Transpn Res.-A Vol. 17A, No. 6, pp. 419-427, 1983
Printed in Great Britain.

0191-2607/83 $3.00 + .00

THE DEMAND FOR FREIGHT TRANSPORTATION: MODELS AND APPLICATIONS

CLIFFORD WINSTON
Center for Transportation Studies, Massachusetts Institute of Technology, Cambridge, MA 02139, U.S.A.

(*Received* 12 *October* 1982)

Abstract—This paper provides an overview of models of the demand for freight transportation and applications of these models. Aggregate and disaggregate freight demand models are presented and critically evaluated with regard to conceptual coherence and estimability. These models are then discussed in the context of various freight transportation issues including the extent and nature of intermodal competition, the importance of service quality, the desirability and effects of changes in the regulatory environment, and forecasting freight flows that are carried by existing or new freight transportation modes. The paper concludes with suggestions for further work to be done in the area of freight demand.

1. INTRODUCTION

An understanding of the demand for freight transportation† is essential to the analysis of almost every serious research question concerned with the freight transportation system. Consequently, this topic has received a considerable amount of attention throughout the years from a variety of disciplinary perspectives and research contexts. One of the most striking aspects of the literature is the diversity of freight demand models that have been developed. A primary reason for this diversity is that identification of the actual decisionmaker in the demand for freight transportation is not straightforward. That is, although the transportation decision is embedded in the larger production, distribution and location problems faced by a firm, it could ultimately be made by a shipping or receiving manager, or be made jointly by a firm's distribution and inventory managers, or it may simply reflect the solution to a firm's overall profit maximization problem. Clearly, different freight demand models can result depending on how one characterizes the decisionmaking process. In addition, the variety of uses of freight demand models have contributed to the diversity of model development. For example, while one model may be useful for forecasting the demand for a new freight mode, it may have serious deficiencies when it comes to simulating different equilibria that could potentially result from changes in the economic environment.

This paper provides an overview of the different freight demand models that have been developed and illustrates their importance in the context of a number of positive and normative issues concerned with freight transportation. Although we will be concerned with the theoretical foundations of the various models, particular emphasis will be placed on econometric models that have been demonstrated to be empirically operational (for a survey of the demand for freight transportation which emphasizes non-econometric models see Smith (1974)). In the next section, we will describe the different freight demand models that have been developed. The discussion will be organized around the development of aggregate and disaggregate models. In Section 3 we will discuss the application of freight demand models to a variety of issues including the extent and nature of intermodal competition, the importance of service quality, the desirability and effects of changes in the regulatory environment, and forecasting freight flows that are carried by existing or new freight transportation modes. The final section offers suggestions for further work to be done in the area of freight demand.

2. MODELS OF FREIGHT TRANSPORTATION DEMAND

There are a number of different ways in which one could classify freight demand models. For our purposes, it will be useful to classify models as being aggregate (i.e. the basic unit of observation is an aggregate share of a particular freight mode at the regional or national level) or disaggregate (i.e. the basic unit of observation is an individual decisionmaker's distinct choice of a particular freight mode for a given shipment). It is important to note, however, that both aggregate and disaggregate models must ultimately be derivable from individual firm behavior: what is at issue primarily in the aggregate/disaggregate dichotomy is the nature of the data employed. In general, the aggregate models have tended to be either ad-hoc or based on cost minimizing behavior by firms while the disaggregate models have attempted to be more finely-tuned to the behavioral realities of freight transportation decisionmaking. While it could be argued that the disaggregate models are therefore more attractive than the aggregate models from a theoretical point of view, there are some practical drawbacks to these models, such as extensive data requirements, that suggest that

†Throughout this paper, the demand for freight transportation refers to shippers' or receivers' derived demand for a service to move their shipments form a specific origin to a specific destination.

aggregate models can be more useful than disaggregate models in particular contexts.

(a) *Aggregate models*

The most basic aggregate model that has been used in analyzing freight demand is called an aggregate modal split model (see Perle (1964), Morton (1969), Kullman (1973), Boyer (1977), Levin (1978)). It can be specified as

$$\log \frac{S_i}{S_j} = a_0 + a_1(P_i - P_j) + \sum_{k=2}^{K} a_k(X_{ik} - X_{jk}),$$

where S_i/S_j is the ratio of the market share (S) of mode i to the market share of mode j, $P_i - P_j$ is the price difference between the modes, and $X_{ik} - X_{jk}$ is the difference of other variables k, such as average transit time, between the modes†. Clearly, the simple structure of this model facilitates empirical analysis of problems where there may be considerable data and or computational requirements. Unfortunately, the model itself has little theoretical grounding. That is, its inherent structure cannot be claimed to be based on a reasonable theory of individual shipper behavior‡. In addition, the linear functional form that has typically been used restricts the cross-elasticities of the (aggregate) probabilities of choosing various alternative modes with respect to an attribute of any given mode to be equal (see Oum (1979a), Hausman and McFadden (1980)).

In response to the shortcomings of the aggregate modal split models, neoclassical economic aggregate models of freight demand have been developed (see Oum (1979b), Friedlaender and Spady (1980, 1981)). These models assume that the firm is a neoclassical factor price taking cost minimizer. Among the inputs to the production process are transportation activities. One derives the firm's demand for transportation by a particular mode by first specifying a cost function

$$C = C(Y, q, w, P_t),$$

where C = total costs; Y = output; q = vector of shipment characteristics; w = vector of factor prices excluding transportation prices; P_t = vector of transportation prices corresponding to the possible freight modes; and then observing that, by Shephard's lemma (see Varian (1978, p. 32)), the demand for freight transportation by mode i, X_t^i, is simply

$$\frac{\partial C(\cdot)}{\partial P_t^i} = X_t^i(Y, q, w, P_t).$$

In order to obtain an estimable aggregate freight demand model based on this approach, one must specify a functional form for the cost function. For example, assume the firm's technology can be characterized by a translog cost function, which represents a local, second-order approximation to an arbitrary cost function (see Christensen *et al.*, 1973), namely

$$\begin{aligned}\ln C = {} & \alpha_0 + \sum_t \alpha_t \ln P_t + \sum_j \beta_j \ln q_j + \sum_h \gamma_h \ln w_h \\ & + \delta \ln Y + \frac{1}{2}\sum_t \sum_s A_{ts} \ln P_t \ln P_s \\ & + \sum_t \sum_j B_{tj} \ln P_t \ln q_j + \sum_t \sum_h C_{th} \ln P_t \ln w_h \\ & + \sum_t D_{ty} \ln P_t \ln Y + \frac{1}{2}\sum_j \sum_k E_{jk} \ln q_j \ln q_k \\ & + \sum_j \sum_h F_{jh} \ln q_j \ln w_h + \sum_j G_{jy} \ln q_j \ln Y \\ & + \frac{1}{2}\sum_h \sum_g H_{hg} \ln w_h \ln w_g + \sum_h I_{hy} \ln w_h \ln Y \\ & + \frac{1}{2} J_{yy}(\ln Y)^2.\end{aligned}$$

By Shephard's lemma, one therefore derives a factor (expenditure) share equation

$$\begin{aligned}S^i & \equiv \frac{\partial \ln C}{\partial \ln P_t^i} = \frac{P_t^i X_t^i}{C} \\ & = \alpha_i + \sum_s A_{is} \ln P_s + \sum_j B_{ij} \ln q_j + \sum_h C_{ih} \ln w_h + D_y \ln Y,\end{aligned}$$

where S^i represents the expenditure share of the ith mode and the other variables are as defined previously. An aggregate freight demand model can then be obtained by assuming that all firms in a given region have the same technology. Aggregation is then implicitly made over all firms by region to obtain a model that has the same mathematical structure as the share equation given above, but has as its basic unit of observation the aggregate share of a mode by commodity group and by geographical region.

Although such neoclassical models are more attractive than the aggregate modal split models from both a theoretical and an empirical viewpoint§, it

†This model is also referred to as an aggregate logit model. It should be noted that the model's emphasis on the importance of differences between different modes' attributes, such as price and service, is similar to the emphasis that characterizes the structure of the "abstract mode" model developed by Quandt and Baumol (1966). However, as pointed out by Smith (1974), the abstract mode model is very restrictive in that the model posits that the demand for the ith mode depends on its attributes and the attributes of the "best mode". This implies that a change in the attributes of a mode other than these two cannot affect the demand for the ith mode.

‡An important exception to this point occurs in the case where all variation in decisionmakers and commodity attributes is unobserved or unmeasured. In this situation, the modal split model can be shown to be based on individual utility maximizing decisions by shippers.

§It should be noted that the neoclassical models, in contrast to the modal-split models, generally do not place a priori restrictions on the elasticities of substitution if they are based on a translog technology.

should be stressed that the basic unit of observation of these models is still an aggregate share of a particular transportation mode at the regional or national level. The potential drawbacks of this level of aggregation will be discussed shortly.

(b) *Disaggregate models*

A number of theoretical and empirical advantages of disaggregate over aggregate freight demand models are responsible for the recent popularity of the former in the transportation field. First, models that are derived from the disaggregate perspective are firmly grounded in theories of behavior that attempt to reflect the institutional realities of freight transportation decisionmaking†. Second, the disaggregate approach is conducive to much richer empirical specifications, which capture important characteristics of the decisionmaker, than an aggregate approach. Finally, one is able to get a better understanding of the degree of intermodal competition since a disaggregate model is estimated using the actual attributes of the modes for a given movement and the actual characteristics of the commodity that requires transportation. For example, in disaggregate freight demand models one uses the actual shipment size and service characteristics for a given movement, and can thus judge whether it is sensible to characterize particular modes as competitors for the shipments under study. In aggregate analyses, this consideration is often obscured as movements are aggregated into shares at the regional or national level. Consequently, estimates of important effects, such as market elasticities, are generally more accurate in a disaggregate modelling context. In addition to possible specification inadequacies, the basic source of the imprecision of market elasticity estimates obtained from an aggregate freight demand model is due to the use of average values of particular variables as opposed to using the actual values facing each decisionmaker.

Notwithstanding the conceptual strengths of disaggregate freight demand models, it is important to recognize that there are practical limitations to this type of analysis. In particular, there are considerable data requirements that must be met in order to estimate a disaggregate freight demand model. Not only does one have to obtain a sample of firms' mode choices, but one must also collect data on the characteristics of all modes (chosen and unchosen) that are included in each firm's choice set. In addition, even with the advances in computer software that have been made in recent years (see Amemiya (1981) and Daganzo (1979) for descriptions of widely-available computer programs that can be used to estimate disaggregate freight demand models), disaggregate freight demand models can be difficult to estimate, particularly when there are a large number of alternative modes under consideration and/or the specification of demand is complex. Finally, as noted by Anas (1981), models estimated from aggregate data can be more useful than models estimated from disaggregate data in the context of large-scale (regional or national) analyses of freight flows that are designed for policy analysis or practical prediction. Thus, in practice, most disaggregate freight demand studies have been limited to a fairly narrow sample population (e.g. a sample of shippers of manufactured commodities).

There have been two types of disaggregate freight demand models, behavioral and inventory, developed in the literature. The behavioral models (see Winston (1981a), related models can be found in Watson, Hartweg and Linton (1974), Daughety and Inaba (1978), and Daughety (1979)) attempt to focus on the mode choice decisions made by the physical distribution manager of the receiving or shipping firm. The analysis is motivated by the proposition that the manager is concerned with maximizing the utility (i.e. satisfaction), with respect to expense and service, he receives from using a given mode, given the uncertainties, and his attitude toward them, that are associated with the use of that mode. These uncertainties could relate, for example, to the variability in arrival time and potential for loss and damage. Thus, the decisionmaker is actually modelled as maximizing his expected utility from his choice of mode. The empirical model that is used to estimate the demand for freight transportation within this framework is a random expected utility model. This model is composed of an observed component of utility, termed the mean or representative utility, and an unobserved component. It can be specified for the ith mode as

$$EU_i(Z_i, S) = V(\beta;\ \bar{Z}_i, S) + \eta(Z_i, S),$$

where EU_i = expected utility from the ith mode; V = mean or representative utility; β = vector of unknown parameters; $Z_i, \bar{Z}_i$ = vector of actual or mean values of the attributes of the ith mode; S = vector of commodity and firm characteristics; η_i = unobserved characteristics of the ith mode, commodity and firm.

The decisionmaker will select mode i if $EU_i > EU_j \forall_j\ i \neq j$. Since the expected utilities are random, this event is a probability P_i, namely

$$\begin{aligned} P_i &= \text{Prob}\,[EU_i > EU_j \forall_j\ i \neq j] \\ &= \text{Prob}\,[V(\beta;\bar{Z}_i, S) - V(\beta;\bar{Z}_j, S) \\ &\quad > \eta(Z_j, S) - \eta(Z_i, S) \forall_j\ i \neq j]. \end{aligned}$$

If we let ψ denote the cumulative joint distribution function of the random variables

†It should be pointed out that an aggregate freight demand model that is based theoretically on particular optimizing behavior by firms may be implicitly capturing some of the same institutional considerations that are reflected in a disaggregate freight demand model that is based on the same theory of optimal firm behavior. What is often lost, however, in an aggregate model is an underlying characterization of the process by which optimizing behavior is achieved by firms.

$(\eta(Z_i, S) \ldots \eta(Z_J, S))$ and ψ_i denote the derivative of ψ with respect to its ith component then we obtain

$$P_i = \int_{-\infty}^{\infty} \psi_i(t + V_i - V_1,$$

$$t + V_i - V_2, \ldots t + V_i - V_J)\,\mathrm{d}t,$$

where $V_i = V(\beta; \bar{Z}_i, S)$. Actual estimation of the unknown parameters is achieved by first making an assumption regarding the distribution of the η's, thus obtaining a specific functional form for the choice probabilities (for example, if one assumes the errors are distributed according to the extreme value distribution, then the functional form of the choice probabilities is given by the multinomial logit model), and then using an appropriate estimation procedure (for a survey of probabilistic choice models and appropriate estimation procedures see Amemiya (1981)).

The behavioral models developed thus far could be improved in two important ways. First, the basic unit of observation that has been used, namely the shipment of a commodity by a particular mode during a particular time of year, limits the scope of a freight demand analysis as it fails to account for the volume of a given firm's shipping activity over its normal production cycle and tends to average out seasonal effects. In general, the use of a flow variable composed of a set of shipments made over a representative time horizon would help to alleviate these problems. Another drawback of current behavioral models is that they tend to characterize mode choice decisions as being made in something of a vacuum. That is, decisions are modelled in the absence of other considerations within the firm such as those emanating from the inventory department. From the standpoint of the shipper, this may not be a serious problem to the extent that he has simply to respond to purchase orders made by other firms. However, in situations where this is not the case (e.g. when the behavior of the receiver is being considered) it would be expected that the physical distribution manager would coordinate freight transportation decisions with the inventory manager; hence, it would be desirable for the model to account for this behavior.

The final set of models to be discussed, inventory based models, have attempted to analyze freight demand from the perspective of an inventory manager. The inventory approach toward modelling freight demand has received considerable theoretical attention (see e.g. Baumol and Vinod (1970), Das (1974), Constable and Whybark (1978)), but only recently has received empirical attention. The inventory approach is attractive in that it implicitly attempts to integrate the mode choice and production decisions made by a firm. Consequently, in this approach, variables related to production, such as shipment size and frequency of shipments, are treated as endogenous decisions along with mode choice. An inventory theoretic model of freight demand has been recently developed by McFadden and Winston (1981) (for related models see Allen (1977) and Chiang *et al.* (1980)). Essentially, a profit function that accounts for the inventory fluctuations at the firm's shipping origin and the inventory fluctuations at the destination of the firm's shipment is derived. The firm's optimization problem then consists of choosing the shipment size, mode, and shipping interval to maximize its present discounted value of profit subject to the inventory behavior which determines the rate of production at the origin and the rate of consumption at the destination. Formally, the basic notation used in the analysis is: Y = rate of consumption; X = rate of production; $t = 0, \theta, 2\theta$ = dates of shipments; τ_i = transit time, mode i; r = interest rate; λ = loss rate on inventories; $I(t)$ = inventory at origin awaiting shipment; $J(t)$ = inventory at destination awaiting consumption; S = shipment size; $T_i(S)$ = freight tariff, mode i; $R(Y)$ = revenue, m = marginal cost.

The equations (and boundary conditions) describing inventory fluctuations at the firm's origin and firm's shipping destination can be written, respectively, as

$$\begin{aligned} \dot{I}(t) &= X - \lambda I(t), && \text{where } I(0^+) = 0,\ I(\theta) = S \\ \dot{J}(t) &= -Y - \lambda J(t), && \text{where } J(\theta + \tau_i^+) = Se^{-\lambda\tau_i}, \\ & && J(2\theta + \tau_i^-) = 0. \end{aligned}$$

The steady state solutions to these equations are

$$I(t) = S(1 - \mathrm{e}^{-\lambda t})/(1 - \mathrm{e}^{-\lambda\theta}) \quad 0 < t < \theta$$

and

$$J(t) = S\,\mathrm{e}^{-\lambda\tau_i}(\mathrm{e}^{\lambda(\tau_i + 2\theta - t)} - 1)/(\mathrm{e}^{\lambda\theta} - 1)$$
$$\theta + \tau_i < t < 2\theta + \tau_i;$$

hence,

$$X = \lambda S/(1 - \mathrm{e}^{-\lambda\theta})$$

and

$$Y = \lambda S\,\mathrm{e}^{-\lambda\tau_i}/(\mathrm{e}^{\lambda\theta} - 1).$$

The firm's present discounted value profit maximization problem can now be written as

$$\begin{aligned} \max_{i,S,\theta} \prod &= \int_{\theta+\tau_i}^{\infty} R(Y)\,\mathrm{e}^{-rt}\,\mathrm{d}t - \int_0^{\infty} mX\,\mathrm{e}^{-rt}\,\mathrm{d}t \\ &\quad - \sum_{k=1}^{\infty} T_i(S)\,\mathrm{e}^{-rk\theta} \\ &= \frac{R(Y)\,\mathrm{e}^{-r(\theta+\tau_i)} - mX}{r} - \frac{T_i(S)}{\mathrm{e}^{r\theta} - 1}. \end{aligned}$$

Given this framework, mode choice, shipment size and shipping interval equations can be derived by a variant of Hotelling's lemma† and approximated by

†Hotelling's lemma is used to derive factor demand and supply functions. The main difference between this lemma and Shephard's lemma is that it applies to profit functions while Shephard's lemma applies to cost functions.

simple linear-in-parameters functional forms. The underlying parameters can then be estimated by maximum likelihood methods.

It is clear that extending freight demand models to include simultaneously other considerations, such as shipment size and shipment frequency decisions, is extremely important, for these extensions enable one to characterize the mode choice decision in the context of other activities that either require or closely relate to the freight transportation decision. As such, joint choice models are more realistic than conventional single choice models from a theoretical point of view as important endogenous choices are jointly analyzed instead of being treated as exogenous. In addition, this improvement in realism can lead to changes in estimation results. As an example, McFadden and Winston (1981) report that there are significant differences between elasticity estimates that are obtained from a model where mode choice is jointly estimated with shipment size and a model where mode choice is estimated alone.

While it is clear that progress has been made in the conceptual development of freight demand models, further improvements are needed to enable us to capture fully the forces that influence the demand for freight transportation. We will indicate some of these improvements in the final section. In the next section, we will provide additional motivation for the models that have been developed to date by discussing them in the context of various freight transportation issues.

3. APPLICATIONS OF FREIGHT DEMAND MODELS

It is clear that conceptual improvements in freight demand models have been motivated by researchers' desire to overcome the shortcomings of earlier models. They have also been motivated, however, by an interest in analyzing various freight transportation issues that could not be adequately addressed with existing models. In this section, we will discuss the improvements in and use of freight demand models in the context of particular issues such as the extent and nature of intermodal competition, the importance of service quality, regulatory analysis, and forecasting freight flows carried by existing or new freight modes.

(a) *Intermodal competition*

One of the most prominent issues concerned with the freight transportation system is the degree of intermodal competition between railroads and motor carriers. The earliest studies on this topic (see e.g. Meyer *et al.* (1959), Woods and Domencich (1971)) focussed on the comparative costs of providing service by each mode. The main conclusion drawn from these studies was that rail had a significant cost advantage over motor carrier (especially for movements that exceeded a few hundred miles), which if reflected in their rates would enable the railroads to attract a substantial amount of motor carrier traffic. Although these studies were suggestive of the nature of rail's comparative advantage over motor carrier, they did not reflect the actual preferences that shippers have for these modes. Specifically, these studies evaluated the supply characteristics of the modes, but did not attempt to determine the weights that shippers place on particular modal characteristics. It is in this respect that freight demand models have contributed to our understanding of the issue of intermodal competition.

The aggregate freight demand models were the first models developed to confront the issue of shippers' preferences for rail vs motor carrier. Unfortunately, the aggregative nature of some of these models obscured the "competitive interface" between these modes. The notion of a competitive interface between modes simply refers to those dimensions (e.g. shipment size and length of haul) along which intermodal competition could take place. For instance, according to Roth (1977), shipment sizes had to average at least twenty thousand pounds, when lengths of haul were greater than five hundred miles, for motor carrier to be competitive with rail in 1972. This implies that rail-competitive motor freight shipment sizes tend to be those that would be carried by a truckload (TL) carrier such as a private or irregular route carrier. Unfortunately, some of the aggregate freight demand models have focussed on competition between rail and less-than-truckload (LTL) carriers, thus analyzing modes which are not likely to be too competitive. As would therefore be expected, most of these models produced relatively low estimates of the cross-elasticity of demand, thereby suggesting, in sharp contrast to the earlier studies, that rail's ability to attract motor-carrier traffic was fairly limited. In cases where rail-competitive shipment sizes were considered, aggregate models produced results indicating that the existence of intermodal competition in long-haul and/or short-haul markets varied with the value of the commodities carried (see e.g. Oum 1979b).

The aggregate freight demand studies were successful in focussing attention on the responsiveness of the users of the freight system to potential changes in rates, as opposed to inferring responses from comparative cost models. In addition, these studies provided considerable motivation for considering the influence of non-price attributes of freight modes, such as transit time and variability in transit time, on user behavior.

The disaggregate freight demand studies attempted to provide a more precise analysis of the degree of intermodal competition. Not only were additional modes considered (e.g. private carrier), based on a careful analysis of the competitive interface, but more complete specifications were provided. These specifications included additional service variables, such as reliability of transit time, and characteristics of the shipping firm, such as its location and sales volume. As a result, the elasticity estimates produced by these models strongly suggested that in fact each mode had the opportunity to attract traffic in particular markets through price and/or service competition. In general, price competition appeared to be potentially effective in markets (long-haul or short-haul) characterized by significant amounts of bulk movements that did not require especially fast transit time.

(b) *Service quality*

In the process of analyzing the degree of intermodal competition, the comparative cost studies calculated a service differential in order to control for the difference in service quality between rail and motor carrier. Unfortunately, this measure has been shown (see Boyer 1975) to be highly sensitive to assumed parameter values and, therefore, likely to lead to biased estimates in either direction of the service advantage that motor carriers have over railroads.

Freight demand studies have contributed to our understanding of the importance of service quality in freight transportation by estimating directly the users' valuation of service (generally represented in terms of the mean and standard deviation of transit time). Estimates have been provided by aggregate models (see Levin 1978) and disaggregate models (see Winston 1979). These estimates have suggested that for some commodity groups, such as perishable and high-valued commodities, the users' monetary valuation of service quality exceeds the transportation charges. This, of course, indicates the potential competitive advantage that motor carriers have over the railroads.

Estimates of the users' valuation of service quality are particularly important inputs to cost–benefit questions in freight transportation. For instance, in an analysis of the potential benefits of railroad mergers, Harris and Winston (1983) used estimates of the users' value of transit time in reaching the conclusion that end-to-end mergers appeared to be more socially beneficial than parallel mergers with the primary benefits (as measured by the users' valuation of them) accruing in the form of potential service improvements. In future work, estimates of the value of service quality can be of use in the analysis of issues that deal with physical changes in the freight transportation system, such as the desirability of investments in rail and highway infrastructure, and issues that deal with carrier operations, such as the desirability of increased weight limits for motor carriers.

(c) *Regulatory analysis*

Welfare considerations. One of the most important recent policy issues concerned with the U.S. freight transportation system has been the social desirability of rate, entry, and exit deregulation. Essentially, the desirability of rate deregulation has been motivated by the possible existence of a large deadweight loss to society caused by having rates set in excess of long-run marginal cost. The first empirical study (see Harbeson 1969) to analyze the potential desirability of rate deregulation relied upon the comparative cost approach. The comparative cost methodology consists of calculating the difference between truck and rail marginal cost (adjusting rail's to account for its inferior service quality) and multiplying this difference by the amount of traffic that should (on the basis of lower freight costs) be reallocated to rail. Using marginal cost pricing as a benchmark, Harbeson concluded that the welfare loss from railroad rate regulation was quite large, roughly two billion dollars a year.

In recent years, freight demand studies have been useful in assessing the welfare effects of rate regulation by attempting to calculate directly these effects by well-known welfare economics formulae†. The first study that attempted to do this was by Friedlaender (1969). Drawing upon Perle's (1964) freight demand work, she concluded that the welfare loss from rate regulation was roughly \$300–\$400 million annually. Boyer (1977) and Levin (1978) obtained estimates based on the use of their aggregate modal split models that suggested that the welfare loss from railroad rate regulation was virtually negligible when the relative levels of service quality provided by rail and motor carrier were taken into account. Most recently, Winston (1981b) took into account the fact that rate regulation has occurred in both the rail and motor carrier industries. An estimate of the freight system welfare loss, which lay between Harbeson's estimate and those of Boyer and Levin, was obtained with the use of a disaggregate freight demand model. Interestingly, Boyer's and Levin's estimates have turned out to be based on flawed calculations, which when corrected yielded results that were fairly consistent with Winston's (see Levin 1981a on this point).

In summary, the freight demand studies have reached considerable agreement that the welfare loss from rate regulation has not imposed as large a social cost as Harbeson initially claimed; on the other hand, there is also agreement that the cost has not been trivial. Unfortunately, it is not clear that one can conclude from these studies that deregulation will eliminate the welfare loss because of the likelihood that railroads will exercise market power in order to achieve financial viability (see Levin 1981b). In other words, regulatory reform which requires that rates be set at marginal cost might be what is needed to eliminate the welfare loss.

The Deregulated Environment. The current transition to a deregulated freight transportation environment has raised questions as to what effects this change will have on the users and carriers in the freight transportation system. For instance, which modes and shippers will gain from deregulation? Which ones will lose? What configuration of prices and carrier profit levels will result from this policy?

†The standard formula for computing a change in welfare (using marginal cost pricing as a benchmark) due to a change in rates is given by $1/2\ \Delta P \Delta Q$, where P and Q represent rates and output respectively.

While definitive answers to these questions have not been obtained, a number of studies, relying upon different freight demand models, have attempted to simulate the likely effects of deregulation on the agents in the freight system.

Drawing upon his earlier freight demand work, Levin (1981a) attempted to provide estimates of rail prices, rail profitability, and welfare losses under deregulation. The principal conclusion from this study is that the achievement of financial viability for the railroads will require significant rate increases and concomitant welfare losses. In a study confined to agricultural commodities, Daughety and Inaba (1981), relying upon estimates obtained from a disaggregate behavioral freight demand model, also concluded that railroad rates would rise under deregulation. The implication of both of these studies is that the relative change in rail and motor carrier rates will encourage a redistribution of freight patterns between these modes. In all likelihood, rail will only dominate the movement of bulk commodities, particularly where there is little intermodal competition and no destructive intramodal competition.

In a general equilibrium model of the freight system, based on neoclassical aggregate freight demand and cost models, Friedlaender and Spady (1981) analyzed the distributional effects of deregulation. To the extent that deregulation leads to a competitive equilibrium, they concluded that this policy would lead to losses in income for rail shippers of manufactured commodities, and lower profits for motor carriers throughout the country and lower profits for railroads in the South-West Region. Countering these effects are likely increases in the profits of rail firms in other regions of the country and increases in the profits of motor carrier shippers. Although all of the studies discussed are subject to the technical criticisms of their freight demand models that were discussed previously, their findings are nonetheless suggestive of the likely effects deregulation will have on the freight transportation system.

(d) *Forecasting freight flows*

One of the most practical potential applications of freight demand models is in forecasting freight flows at the regional or national level, and predicting the potential demand for a new freight transportation mode. In the past few decades, there have been several attempts to forecast freight flows, however, these analyses have not relied upon the type of freight demand models discussed here. That is, linear programming models (see Henderson 1959), interregional flow models (see Vinod (1969), Netherlands Institute of Transport 1978), and input–output models (see Polenske 1980) have been used to obtain the forecasts. Unfortunately, none of these models closely captures (or attempts to capture) the essence of freight transportation decisionmaking. For this reason, realistic freight demand models that are embedded in a forecasting system could contribute significantly to the accuracy of and basis for particular forecasts. In addition, some of the forecasts produced by freight demand models could be of use as inputs to network carrier models that are designed to provide optimal routing, scheduling, and warehouse location decisions.

To the best of my knowledge, there have been only a few attempts to use a freight demand model to forecast the potential demand for a new mode (see Roberts and Miller (1977), Wilson (1977), Winston (1981c)). In these studies, disaggregate freight demand models were used to forecast the potential demand for a hypothetical surface mode, air freight transportation, and ocean container service on the West Coast of the United States, respectively. Although the underlying models are subject to the technical criticisms discussed previously, the studies are suggestive of the way in which freight demand models can be used to forecast potential user interest in new modal offerings. In a deregulated environment, it is likely that forecasts of the potential demand for intermodal freight transportation will be particularly useful.

4. SUGGESTIONS FOR FURTHER WORK

This paper has provided an overview of the development and applications of models of the demand for freight transportation. Although we have attempted to highlight the considerable progress that has been made, it should be clear that a number of important gaps in this research area remain. One of the most significant of these is the failure, thus far, to integrate the analysis of freight demand with shippers' location decisions. Clearly, a firm's location and market area can materially affect and be affected by its choice of freight mode. Thus, models that can incorporate this aspect of the problem will be successful in adding a further dimension of realism to the analysis of the freight transportation decisionmaking process. It is worth noting that the question of location and transportation interactions has become an important component of much of the regional science and urban economics literature (see e.g. Fujita and Ogawa (1982) and Ogawa and Fujita (1980)).

As mentioned in the previous section, freight demand models should have fruitful application in helping to provide forecasts of future freight flows. Beyond this application, however, is the need to use freight demand models to increase our understanding of the relation between the freight transportation system and the macroeconomy. That is, freight demand models can be potentially useful inputs to analyses which are concerned with estimating the impact of changes in the freight transportation system, either initiated by new technologies or policies, on an economy's performance (for an illustrative analysis of this problem see Kresge and Roberts (1971)).

Finally, it is important to recognize that these research topics and others will be slow in developing unless more extensive and high-quality data bases are developed. Currently, there are very few, if any, readily accessible disaggregate data bases. Consequently, major efforts by researchers and cooperation by firms and government agencies will be necessary to overcome the lack of quality data and to enable the transportation profession to continue to contribute to our understanding of the demand for freight transportation and ultimately the complex workings of the freight transportation system.

Acknowledgements—I am grateful to P. Viton, A. Friedlaender, G. Kocur, Y. Sheffi and a referee for their comments on previous drafts.

REFERENCES

Allen W. Bruce (1977) The demand for freight transportation: A micro approach. *Transpn Res.* **11**, 9–14.

Amemiya Takeshi (1981) Quantal response models: A survey. *J. Economic Literature* **19**, 1483–1536.

Anas Alex (1981) The estimation of multinomial logit models of joint location and travel mode choice from aggregated data. *J. Regional Sci.* **21**, 223–242.

Baumol W. J. and Vinod H. D. (1970) An inventory-theoretic model of freight transport demand. *Management Sci.* **16**, 413–421.

Boyer Kenneth D. (1975) The Price Sensitivity of Shippers Mode of Transport Selection and the Inter-Modal Allocation of Freight Transport. Unpublished Ph.D. dissertation, University of Michigan.

Boyer Kenneth D. (1977) Minimum rate regulation, modal split sensitivities, and the railroad problem. *J. Political Economy* **85**, 493–512.

Chiang Yu-Sheng, Roberts Paul and Ben-Akiva Moshe (1980) A Short-run Freight Demand Model: The Joint Choice of Mode and Shipment Size. Center for Transportation Studies, M.I.T. Cambridge Mass.

Laurits, Jorgensen Dale and Lau Laurence (1973) Transcendental logarithmic production functions. *Review of Economics and Statistics* **55**, 28–45.

Constable Gordon K. and Whybark D. Clay (1978) The interaction of transportation and inventory decisions. *Decision Sci.* **9**, 688–699.

Daganzo Carlos (1979) *Multinomial Probit*. Academic Press, New York.

Das C. (1974) Choice of transport service: An inventory theoretic approach. *The Logistics and Transportation Review* **10**(2), 181–187.

Daughety A. F. (1979) Freight transport demand revisited: A microeconomic view of multimodal multicharacteristic service uncertainty and the demand for freight transport. *Transpn Res.* **13B**, 281–288.

Daughety A. F. and Inaba F. S. (1978) Empirical aspects of service-differentiated transport demand. *Motor Carrier Economic Regulation: Proceedings of a Workshop*, pp. 329–349. National Academy of Sciences.

Daughety A. F. and Inaba F. S. (1981) An analysis of regulatory change in the transportation industry. *Review of Economics and Statistics* **63**, 246–255.

Friedlaender Ann F. (1969) *The Dilemma of Freight Transport Regulation*. Brookings Institute, Washington, D.C.

Friedlaender Ann F. and Spady Richard (1980) A derived demand function for freight transportation. *Review of Economics and Statistics* **62**, 432–441.

Friedlaender Ann F. and Spady Richard (1981) *Freight Transport Regulation*. M.I.T. Press, Cambridge.

Fugita Masahisa and Ogawa Hideaki (1982) Multiple equilibria and structural transition of non-monocentric urban configurations. *Regional Sci. and Urban Economics* **12**, 161–196.

Harbeson R. W. (1969) Toward better resource allocation in transport. *J. Law and Economics* **12**, 321–338.

Harris Robert and Winston Clifford (1983) Potential benefits of rail mergers: An econometric analysis of network effects on service quality. *Rev. of Economics and Statistics* **65**, 32–40.

Hausman Jerry and McFadden Daniel (1980) A Specification Test for the Multinomial Logit Model. Unpublished working paper, Department of Economics, M.I.T., Cambridge, Massachusetts.

Henderson James M. (1958) *The Efficiency of the Coal Industry: An Application of Linear Programming*. Harvard University Press, Cambridge.

Kresge David T. and Roberts Paul O. (1971) *Systems Analysis and Simulation Models*. Volume II of *Techniques of Transport Planning* (Edited by J. R. Meyer). The Brookings Institution, Washington, D.C.

Kullman Brian C. (1973) A model of rail/truck competition in the intercity freight market. Unpublished Ph.D. dissertation, Massachusetts Institute of Technology.

Levin Richard C. (1978) Allocation in surface freight transportation: Does rate regulation matter? *Bell J. Economics* **9**, 18–45.

Levin Richard C. (1981a) Railroad rates, profitability and welfare under deregulation. *Bell J. Economics* **12**, 1–26.

Levin Richard C. (1981b) Railroad regulation, deregulation, and workable competition. *Am. Economic Rev.* **71**, 394–398.

McFadden Daniel and Winston Clifford (1981) Joint Estimation of Discrete and Continuous Choices in Freight Transportation. *Pres.* 1981 *Meeting of the Econometric Society*.

Meyer John R., Peck Merton J., Stenason John and Zwick Charles (1959) *The Economics of Competition in the Transportation Industries*. Harvard University Press, Cambridge.

Morton Alexander L. (1969) A statistical sketch of intercity freight demand. *Highway Research Record*, 196.

Netherlands Institute of Transport (1978) *A Freight Transport Simulation System for the European Community and Spain*. Parts 1 and 2, December.

Ogawa Hideaki and Fujita Masahisa (1980) Equilibrium land use patterns in a nonmonocentric city. *J. Regional Science* **20**(4), 455–475.

Oum Tae Hoon (1979a) A warning on the use of linear logit models in transport modal choice studies. *Bell J. Economics* **10**, 274–387.

Oum Tae Hoon (1979b) A cross sectional study of freight transport demand and rail–truck competition in Canada. *Bell J. Economics* **10**, 463–482.

Perle Eugene (1964) *The Demand for Transportation: Regional and Commodity Studies in the United States*. Department of Geography, University of Chicago, Chicago.

Polenske Karen (1980) *The U.S. Multiregional Input–Output Accounts and Model*. D.C. Heath, Lexington, Massachusetts.

Quandt Richard E. and Baumol William J. (1966) The demand for abstract transport modes: Theory and measurement. *J. Regional Sci.* **6**(2), 13–26.

Roberts Paul O. and Miller Carol A. (1977) A parametric study of the demand for a high performance new technology freight transport system. *CTS Report Number* 77-17, Center for Transportation Studies, Massachusetts Institute of Technology.

Roth Ronald (1977) An Approach to Measurement of Modal Advantage. Department of Economics, American Trucking Association.

Smith P. L. (1974) Forecasting freight transport demand—The state of the art. *Logistics and Transportation Review* **10**(4), 311–326.

Varian Hal (1978) *Microeconomic Analysis*. Norton Press, New York.

Vinod H. D. (1969) Forecasting the Freight Demand by Stages. In *Studies on the Demand for Freight Transportation: Volume II*. Prepared for the Northeast Corridor Transportation Project by Mathematica, Inc., Princeton, New Jersey.

Watson Peter L., Hartweg James C. and Linton William E. (1974) Factors influencing shipping mode for intercity freight: A disaggregate approach. *Transpn Res. Forum* **15**, 138–144.

Wilson Lawrence B. (1977) Policy analysis and forecasting models for U.S. domestic air cargo movements. *CTS Report Number* 77-12, July, Center for Transportation Studies, Massachusetts Institute of Technology.

Winston C. (1979) A disaggregated qualitative mode choice model for intercity freight transportation. *Working Paper No.* SL 7904, U.C. Berkeley.

Winston C. (1981a) A disaggregate model of the demand for intercity freight transportation. *Econometrica* **49**, 981–1006.

Winston C. (1981b) The welfare effects of ICC rate regulation revisited. *Bell J. Economics* **12**, 232–244.

Winston C. (1981c) A multinomial probit prediction of the demand for domestic ocean container service. *J. Transport Economics and Policy* **15**, 243–252.

Woods, Douglas and Thomas Domencich (1971) Competition between rail and truck in intercity freight transportation. *Transpn Res. Forum* **12**, 257–288.