

## Inventory theory, mode choice and network structure in freight transport

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In passenger transport, hub-and-spoke networks allow the transportation of small passenger flows with competitive frequencies, in a way that direct line networks cannot. Equivalently, in freight transport, it can be expected that small shipper-receiver flows of high added value commodities transit through hub and spoke networks, while larger shipper-receiver flows of less expensive commodities are transported directly, without transshipment. The objective of this paper is first to present an analytical model, based on inventory theory, explaining how for a given commodity flow, the organisation of freight transport operations is closely related to the characteristics of the shipper-receiver relationship; second to assess empirically this model. Special emphasis is put on the number of transshipments in the transport operation, as an indication of organisation of the transport operations.

The theoretical model is a simplified microeconomic model, built on principles of inventory theory. The empirical assessment of this model is based on the French shipment survey ECHO, which provides both the details of the transport operation and of the shipper-receiver relationships. With this database, we first provide a straightforward, graphical verification of the prediction of the theoretical model; secondly, we estimate it econometrically.

*Keywords:* freight mode choice, shipper, shipper-receiver relationship, shipment, transshipments, inventory theory, discrete choice modelling.

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### 1. Introduction

In freight transport demand models, mode choice is a critical component, as it determines the model's sensitivity to supply or demand changes. Current mode choice modeling practices are still based on rather crude approaches inspired by passenger modeling practices, and lack a solid theoretical underpinning from the logistics perspective.

Freight mode choice is usually represented as a microeconomic discrete choice process: for a given origin-destination pair, a discrete set of transport alternatives are available. These alternatives are characterized by utility functions which represent the value of each of these options from the perspective of shippers. The shippers themselves are not considered individually: a segmentation by commodity type or some other macroscopic criterion is generally assumed to be sufficient.

The specification and estimation of the utility functions is a crucial stage in the design of a freight mode choice model. However, due to theoretical and practical limitations, freight utility

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functions are generally simple, most often linear combinations of characteristics of the transport alternatives, such as price and travel time and, depending on the model, other variables such as travel time reliability (Blauwens et al., 2002; de Jong et al., 2004). Often the theoretical justifications are limited to microeconomic consistency and statistical fit.

Indeed, freight transport does not have the same body of microeconomic theory as passenger transport. For example, there is no freight equivalent to the theory of the allocation of time of Becker (1965), which explains why passengers have a willingness to pay for travel time savings. A number of recent works, mainly inspired by inventory theory, are progressively bridging this gap, such as Combes (2010) which analyses a classic model describing a just-in-time supply chain (Arrow et al., 1958) from a microeconomic perspective, in order to identify the logistics drivers of shippers' value of time.

Operations research also suggests that the commodity flow rate between the shipper and the receiver is one of the main determiners of mode choice (Baumol and Vinod, 1970; Hall, 1985). As a matter of fact, freight transport consists of discrete operations, the transport of shipments. Transport costs and logistic costs (including inventory costs) depend on shipment frequency: more frequent shipments generally imply higher transport costs, but lower inventory costs. The simple Economic Order Quantity (EOQ) model (Harris, 1913) illustrates this trade-off mathematically. Baumol and Vinod extend the EOQ model to mode choice: they introduce an important concept, the Total Logistic Cost (TLC), which is an extension of the generalized cost usually met in classic freight models. The commodity flow rate has an important, nonlinear place in the TLC, and therefore on mode choice.

These theoretical models are not recent; however they have not been introduced in practical freight transport models, due to the lack of adequate data. Indeed, freight transport surveys most often target carriers; shipper surveys are rare and, unfortunately, almost never observe the shipper-receiver relationships. This makes it extremely difficult to apply the theoretical models discussed above.

A number of econometric studies have tried to overcome this limitation; they identify interdependency between mode choice and shipment size, but are generally unable to clearly identify the explanatory variables. A non-exhaustive list, representative of the various methods tested, is McFadden et al. (1985), Abdelwahab and Sargious (1992), Holguin-Veras (2002), or Pourhabdollahi (2013). For a more complete review and discussion, see Combes (2014). For the same reason, freight transport models have not incorporated inventory theoretic concepts, with the exception of De Jong and Ben-Akiva (2007).

To our knowledge, only one database makes it possible to overcome this obstacle: the ECHO database, a French shipper survey of 2004-2005 which describes individual shipments including the logistical context within which they took place (Guilbault, 2008). One of the distinctive features of the ECHO survey is that it observes the shipper-receiver relationship, in particular the total commodity flow rate from the shipper to the receiver. With this database it was possible to validate empirically the EOQ model (Combes, 2012). It was also possible to estimate a mode choice model based on the EOQ model, with the shipper-receiver commodity flow rate as an explanatory variable of mode choice (Lloret-Batlle and Combes, 2013), and to confirm its importance in mode choice.

This paper focuses on another question that can be addressed with inventory theory and an adequate freight survey. This question concerns the relationship between network structure and freight rates. In other words, why do transport costs have a certain shape for direct door-to-door transport, and another for hub-and-spokes networks? Classic freight transport models usually ignore transshipments, or when they don't, they only consider multimodal transshipments. However, unimodal transport chains with transshipments (typically road-road transport chains) play a very important role in logistics and freight transport economics: they offer excellent responsiveness and flexibility at an acceptable cost for small, frequent shipments; all this at the

cost of longer transport distances, lower loading factors (and thus higher environmental impacts) and additional land use for warehouses and cross-docking platforms, in particular in the proximity of cities. Very few models attempt to take properly transshipments into account. Groothedde et al. (2005), designed a model where both the transport supply and costs adapt to the demand quantity, but where there is no choice of shipment size. De Jong and Ben-Akiva (2007) included the possibility that shipments can be consolidated, but without an impact on mode choice. Tavasszy et al. (1998), Jin et al. (2005) and Davydenko (2015) include distribution centers in origin-destination matrices and calculate the locations of transfers. Also here, shipment sizes are implicit or exogenous.

This paper extends Lloret-Batlle and Combes (2013) by introducing a distinction between direct road transport, road transport with one transshipment and road transport with two or more transshipments. Lloret-Batlle and Combes developed a model of mode choice based on inventory theory. Two important explanatory variables were introduced: the value density (i.e. the value in euros per unit of weight) and the shipper-receiver commodity flow rate. The model was estimated with the ECHO database. It considered the main modes of transport chains, based on a predefined hierarchy (e.g. when road and rail are used, the main mode is rail, etc.) In this paper, we discuss theoretically and econometrically the number of transshipments taking place during the transport of a shipment. A theoretical model gives some elements of explanation regarding the structure of freight rates for direct door-to-door transport vs hub-and-spoke networks, and the demand segments they are adapted to. Then, the econometric model of freight mode choice of Lloret-Batlle and Combes is extended to incorporate the number of transshipments within the transport chain and it is estimated against the ECHO database.

The paper proceeds as follows: Section 2 reviews the basic elements of inventory theory on which the rest of the paper is based; Section 3 presents the data; Section 4 presents the model specification and the estimation procedure and Section 5 discusses the results.

## 2. Network structure and inventory theory

This section briefly reviews the economic order quantity (EOQ) model and the concept of total logistic cost (TLC). Then, it presents a simple model explaining the relationship between the number of transshipments in a transport operation and mode choice.

### 2.1 Total logistic cost function, joint mode choice and shipment size

Consider a firm sending a regular commodity flow of constant rate  $Q$ , from a given location to another by a given transport mode, in shipments of size  $s$ . Each shipment is dispatched as soon as possible, so that the average origin inventory is  $s/2$ . The average destination inventory is assumed to be the same, so that the total inventory level is  $s$ , on average. Note that in general, the demand at destination is neither constant, not perfectly predictable. As a consequence, supply chain managers maintain a minimum inventory level, or safety stock, in order to prevent shortages. Taking the safety stock into account is mathematically complex, and requires data which are not available, it is therefore ignored here.

Now denote  $a$  the commodity value of time, i.e. the willingness of the shipper to pay for a reduction of the time the commodity remains in its possession. The cost to transport a shipment with a given transport mode  $m$  is assumed to consist of a fixed cost  $b_m$ , independent of the shipment size, and a variable cost, proportional to the shipment size, up to a multiplicative constant  $c_m$ . The travel time is denoted by  $t_m$ . It is now possible to introduce the following total logistic cost function, denoted by  $g_m$ :

$$g_m(s) = as + (at_m + c_m)Q + \frac{Qb_m}{s} \quad (1)$$

The optimal shipment size is obtained by minimizing this cost function. It depends only on  $a$ ,  $Q$ , and  $b_m$ :

$$s^* = \sqrt{\frac{Qb_m}{a}} \quad (2)$$

Equation (2) is the EOQ model. From the perspective of freight transport demand modeling, the advantages of the EOQ model are its simplicity and empirical validity (Combes, 2012). Note that it does not include the vehicle capacity constraint. Also, it can be easily extended to a mode choice model. Indeed, replace  $s$  by  $s^*$  in the total logistic cost function:

$$g_m(s^*) = 2\sqrt{ab_mQ} + (at_m + c_m)Q. \quad (3)$$

This new function is the cost for the shipper of using mode  $m$ , provided he chooses the optimal shipment size. It is a non-linear function of  $a$ ,  $Q$ , and of the cost and travel time of transport mode  $m$ . Heavier transport modes are characterised by a higher  $b_m$  and a lower  $c_m$ , and are thus competitive for larger commodity flows, all other things equal and provided their travel times are not comparatively too large.

The total logistic cost function can also be written per ton, and then take the role of the generalised cost function usually met in mode choice models:

$$\frac{g_m(s^*)}{Q} = 2\sqrt{\frac{ab_m}{Q}} + at_m + c_m. \quad (4)$$

This function is very similar to a classic freight transport modelling generalised cost function, except for the additional "EOQ term".

Then, any discrete choice model structure can be branched upon these utility functions. In this paper, mode choice is simply modelled as a classic multinomial logit model (Ben-Akiva and Lerman, 1985). It should be noted that while this approach acknowledges that shipment size and mode choice are joint decisions, the shipment size variable does not appear explicitly in the model. It has the merit of simplicity, but it makes it difficult to take into account the capacity constraint of vehicles.

## 2.2 Network structure and freight transport costs

In order to consider the difference between the cost structure of a road carrier operating direct transport operations and one of a carrier operating a hub-and-spokes network, we propose the following simple model. Consider three zones, A, B, and C, with shippers sending shipments from A towards B and C. Consider a carrier transporting  $n$  shipments directly from A to B. The shipper has to pick the shipments up in A, transport them towards B and deliver them (Figure 1: the green solid arrows represent the pick-up tour, long haul and delivery tour of one vehicle between A and B; the blue dotted arrows of another vehicle between A and C).

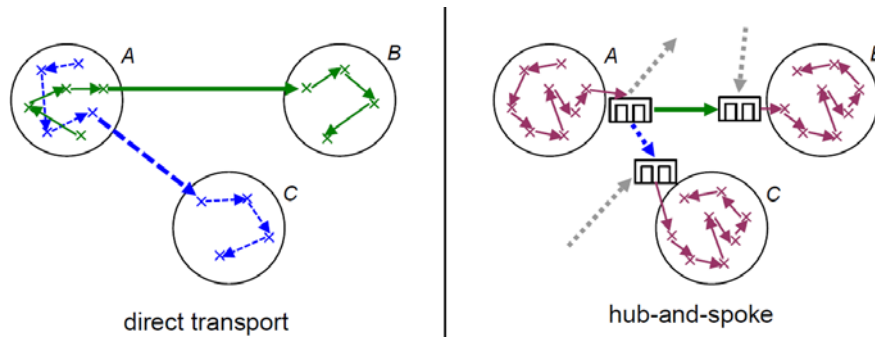


Figure 1. Organisation of road transport operations: direct transport vs hub-and-spokes network

Denote by  $s_i$  the size of shipment  $i$ , with  $i$  in  $\{1, \dots, n\}$ . Let  $n_v$  denote the number of vehicles necessary to transport the shipments from A to B. Then:

$$n_v = \frac{\sum_{i=1}^n s_i}{K} \quad (5)$$

where  $K$  is the capacity of each truck. Let  $d$  denote the distance which separates A and B.

Also, denote by  $d_A$  (resp.  $d_B$ ) the average distance between two pickup operations in zone A (resp. B or C). Whatever the number of trucks involved, the total distance associated to pickup and delivery operations is  $n(d_A + d_B)$ . Denote by  $c$  the cost of truck operation per km. Denote by  $d$  the distance separating zone A from zone B. The cost function of the carrier is:

$$C(\{s_i\}_i) = cd \frac{\sum_{i=1}^n s_i}{K} + c(d_A + d_B)n \quad (6)$$

The cost function depends both on the number of shipments to be transported and on their sizes. The price structure consistent with perfect competition is the one covering costs and equating marginal costs and marginal revenues calculated at constant prices:

$$p(s) = \frac{cd}{K} s + c(d_A + d_B) \quad (7)$$

Price is a linear function of shipment size. It covers a shipment-size independent cost, which corresponds to the approach trip, manoeuvres, and administrative tasks, and a shipment size-dependent cost component, which corresponds to the haulage, and in which the capacity constraint of the truck appears.

Now, consider a carrier operating a hub-and-spoke network (e.g. parcel or palletized freight transport). There are two important differences with the direct transport operation. First, all shipments go through break-bulk platforms (Figure 1). Let us assume that the cost of processing a shipment of size  $s$  is  $b_t + c_t s$ . Second, pickup and delivery operations are made without distinction of origin or destination, since the shipments are sorted in the break-bulk platforms. As a consequence, the average distance between two pickup operations in zone A (resp. B or C) is different from the previous case, and denoted by  $\bar{d}_A$  (resp.  $\bar{d}_B$  or  $\bar{d}_C$ ). The cost function of the carrier is a bit more complicated, due to the fact that all destination zones have to be taken into account (destinations are indicated as superscripts):

$$C(\{s_i^B\}_i, \{s_j^C\}_j) = \left( \frac{cd^B}{K} + c_t \right) \sum_{i=1}^{n^B} s_i^B + \left( \frac{cd^C}{K} + c_t \right) \sum_{i=1}^{n^C} s_i^C + c(\bar{d}_A + b_t)(n^B + n^C) + c\bar{d}_B n^B + \bar{d}_C n^C \quad (8)$$

The perfect competition prices are then, towards  $B$ :

$$p^B(s) = \left( \frac{cd^B}{K} + c_t \right) s + c(\delta_A + \delta_B + c_t) \quad (9)$$

The price to transport a shipment from  $A$  to  $B$  covers the same elements as in the direct line case, plus the processing costs at the terminal.

At first glance, one would conclude that hub-and-spoke is never competitive, due to the additional processing costs incurred in the break-bulk platforms. This effect is compensated by the fact that shipments are picked up and delivered without distinction of destination or origin. Indeed, the possibility to pick shipments up without distinction of destination vastly decreases the average distance between two places where shipments have to be picked up, with a large downward impact on  $d_A$  (and  $d_B$  and  $d_C$ ), and therefore on pickup and delivery costs. The reader may find a solid theoretical discussion of this effect in Daganzo (2005), for example.

As a consequence, the shipment-size independent component of freight rates is smaller via a hub-and-spoke network than via direct transport; conversely, the shipment-size dependent component is higher via a hub-and-spoke network than via direct transport. Transport with transshipments is therefore more competitive for smaller shipments. Also, as it can be deduced from Equation (4), transport with transshipments is adequate for small commodity flows with a high value of time; whereas direct transport is relevant for larger flows of less time sensitive commodities.

### 3. Data presentation

#### 3.1 Shipment data

The ECHO database describes 10,462 shipments sent by about 3,000 shippers. Some commodity types are excluded from the database (such as mining, agriculture, waste, etc.) The shipments observed in the ECHO survey are either sent from or received in France; the other end of the transport operation can be anywhere within or outside France.

All transport modes are represented. For road transport, private carrier and common carrier transport are distinguished. Shipments sent by non-road land modes (i.e. railway, combined transport and inland waterway) were oversampled in order to obtain enough observations. The transport mode is defined as the main mode of a transport operation, according to a predefined hierarchy: for example, the main mode of a shipment transported by road and air is air. More details are available in Guilbault (2008). In the frame of this study, we only pay attention to the main transport mode, except when the main mode is common carrier, in which case the number of transshipments is also taken into account. Transport mode summary statistics are given by Table 1. We note here the favorable circumstance that a high number of shipments is available in the database, which are moved over more than one transport leg.

**Table 1. Main transport mode summary statistics**

<i>m</i>	Number	%
Private carrier	1727	16.5
Common carrier - one leg	3409	32.6
Common carrier - two legs	1113	10.6
Common carrier - three+ legs	2126	20.3
Rail	224	2.1
Combined transport	133	1.3
Inland waterway	44	0.4
Sea	825	7.9
Air	859	8.2
NA's	2	0

For each shipment, the shipping and the receiving firms are also observed, as well as the relationship between these two firms, and the shipment itself. In each of these categories, many variables related to economic, logistic or transport related aspects are available, up to about 700 distinct variables.

The variables used in this study are the commodity density value (k€/t), the commodity flow rate between the shipper and the receiver (kt/y), the main mode of the transport operation (including the number of legs if the main mode is road), a few variables related to the way the shipment should be handled, a few variables related to the transport infrastructures available to the shipper (e.g. rail sidings), and the number of transshipments in the transport operation.

Strictly speaking, the rate  $Q$  of the commodity flow between the shipper and the receiver is not available in the ECHO database. The closest available variable is the total commodity flow between the shipper and the receiver, denoted by  $Q_{tot}$ , without distinction of commodity types. This variable is available for 81.5% of the observations. It is expected that, given the fact that shippers and receivers are disaggregated at the level of the premises of firms both for the origin and the destination,  $Q$  and  $Q_{tot}$  should most often coincide.

The commodity value of time  $a$  is not directly available either. Fortunately, there is also a good candidate to replace it. Indeed, for 64.5 % of shipments, the market value in euro (tax excluded) is indicated. Combined with the shipment weight, it is possible to calculate the value density of these shipments, i.e. the market value per unit of weight. Value density is typically very low for minerals and cereals; it is high for fast moving consumer goods and extremely high for smartphones. The value density is denoted by  $a_{dens}$ , and is measured in euro per kilogram. It is reasonable to assume that  $a$  and  $a_{dens}$  are strongly correlated, and consequently that  $a_{dens}$  is a good proxy for  $a$ .

Summary statistics are given by Table 2. An interesting characteristic of some variables is the very large range of values they cover, and their strongly asymmetric distributions. Table 2 also provides summary statistics of the product of the value density and distance ( $a_{dens}d$ ).

**Table 2. Summary statistics of some variables of the ECHO database**

Variable	Min.	Q1	Med.	Mean	Q3	Max	NA's
$s$ (t)	0.00	0.05	0.65	19.58	7.8	10,800	0
$Q_{tot}$ (kt/y)	0.00	1.00	18.00	2.12	350	63,000	1,934
$a_{dens}$ (k€/t)	0.00	1.07	4.56	59.37	20	10,400	3,715
$d$ (km)	1.00	74.00	278.00	1253.00	611	18,840	8
$a_{dens}d$ (k€ km/t)	0.00	$1.25 \times 10^5$	$1.12 \times 10^6$	$1.85 \times 10^8$	$9.99 \times 10^6$	$1.12 \times 10^{11}$	3,716

A dummy variable is also taken into account:  $X_{haz}$  which is 1 if the commodity is a hazardous material, 0 else (other variables related to the type of commodity: refrigerated transport, and fragile goods, etc.; they were tested without success).

It should be noted that freight rates are available in the ECHO survey. However, using freight rates for estimation purposes involves the reconstitution of freight rates of all the transport alternatives for each shipment, with a distinction of their shipment size dependent and shipment size independent components; a difficult task. Also, a transport operation also incurs non-monetary costs to shippers; those need to be accounted for in a mode choice model. Third, part of the transport cost is sometimes borne by the receiver. Fourth, the structure of freight rates is complex, and depends not only on the mode and distance, but also on many other variables which are not captured by the ECHO database. For these reasons, a simpler approach is preferred, where freight rates are not taken into account.

### 3.2 Transport supply data

In line with the modeling approach taken in Section 2.2, transport costs and travel times are assumed to depend solely on distance. The transport distance data used in this study comes from three sources: road shortest path (available in the ECHO survey) for road transport (private carrier and common carrier, whatever the number of transshipments), as-the-crow-flies distances for sea and air transport (which almost exclusively concern overseas transport), and network data from the Trans-Tools model version 2 for rail, inland waterway and combined transport (Rich et al., 2009).

More precisely, for non-road land modes, the following procedure was applied: from the shipment's origin, find the closest node of the relevant network (i.e. rail – for rail transport and combined transport – or waterways) according to road distances; idem at destination. Then, find the shortest path between the two network nodes. Finally, the total distance is the sum of the distances of these three trip components. In some cases, the “access distance”, i.e. the sum of the distances covered by road to reach the network at the origin and at the destination, and the “main distance”, that is to say the distance actually covered on the network, are distinguished.

No travel time data was available to the authors at the time of the study. As explained later, this has consequences for the empirical analysis.

### 3.3 Qualitative analysis of transport modes in the ECHO survey

Before proceeding to the statistical analyses, let us discuss qualitatively the mode choices observed in the ECHO database. Figure 2 illustrates the transport modes observed in the ECHO database, in relationship with  $\ln(a_{dens})$ ,  $\ln(Q_{tot})$ , and the crow-fly distance between the origin and the destination (each of the eight plots corresponds to a given distance range). In each plot, the strong correlation between distance and total flow is visible as a diagonal shape of the clouds in the boxes. But this is not the main purpose of our exposition.

Clear patterns are apparent for the choice of mode. First, distance plays a major role: sea and air transport, of course, are only used on long distances (starting from 1000 km); whereas common



carrier, railway, inland waterway and combined transport compete on intermediate distances (above 50 km and below 1000 km). Private carrier prevails on short distances.

More interestingly, for a given distance range, the  $a_{dens}/Q_{tot}$  ratio has a major influence on mode choice. Actually, and consistently with the theoretical model reminded in the previous section, heavy modes (i.e. rail, IWT, and sea transport) are relevant for low  $a_{dens}/Q_{tot}$  ratios (upper left corner of the plots), and road transport and air transport are relevant for high  $a_{dens}/Q_{tot}$  ratios (lower right corner). Also, for the particular case of common carrier transport, direct transport (i.e. one leg transport, represented by the dark red dots) is concentrated in the top left parts of the subplots, whereas shipments transported via two transshipments or more (represented by light red dots) appear mostly to the bottom right. Transport chains with a unique transshipment are in a somewhat intermediary situation (they are represented by medium red dots).

This confirms that direct line transport operations are associated to larger commodity flows and less valuable commodities, while hub-and-spoke networks are adapted to smaller flows or more valuable commodities, as explained from a theoretical perspective in Section 2.2.

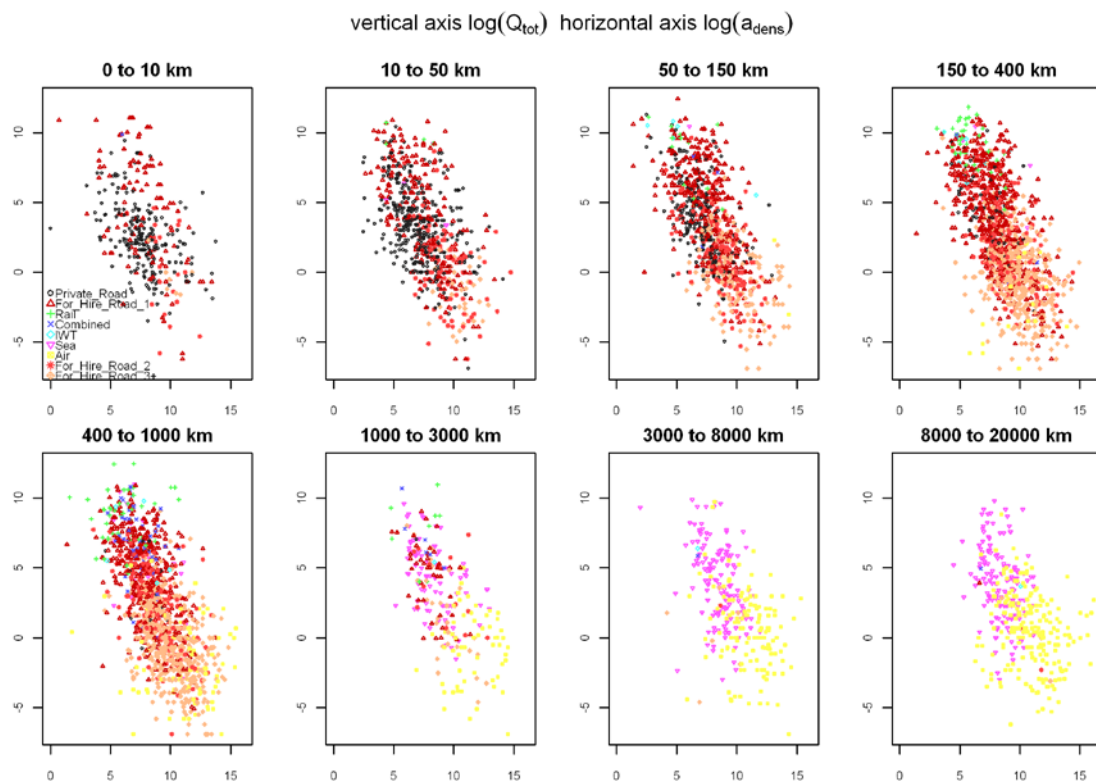


Figure 2. Observed mode choices in the ECHO database

#### 4. Estimation of the mode choice model

A mode choice model is now estimated on the basis of the theoretical discussion in Section 2. The objective is to explain the transport mode, with the number of legs in the case of road transport (1, 2 or 3+), as a function of the characteristics of the shipper-receiver pair (mainly described by the value density of the shipments and by the shipper-receiver commodity flow rate), and as a function of the transport supply.

### Specification

On the basis of Equation (4), each mode  $m$  is described by a utility function  $V_m$ . The first explanatory variable is the “EOQ” term  $\sqrt{a_{dens}/Q_{tot}}$ . The other variables were introduced with the objective to approximate a classic generalized cost function, but without cost and travel time data. As a consequence, the distance variable  $d_m$  is introduced, as well as the product of the distance with the value density  $a_{dens}d_m$ , in order to represent the pipeline inventory term of Equation (4). In addition, a number of dummy variables  $X_i$  were also taken into account. Finally, the utility function also consists of the i.i.d random error term  $v_m$ , assumed to follow a Gumbel distribution. The specification is:

$$V_m = ASC_m + \beta_m \sqrt{\frac{a_{dens}}{Q_{tot}}} + \gamma_m d_m + \varepsilon_m a_{dens} d_m + \sum_{dummies} \delta_{im} X_i + v_m. \quad (10)$$

Note that while Equation (4) represented a Total Logistic Cost function (i.e. lower is better), Equation (10) represents a utility function, so that signs are reversed.

The following results are expected:

- “EOQ term”: according to the theoretical EOQ model, the coefficient  $\beta_m$  should increase in absolute value with the shipment size independent component of the cost of mode  $m$  (including non-monetary costs). In other words,  $\beta_{rail}$  and  $\beta_{IWT}$  should be lower than  $\beta_{prvcar}$  (for private carrier) or  $\beta_{comcar}$  (for common carrier); and  $\beta_{air}$  should be larger than  $\beta_{sea}$ . Also, more transshipments are expected to be associated to higher coefficients:  $\beta_{comcar1} < \beta_{comcar2} < \beta_{comcar3+}$ .
- Distance: there is no direct cost information in the model. The distance variable should capture that. However, without proper cost and travel time information, the distance coefficients  $\gamma_m$  will only show how the relative competitiveness of the various modes changes when the distances change: a larger  $\gamma_m$  means that mode  $m$  is more competitive for longer distances.
- “pipeline inventory term”: here as well, the objective is that the model’s specification is close to a classic generalized cost formulation, plus the EOQ term. However, the model cannot benefit from proper travel time data. As a consequence, the  $\varepsilon_m$  will only show how the relative competitiveness of each mode will change when, for a given distance, the value density of the commodities change.
- dummy variables: these variables may reveal some technical capabilities or limitations of some modes, which can be more fit than others to carry commodities with specific handling protocols. In particular, hazardous materials are expected to be associated to non-road land modes.

### Estimation

The model is estimated using Biogeme (Bierlaire, 2003). The estimation results are given in Table 3. For readability, the alternative specific constants are not reported. Note that given the sampling procedure of the ECHO survey, the estimates of the alternative specific constants are biased. The non-significant coefficients (at the 0.1 level) were removed. A number of coefficients were removed in order to minimize as much as possible the correlations between the estimated parameters: it was not possible to make all the parameters independent at the 0.1 level (concerning 8 couple of parameters over 300 are significantly correlated) but these correlations do not involve the EOQ term, except in one case.

In addition to the final log-likelihood (LL), the log-likelihoods of the null and constant models are provided. To assess the contribution of the “EOQ” variable  $\sqrt{a_{dens}/Q_{tot}}$  to the model’s fit, the

likelihood of a corresponding model without this variable is computed (denoted by “LL without EOQ”).

**Table 3. Estimation of the mode choice model**

Coefficients	Model A	t-test
$\beta_{prvcar}$	$-1.66 \cdot 10^{-3}$	-5.74
$\beta_{comcar1}$	0.00	fixed
$\beta_{comcar2}$	$3.96 \cdot 10^{-4}$	3.28
$\beta_{comcar3+}$	$8.82 \cdot 10^{-4}$	8.24
$\beta_{rail}$	-0.803	-6.30
$\beta_{combined}$	-0.0227	-3.75
$\beta_{NWT}$	-0.142	-2.26
$\beta_{sea}$	$-6.44 \cdot 10^{-3}$	-6.01
$\beta_{air}$	$9.74 \cdot 10^{-4}$	8.62
$\gamma_{prvcar}$	-6.05	-
$\gamma_{comcar1}$	-1.08	-9.64
$\gamma_{comb}$	1.31	5.90
$\gamma_{sea}$	2.57	11.79
$\gamma_{air}$	2.53	11.54
$\varepsilon_{comcar1}$	-0.0636	-4.73
$\varepsilon_{rail}$	0.364	3.13
$\varepsilon_{air}$	0.0314	7.38
$\delta_{rail\ hazmat}$	1.95	7.59
$\delta_{comb\ hazmat}$	0.949	3.23
N	5646	
# Params	25	
LL(0)	-11233.7	
LL(c)	-8414.8	
LL without EOQ	-7301.3	
Final LL	-6937.5	

## 5. Discussion

The results of the estimation are globally consistent with the discussion above. The model clearly confirms the theoretical discussion of Section 2. In particular, the “EOQ term” contributes significantly to the model’s explanatory power, confirming the very important role of the commodity flow rate variable  $Q_{tot}$  in both the shipment size and the transport mode decisions, and the related coefficients’ hierarchy is theoretically consistent. However, some coefficients have surprising signs and relative values, as a probable consequence of the lack of precision and inadequacy of the supply data.

### *The “EOQ” coefficients*

Given the model’s structure, the EOQ coefficients can only be estimated relatively to one another; the coefficient for common carrier transport without transshipment was chosen as reference and set to zero.

The relative values of the coefficients are in line with the theoretical predictions. Globally, two transport markets should be distinguished: continental Europe, and overseas. For shipments arriving from or sent to continental Europe, the alternatives are private carrier, common carrier, combined transport, railroad and inland waterways. According to the theory, the heavier the

mode, the lower the coefficient should be. And indeed, we observe that the coefficients of road based modes (including combined transport), are very close, while inland waterway and railroad are much lower.

For shipments going overseas, the only reasonable transport alternatives are sea transport and air transport. Here, the coefficient of sea transport can be expected to be lower than that of air transport, and that is indeed the case. However, to the extent that this comparison has a sense, one can observe that they are quite close to the coefficients of road transport. This may stem from the fact that air transport and sea transport almost always involve road transport anyways (most bulk commodities are outside the scope of the ECHO survey), and also from the fact that overseas transport concern higher added value goods in general.

Finally, and that is crucial to this study, the comparison of  $\beta_{comcar1}$ ,  $\beta_{comcar2}$  and  $\beta_{comcar3+}$  is in line with the theoretical discussion of Section 2.2: a transport chain with more transshipments is preferred to direct transport by shippers with a higher  $a_{dens}/Q_{tot}$  ratio. Combes (2012) had already shown that this explanation was consistent with the observed shipment sizes in the ECHO database (more numerous transshipments are associated to smaller shipments), this estimation shows that it is also consistent with the observed mode choices.

#### *The distance and travel time coefficients*

The transport data on which the model is based is not entirely accurate and complete. The geographic detail is not excellent, and it is even absent for the overseas modes (sea and air transport). Also, there is, at this stage, no distinction of per kilometer cost or travel time for direct road transport or transport with transshipments. Due to these limitations, the coefficients are not all of the correct sign. It is a rather serious problem, meaning that the objectives to capture both transport costs and pipeline inventory costs through  $d_m$  and  $a_{dens}d_m$  are not reached.

However, the estimates of the parameters are intuitive and consistent: private transport, which is quite specific to short distance transport, has a strongly negative distance coefficient. Compared to road transport with transshipments, road transport without transshipment also has a negative distance coefficient. This is also an expected result: direct transport costs and prices increase quite fast with distance; this is much less the case for parcel or palletized transport. It is also known (Nierat, 2002) that combined transport is all the more competitive with respect to road freight transport as the distance increases; the combined transport distance coefficient is consistent with this statement. Regarding overseas transport we find that (1) the distance coefficients are significantly positive and large; (2) they are of similar order of magnitude, the difference between air and sea being relatively small.

The pipeline inventory coefficients can be interpreted as the variation of the relative efficiencies of the different modes when the value density of the commodities changes, in addition to the effect capture by the EOQ term. Many of the  $\varepsilon_m$  coefficients were dropped, either because they were not significant, or because they were too correlated with other parameters. The sign of the air coefficient is positive, consistently with the associated transport speed, all the more profitable to shippers as the commodities are expensive. The rail coefficient is much more difficult to interpret, and may arise from the lack of quality of the rail travel time data used in the model (which does not distinguish full trains and wagon loads). The coefficient of direct road freight transport is negative: this may be interpreted as the relative lack of competitiveness, in terms of speed, of this transport organization compared to road freight transport with transshipments, which generally offers higher responsiveness to shippers.

#### *Dummy variables*

For a majority of the dummy variables, the results of the estimation were not conclusive. There is one exception: hazardous materials. This variable has a significant effect on the competitiveness of rail and combined transport. Indeed, the transport of hazardous materials has strong

implications regarding the organization of transport, and their impact is particularly severe for road transport, thus increasing the relative competitiveness of the other modes.

## 6. Conclusion

Freight transport networks are complex, and continuously adapt to offer shippers adequate transport operations at adequate prices. Shippers have varied needs, which explain why many transport modes and organizations co-exist, without one clearly dominating the others. Classic freight transport models, which base their representation of shippers' preferences on travel time, cost and commodity type, only grasp a part of the logic underlying mode choice.

A number of models and econometric studies inspired from inventory theory have extended the potential of freight transport models to capture the logistic drivers underlying their choices on the freight transport market. They showed that shippers make trade-offs between transport costs and other logistic costs. When they opt for fast and expensive transport modes, additional expenses are generally overcompensated by the benefit in terms of other monetary and non-monetary costs, including warehousing costs, capital opportunity costs, etc.

However, while the potential of inventory theory to provide microeconomic explanations of the behavior of shippers has been substantially explored, its potential to explain the structure of transport supply and how it adapts to transport demand has received less interest. This paper shows that there are very interesting issues to address in this field as well.

The problem raised in this study is that of the network structure of road carriers. Road transport can proceed either in direct lines or through break-bulk centers. A theoretical discussion shows that while the first structure limits the resources involved, saving for example the costs of break-bulk platforms, the second benefits from the economies of scale made possible by the consolidation of shipments during pickup and delivery operations. It also shows that direct transport remains competitive for larger shipments, while hub-and-spoke networks are more profitable for the transport of smaller shipments.

We propose an approach based on an inventory theoretic model of joint mode choice and shipment size, to identify the shippers who are likely to use direct transport and those who will opt for hub-and-spokes networks. This approach postulates that expensive commodities exchanged in small amounts will tend to be transported via break-bulk platforms, while less costly commodities exchanged in larger quantities will be transported directly.

This theoretical result is then confirmed empirically using the French shipper survey ECHO. The particularity of this survey is that it observes the commodity flow rate between the shipper and the receiver. With the ECHO survey, it is possible to confirm the theoretical results both qualitatively and econometrically, through the estimation of a mode choice model. The paper demonstrates that observing the logistic context within which freight transport operations take place is essential to understanding the freight transport system.

Directions for future research include the use of more accurate and extensive transport supply data, including travel times. It would also be interesting to extend the simple theoretical model developed in the first part of the study, and to completely specify the market equilibrium determining the freight rates, supply characteristics and market segments for direct line transport and hub-and-spokes networks. Finally, an important research direction involves the introduction of such network structures in comprehensive freight transport demand models.

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