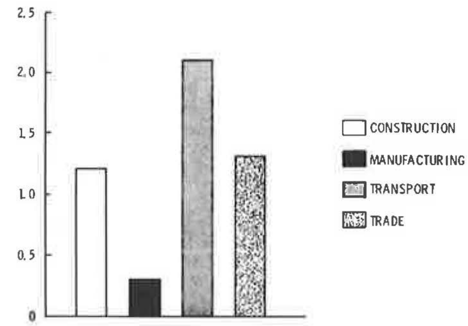


Figure 2. Daily trips generated per employee.



Because economic (production and consumption) and transport effects are not differentiated in trip generation models, nonlinearities and locational effects can stem from either source. Economies of scale in production, for example, would lead, if all other things are equal, to higher trip generation rates for the shipment of output with increasing scale as output/employee ratios increase. However, economies of scale derive from greater levels of output per unit of other factor inputs as well and possibly achieve a reduction in the amounts of transportable inputs required per employee. This may yield, if all other things are equal, fewer trips for obtaining inputs per employee and perhaps offset the increase in trip generation for the distribution of output.

Locational effects on trip-end generation may arise from external economies and trade considerations. External economies derive from the colocation of activities, are thus most prevalent in the densest areas of the region, and may cause increased transport demand per unit of output. For small plants, which Starkie (11) has suggested have higher trip-end rates per employee, external economies may be of greater consequence than internal economies of scale.

Local market activities also have higher intraurban road transport demands than activities that specialize in interregional trade have. The former activities will also tend to be located in relatively central locations and thus at higher densities. As a result, at locations of increased density, one would expect to find activities that interact more frequently with one another and over shorter distances than at distal locations within a region.

Goods transport demanded by firms is also likely to be influenced by levels of inventories of inputs and outputs. Firms that hold high inventories may require fewer goods vehicle trips. Because the price of space declines significantly with distance away from the center of metropolitan regions, this too would imply that increased trip-end rates will be observed in central locations rather than in distal locations where the land and space inputs needed to hold higher stocks are of reduced cost and increased availability.

The technology of urban goods transport reinforces these density and locational effects. At higher densities, serving multiple collection and delivery points is relatively more efficient. In these locations, market thresholds are of considerably smaller spatial extent (17, p. 271) than at lower densities of activity, and the distances between customers are relatively short. Where the possibilities of serving more than one customer on the same route are slight, there is an increased inducement to economize on trips and achieve higher load factors particularly when the line-haul component of transport costs is large. This applies especially to firms that are heavily engaged in exporting their output. Furthermore, in the case of the Boston region, which is abutted by other dense concentrations of activity, more transport demand is presumably satisfied at the periphery of the region by road transport services produced in abutting regions.

The linked nature of goods vehicle trips has several specific impacts on the relationship between traffic and location of activities. [Slavin (4) offers a fuller exposition.] First, because the destinations of most trips are the origins of succeeding trips in route sequences, there is a rough equivalence between zonal trip origins and destinations unless many trips span spatial or temporal accounting boundaries. For the Boston region data, the correlation of zonal trip origins and destinations was 0.995. As a result, model equations were developed to explain the sum of zonal trip origins plus destinations, which are referred to as trip ends.

Second, the linked nature of goods vehicle trips accounts for the fact that many trips connect activities and locations that are distinct from the activity and location at the origin of a route. This leads to the spatial disparity between the respective origins and destinations of commodity flows and the truck trips that effectuate them.

Third, the fact that most intraurban truck trips connect consumers of goods follows directly from the occurrence of trips in routes and the predominance of delivery routes over all other types of routes. As a result, higher trip-end generation rates are associated with the consumption of goods rather than the production of goods.

Finally, the level of trip-end generation, which holds production and consumption rates constant, should also be a function of the mix of goods vehicles used; in this case fewer trip ends are associated with large vehicles. Because of congestion, this effect may also result in locational variation where high density and municipal regulations impose impediments on the use of heavy vehicles in central locations.

These arguments resulted in the formulation of the trip-end models with employment variables expressed as densities, a location variable, and a submodal split ratio. The inverse of travel time to the center of the region was used as a measure of location. After some experimentation, the zonal ratio of heavy truck (those with 3 axles or more) trip ends to total trip ends was selected to test for the influence of vehicle size. The model, which follows, proved to be vastly superior to previous versions in terms of theoretical consistency, the degree of explanation obtained, and conformance to ordinary least squares assumptions.

$$T/A = 1.41 + 0.45E_1/A + 0.91E_2/A + 0.29E_3/A + 6.63E_4/A + 0.07E_5/A + 0.20P/A - 4.7R + 90.8(1/C) \quad (1)$$

where

T = trip ends,
E_1 = employment in manufacturing,
E_2 = employment in wholesale trade,
E_3 = employment in retail trade,
E_4 = employment in motor freight transport and warehousing,
E_5 = employment in all sectors other than those explicitly represented,
P = population,
R = ratio of heavy vehicle trip ends to total trip ends,
A = area, and
C = travel time to the center of the region in minutes.

In this model, $r^2 = 0.93$ and $F = 1006.2$ for 626 observations.

The overall equation and all the variables, with the exception of the vehicle mix ratio R, are significant at the 1 percent level; R is significant at the 10 percent level. The regression coefficients are of the correct sign, and the regression residuals are random with respect to the patterns of development. Furthermore, the model significantly outperforms a log-linear equation with the same variables.

Inspection of the coefficients in the model illustrates the differential impacts of the various activity sectors on trip-end rates. In particular, the influence of E_4 is striking because it implies that the location of new terminal facilities will exert a substantial influence on the generation and attraction of goods vehicle trips. Explicit representation of this variable in aggregate goods vehicle trip generation equations would seem imperative because the consequence of aggregating it with other variables is to grossly underestimate goods traffic. E_2 also has a relatively high impact on trip-end generation when compared to other activities, as might be expected. In contrast, the smaller effect of E_3 is possibly the consequence of consumers' substituting passenger transport, in the form of shopping trips, for delivery services.

As hypothesized, increased travel times from the center of the region are associated with decreased levels of trip making. A negative relationship between the proportion of heavy vehicle trips and trip-end generation is also in evidence. This last finding would be easily explained by the carriage of larger loads in heavier vehicles.

In the model presented here, travel time is entered as a locational variable and not strictly as a measure of transport costs. In the remainder of this paper, the influence of transport supply on trip generation and distribution is assessed more fully.

MODEL OF GENERATION AND DISTRIBUTION OF GOODS VEHICLE TRAFFIC

Previous models of goods vehicle trip generation have characterized the level of commercial vehicle traffic as wholly inelastic with respect to the supply of transport in viewing traffic solely as a function of activities. A direct demand model has been used to examine the more comprehensive hypothesis that both the generation and distribution of goods vehicle traffic are a function not only of the location, intensity, and mix of activities but also of the supply transport. At the same time, this analysis illustrates some special considerations that must be taken into account in modeling urban goods vehicle trips and provides a demonstration of the effect of route making on the relationship between goods transport and urban spatial structure.

Although the model formulation is more general, its estimation has been based on a subsample of the survey data restricted to trips made in a subarea of the region by a single industry group in delivering its output. These restrictions are consistent with aggregation over behavioral units with a presumed similarity in the factors that influence their transport operations, including their location, market areas, commodities produced, and vehicle fleet mix.

Data

The subsample chosen consisted of 139 light (2-axle) goods vehicle trips that were made by manufacturers of food products within 16 contiguous suburban traffic zones located in Boston's North Shore. Restricting the sample to a small area reduced the amount of variability that might be introduced as a result of locational influences. Although long journeys were thus excluded, the model results will illustrate that, even in this context, there is sensitivity to small variations in transport supply (travel time).

As indicated by the land use matrix (Table 1) specifying the incidence of trips between land use classes, the output of the food processors is distributed primarily to retail outlets (restaurants and retail food shops) and to households. Thus, most of the trips connect these activities with themselves.

The number of home-based trips is remarkably small, which indicates that most of the food distribution trips within the subsample study area were made by vehicles that were based elsewhere. This is one natural feature of the linkage of commercial vehicle trips.

Model Specification

When the transport behavior to be examined is extended to include both trip generation and trip distribution, the problem of destination choice as it appears to decision makers must be considered. For trips within delivery routes, the set of alternate trip destination (and origin) choices is postulated to include alternative consumers of the commodity distributed and the home base (for the return journey). Thus the set of possible trip connections between activities is defined as the set of all ordered pairs of activities $(a_1, \ldots, a_n) \times (a_1, \ldots, a_n)$ where $(a_1, \ldots, a_n)$ = the set of all activities that occur in the same vehicle routes.

The maximal set of activity variables relevant to explaining the generation and distribution of trips then can be specified as those variables that correspond to the set of activities that either generate or attract trips, or, in other words, those variables that correspond to the activities for which row or column sums of the land use matrix are greater than zero. If A_k^i is a measure of the level of activity a_k in zone i, then it is hypothesized that the number of trips between zones i and j, which is T_{ij}, is a joint function of the elements of the sets of activity variables $\{A_k^i | a_k \epsilon R\}$ and $\{A_\ell^j | a_\ell \epsilon C\}$ where R = the set of activities at which trips originate and C = the set of activities at which trips terminate.

The set of (nonspatial) activity variables relevant to explaining trip generation and distribution may be thought of as maximal for one conceptual and two empirical reasons. First, further disaggregation may be desirable in modeling trips when disjoint subsets of activities are served by disjoint subsets of trips. Second, a very low incidence of trips between zones i and j may render certain activity measures insignificant in explaining trips. Last, selecting a subset of activity variables may be necessary if multicollinearity is severe.

Various behavioral paradigms of route formation [Webb (18) and Slavin (4)] suggest that T_{ij} is also a function of the spatial separation between zones i and j. In other words, the likelihood of the linkage of destination pairs is dependent on the distance between the two activities.

The preceding characterization of destination choice results in the following functional relationship

$$T_{ij} = f\left[\left\{A_k^i \mid a_k \epsilon R\right\}, \left\{A_\ell^j \mid a_\ell \epsilon C\right\}, g(t_{ij})\right] \tag{2}$$

where $g(t_{ij})$ = a function of the travel time t between zones i and j. Aggregating over activities, as just shown, is consistent with representing alternative destination choices in the same equation and requires that decision makers respond to travel times in uniform fashion for all alternative destinations.

The traditional direct demand model functional form (19) has been adapted for use in estimating the generation and distribution of goods vehicle trips. Thus, with the notation that has been defined, flows are postulated to be represented by the following function in which the c_i's are coefficients to be determined and the activity variables are chosen in the manner described:

$$T_{ij} = c_0 (A_1^i)^{c_1 (A_2^i)^{c_2} \ldots (A_m^i)^{c_m} (A_1^j)^{c_{m+1}} \ldots (A_n^j)^{c_{m+n}} g(t_{ij})} \tag{3}$$

Because the number of trips arriving at an activity in a zone is equal to the number of trips leaving the activity in the zone (if there are no import and export trips), the influence of an activity variable on trip origination must be equal to its influence on trip destination. For this reason, identical activity variables must be constrained to have equal coefficients when they appear as both generation variables, superscribed i, and attraction variables, superscribed j. If we group the same activity variables, the previous equation can be rewritten to this end (for n = m) as follows:

$$T_{ij} = c_0 (A_1^i A_1^j)^{c_1 \ldots (A_n^i A_n^j)^{c_n} g(t_{ij})} \tag{4}$$

Because, in general, all activities that generate trips will attract trips and all activities that attract trips will generate trips (i.e., n = m), all activity variables can be grouped in pairs in most cases. If, however, an activity generates trips but does not attract trips or vice versa, the corresponding activity variable or variables will appear singly with separate coefficients with no loss of generality.

Based on the findings from the trip-end model, density variables were selected as the appropriate activity measures. Viewed in these terms, the generation and distribution of trips are, if all other things are equal, proportional to the spatial extent (areas) of the origin and destination zones. Following Wohl (20, p. 26), we constrained the coefficients of the area variables to be unity, which yields the function in equation 5 that is linear in the logarithms and, for $g(t_{ij}) = t_{ij}^{-\beta}$, has been estimated with ordinary least squares.

In initial testing, the food manufacturing employment density coefficient, which was not significant at the 50 percent level, was deleted from the model. This was not

Table 1. Trips between land use classes.

	To		
From	Manufacturers	Retailers	General Population
Manufacturers	0	3	0
Retailers	2	68	2
General population	0	2	60

an unanticipated result because so few trips originated or terminated at this activity.

Model Results

The final form of the model is as follows:

$$\ln(T_{ij}/A_iA_j) = -10.7 + 0.41 \ln [(R_i/A_i)(R_j/A_j)] + 0.31 \ln [(P_i/A_i)(P_j/A_j)] - 1.2 \ln (t_{ij}) \quad (5)$$

where

T_{ij} = trips between zones i and j,
A_i = area of zone i,
R_i = retail in zone i food employment (shops and restaurants),
P_i = residential population of zone i, and
t_{ij} = travel time in minutes between zones i and j.

In this model, $r^2 = 0.80$ and $F = 51.7$. As is evident, the model performs rather well in explaining the generation and distribution of the trips in the subsample. All of the coefficients, as well as the overall relationship, are significant at the 1 percent level. The coefficients are all of the correct sign; there are positive elasticities of demand with respect to the activity variables and negative elasticity of demand with respect to travel time.

The model illustrates that a consequence of the occurrence of trips in delivery routes is that trip generation and distribution are strong functions of the location of consuming activities. The model also provides additional support for the existence of the density relationship described previously. Removing the zonal area terms from the equation, as was done in one experiment, reduced r^2 to 0.52.

Slavin (4) has suggested that a variety of paradigms that describe the formulation of routes by dispatchers provide a behavioral basis for gravity trip distribution of intraurban truck movements and has argued that the distribution of goods vehicle trips should be extremely sensitive to interzonal travel times or distances as a consequence. The model results are in accord with this hypothesis particularly when one considers that more than 90 percent of the trips in the data were less than 10 min in duration. Thus the estimation indicates the sensitivity of interzonal trips over this narrow range.

Although not attempted, disaggregation of the demand model to explain submodal split would be perfectly consistent with the modeling framework and with aggregating over goods vehicle routes because the submode is obviously employed on each trip within a route. The specification of the activity variables, however, might have to be modified if, for a given submode, a smaller set of activities are found to be considered as alternative destination choices. Also, the submode split must be presumed to be influenced by the supply of vehicles, commodity characteristics, average delivery sizes, and other factors. Thus further research and better data will be required to achieve a deeper understanding of this aspect of urban goods movement.

The reasoning employed in the formulation of this model of trip generation and distribution may also be transferred to conventional urban transport model sequence. Required would be the construction of separate trip generation and distribution models disaggregated so that trips are modeled in a manner consistent with aggregation over routes and with disaggregation to ensure that only alternative destination choices are treated simultaneously.

CONCLUSIONS

In this paper, the relationship between the transport of goods and the spatial structure of a metropolitan region has been explored with two analytical models framed to examine the hypothesis that goods vehicle traffic is a function of the location, intensity, and mix of socioeconomic activities. Each model provides strong empirical support for this hypothesis.

An important finding of this investigation is that zonal trip making is a strong function of activity densities and proportional to zonal area. This formulation consistently outperformed other alternatives in both models.

The trip-end model demonstrates that, because of the density relationship and locational effects, higher rates of trip making are present in the most congested portions of metropolitan regions. This would suggest that greater attention should be paid to planning for urban freight traffic.

The assessment of the differential contribution of different sectors to trip-end generation underscores the relative importance of distributive activities in this regard. Because of its large effect on the level of traffic and its potential role as a policy and planning variable, a measure of motor freight and warehousing activity should be entered explicitly in aggregate trip generation models.

The direct demand model illustrates that the supply of transport as represented by a function of travel times between zones substantially affects the generation and distribution of urban truck trips. This is consistent with the hypothesis that the distribution of goods vehicle trips is strongly determined by route choice behavior. Further study broadened to consider the interrelationship of other supply variables, route decision making, and submodal choice would be a logical extension of this research.

As assessed by the direct demand model, the generation and distribution of trips made by food manufacturers in delivering their products were governed by the location, intensity, and type of consuming activities. The model thus provides an illustration of the differential contributions of goods production and goods consumption to truck trip generation. This is a consequence of the linkage of goods vehicle trips in routes that imparts special characteristics to the relationship between goods transport and urban spatial structure.

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