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Freight Market Interactions Simulation (FREMIS): An Agent-Based Modeling Framework

Rinaldo A. Cavalcante[a*] and Matthew J. Roorda[a]

[a]*University of Toronto, 35 St. George Street, Toronto, Ontario, Canada, M5S 1A4*

Abstract

Freight modeling frameworks are frequently based on passenger modeling approaches. Comprehensive and specific freight modeling frameworks are required to improve the evaluation of freight related policies. In this paper, a new agent-based freight modeling framework is presented which is able to incorporate important elements in modern freight markets: agent interactions, product differentiation and economies of scope/scale. These elements are combined in a market dynamic environment assuming agent rationality and that agents acquire information while interacting with each other. The conceptual presentation of this framework is the focus of this paper and the data required for its implementation is also discussed.

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1. Introduction

A market is a place where the exchange of resources, products or services happens between buyers and sellers. Freight transport is the provision of a service and it is an output of the interactions of two markets: a commodity market and a freight market. In a commodity market, producers (vendors) sell commodities/products to receivers (buyers) and receive resources in exchange. After a transaction is established, a list of shipments (commodity flows) is forwarded to a shipper who is responsible for arranging logistics services for them [1].

The focus of this research is on freight markets and they are discussed in the rest of this paper. The input of the freight market is composed of sets of shipments, which can be represented by commodity flow matrices. The transactions in a freight market assign commodity flows to different carriers who use

* Corresponding author. Tel.: +55-85-3265-1262.

E-mail address: racavalcante@gmail.com .

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vehicles to provide the services contracted. The final output is a set of vehicle flows. These vehicle flows can be represented by vehicle flow matrices.

Freight modeling is used to analyze the impact on freight transport of many diverse related measures such as building new infrastructure (e.g. highways, ports, truckway facilities), implementing truck route restrictions and raising or lowering fuel prices. Most current freight modeling frameworks used for planning purposes are still based on passenger approaches [2], even though there are fundamental differences between passenger and freight travel. Some examples of freight modeling using passenger approaches are presented in Cambridge Systematics [2] which basically consist of applications of the commodity-based (four stages) and the truck-based (three stages) approaches.

Since freight transport is the output of two economic markets (commodity market and freight market), freight modeling frameworks should incorporate a modeling approach for these markets, therefore aiming to increase the accuracy of their forecasts and consequently improve the evaluation of freight-related measures in transportation planning.

Freight markets are complex markets with characteristics that violate competitive equilibrium conditions such as product differentiation and economies of scale/scope. Product differentiation exists in a market if consumers assign a diverse value for distinctive products [3] while economies of scope and scale are advantages in cost savings that companies have when providing an additional service or product [4]. Both characteristics exist in freight markets because the selection of a carriers to deliver shipments is based on their level of service [5] (e.g. time reliability), i.e. product differentiation, and the combination of some type of shipments (e.g. backhaul shipments) results in a lower operating cost [6], i.e. economies of scale/scope. Both of these conditions influence the market power of carriers in the market which consequently results in equilibrium prices above the competitive level (see Mas-Colell et al [7] for a discussion about market power and other market failures).

When competitive equilibrium conditions do not hold, two approaches have been used in the economic literature [3,8]: game-theoretical approaches and agent-based approaches. Game-theoretical approaches use the concept of Nash equilibrium. The identification of these equilibrium points in complex markets is a challenging problem and it usually requires the adoption of some simplifying assumptions (e.g. Friesz and Holguín-Veras [9]). On the other hand, agent-based approaches do not require the identification of equilibrium points and they are built from "bottom-up" with a disaggregate representation of agent interactions.

Some agent-approaches have been used to simulate freight markets (e.g. Liedkte [10]; Baindur and Viegas [11]). However, they do not include a representation of all elements included in FREMIS. For instance, Liedtke [10] does not include product differentiation and Baindur and Viegas [11] do not include economies of scope/scale. These two elements (product differentiation and economies of scope/scale) are important in the analysis of the motivations for the size of companies in the market [4].

Based on the above considerations, a freight market interactions simulation framework was developed using an agent-based approach to ultimately improve the accuracy of freight models. This framework is called FREMIS and its formulation is presented in the next section. In the final section of this paper, the implementation of FREMIS is discussed with an analysis of the required information for it.

2. FREMIS Formulation

FREMIS is developed based on the conceptual framework presented in Roorda et al [1] with the incorporation of many other aspects such as: bundling of shipments in a contract, learning approaches for shippers and carriers in the market, carrier pricing models for each contract based on the locations in the shipments (incorporating economies of scope) and competition in the market (incorporating product differentiation). The framework is also flexible and it can incorporate some other aspects such as different carrier pricing strategies (cost-plus pricing, profit-maximizing).

FREMIS is a framework used to implement one of three stages outlined by Roorda et al [1]: the Logistics Services Contract Formation. A detailed representation of FREMIS is presented in Figure 1. Five models are proposed in FREMIS: vehicle/mode choice, shipment outsourcing, bundling of shipments / contract formation, carrier pricing and carrier selection. Model 1 (vehicle/mode choice) is not presented in this paper since there is an extensive literature with this type of model, e.g. Cavalcante and Roorda [12]. Model 2 (outsourcing model) is also not presented in this paper because it is the subject of future research. Therefore, the demand side in this paper is presented assuming that shippers are outsourcing their deliveries and they know the vehicle/mode to be used in each shipment.

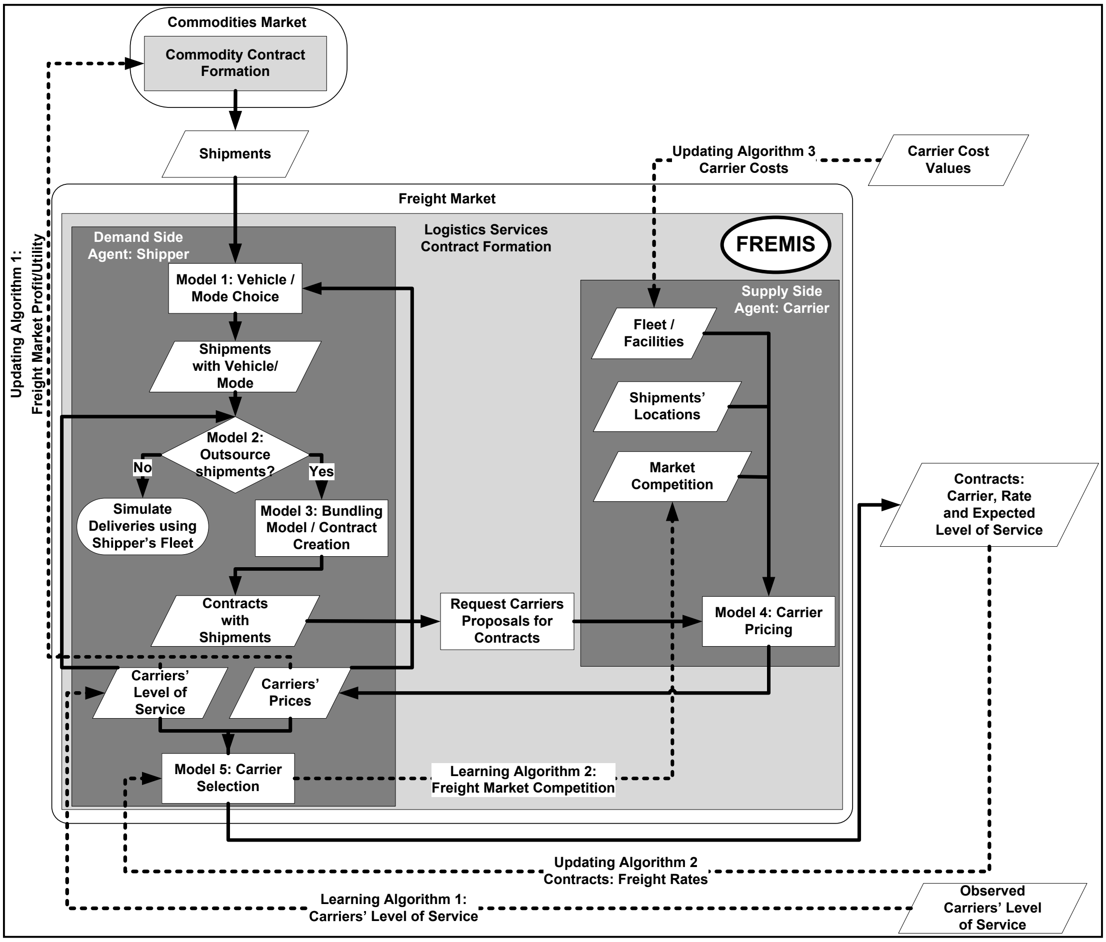

Fig. 1: FREMIS Detailed Framework

2.1. FREMIS: Demand Side

Shippers receive a list of shipments from the Commodities Market to contract logistics services in the freight market. Shippers perform two sequential decisions to maximize their utility level:

- Selection of the shipments in each contract: Shipment Bundling Model.
- Carrier selection for each contract: Carrier Selection Model.

Since economies of scale/scope exist in freight markets, shippers have an incentive to combine diverse shipments in the same contract because it may result in reduced contract costs. There are some types of shipments that have to be combined regularly (e.g. backhaul shipments). For these shipments, the market expected price of the combined contract would often be lower than individual contracts, because the same vehicle can be used in both shipments. In all other situations, the decision depends on the characteristics of the freight market since the market expected price is defined endogenously.

In the FREMIS framework, the proposition is a probabilistic model that relates the concept of dead head distances (distance travelled by freight vehicles without cargo) and distances to locations with large concentration of freight flows (e.g. downtown areas, seaports, airports). The detailed formulation of this model is the subject of a separate on-going research project. The simplified formulation is as follows. If the dead head distance of a combination U of S shipments is DHD_U, the distances between shipment's origin/destination and P freight poles (locations with a concentration of freight flows) in a region is d_{1U}, d_{2U}, ... , d_{PU} and using a multinomial logit specification, then the probability that these S shipments would be bundled using combination U is (μ is a calibration parameter to represent the variance of shippers' behavior and β's are parameters that weight elements in the utility function):

$$P(U) = exp(\mu\beta_1 DHD_U + \mu\Sigma\beta_k d_{kU}) / [exp(\mu\beta_1 DHD_U + \mu\Sigma\beta_k d_{kU}) + \Sigma_{W\neq U}\, exp(\mu\beta_1 DHD_W + \mu\Sigma\beta_k d_{kW})] \quad (1)$$

After shipments are bundled, shippers enter the freight market to select a carrier that would maximize their profit/utility by providing logistics services for each bundle of shipments (a contract). Assuming that shippers' profit/utility in freight markets is a function of each carrier k's level of service in a contract t, represented by LS_{kt}, carrier's current (reputation) and previous (past experience) performance in the market, represented by R_k and E_{ks}, respectively, and price [5], shippers have to obtain information about each carrier k service attributes, represented by a vector of service attributes (e.g. time reliability) for contract t, $\mathbf{X}_{kt}$, and apply a function to estimate carrier k level of service, $LS_{kt} = f(\mathbf{X}_{kt})$. With this information, shipper s selects a carrier k among K_t carriers for each contract t based on the following linear utility function using a multinomial logit model (λ is a calibration parameter to represent the variance of shippers' behavior and β's are parameters that weight the terms of a utility function):

$$V_{sk}(t) = \beta_{LS} LS_{kt} + \beta_R R_k + \beta_E E_{ks} + \beta_p p_{skt} \quad (2)$$

$$P_{sk}(t) = exp(\lambda V_{sk}(t)) / [exp(\lambda V_{sk}(t)) + \Sigma_{j\neq k} exp(\lambda V_{sj}(t)) \quad (3)$$

$$LS_{kt} = f(\mathbf{X}_{kt}) \quad (4)$$

Carriers' level of service is private information and they may use strategic behavior while interacting in the market. For instance, carriers may advertize a high and unrealistic level of service to win some big contracts. The analysis of this strategic behavior is the focus of the economic theory of contracts [13] and their results (e.g. Nash equilibriums) can be used in the validation of FREMIS applications.

A learning algorithm is required to simulate how shippers obtain information of carriers' level of service. Many different agent-learning models exist in economics and psychology literature [14] that can be used in FREMIS. The simplest approach is apparently Q-learning [15], a reinforcement learning approach. Besides that, a formulation is required to associate the values of level of service with reputation and past experience with the shipper. One simple approach is to use the level of service average of each carrier in the market (reputation) and in contracts with the shipper (past experience with the shipper).

2.2. FREMIS: Supply Side

Carriers have resources (vehicles and facilities) and they compete in the freight market by making three decisions: one in the short-run (price proposal in a contract) and two in the medium/long-run (level of service offered in the market and carrier resources). FREMIS current formulation in the supply side only considered carriers' price proposal in contracts (short-run). Other decisions are considered exogenous in this formulation. Two formulations were used to define carriers' price proposal: one for carriers who do not have a contract and another for carriers with at least one contract.

First, we have to assume that each carrier k has v different types of vehicles (e.g. trucks) and each vehicle has a certain operating cost per distance (kilometer or mile) c_v. Second, it is assumed that each carrier k calculate the total distance travelled by each type of their vehicles (d_{tv}) if they operate a contract t of a shipper s. The next step is to define how carriers define their price proposal for a contract. We assumed two limiting approaches: cost-plus pricing (price based only on cost covering) and profit-maximizing (price based on maximizing profit). Carriers' price proposal functions were formulated in two steps. First, expressions for cost-plus pricing and profit-maximization were derived. Then, these expressions were analyzed to identify how to combine them in a single expression. In the end, a parameter α_k ($0 \leq \alpha_k \leq 1$) was used to represent: (1) cost-plus pricing approach: $\alpha_k = 0$; (2) profit-maximizing: $\alpha_k = 1$; (3) intermediate approach: $0 < \alpha_k < 1$. Equations (5) and (6) are carriers' price proposal expressions for carrier without other contracts and with other contracts, respectively.

$$p_{skt} = \Sigma_v c_v d_{tv} \delta_v - \alpha_k \{P_{sk}(t) / [\partial P_{sk}(t) / \partial p_{skt}]\} \tag{5}$$

$$p_{skt} = [\Sigma_v c_v d'_{tv} \delta'_v - \Sigma_v c_v d_{tv} \delta_v] - \alpha_k \{P_{sk}(t) / [\partial P_{sk}(t) / \partial p_{skt}]\} \tag{6}$$

The price proposal for each carrier depends on two values that are endogenous to the market simulation: probability of winning a contract and derivative of this probability with respect to price. Two approaches can be used to estimate these values for each carrier during the simulation. The first approach consists of using Equation (3) for the probability of winning a contract. Adopting this expression and solving the derivatives in Equations (5) and (6), the price proposals for this first approach are presented in Equation (7) and (8). These equations still depend on the values of $V_{sj}(t)$ to permit the estimation of $P_{sk}(t)$. A Q-learning approach [15] can be used to estimate this value in the market.

$$p_{skt} = \Sigma_v c_v d_{tv} \delta_v - \alpha_k \{1 / [\beta_p (1 - P_{sk}(t))]\} \tag{7}$$

$$p_{skt} = [\Sigma_v c_v d'_{tv} \delta'_v - \Sigma_v c_v d_{tv} \delta_v] - \alpha_k \{1 / [\beta_p (1 - P_{sk}(t))]\} \tag{8}$$

The second approach consist of using a Q-learning approach to estimate $P_{sk}(t)$ and a secant approach to build a function relating $P_{sk}(t)$ and p_{skt}. The value of p_{skt} should be derived based on the value of the freight rate, r (in \$/km/kg) to permit the identification of a pricing policy faster in the simulation process. To find the values of $P_{sk}(t)$ and the function with p_{skt}, the carrier should start with a cost-plus pricing approach: $p_{skt} = \Sigma_v c_v d_{tv} \delta_v$. With this approach and the results of multiple requests for proposals (e.g. in auctions), carriers can adjust their pricing policy based on the estimated probability of winning a contract given a price.

3. FREMIS Implementation

FREMIS can be applied in any freight market, but its main contribution is expected to be on applications for urban freight markets, since they are usually not in a stable equilibrium [9] and agent-based modeling can better represent their market dynamics. Besides the characteristics of the transportation network, more information is necessary to permit FREMIS application in a freight modeling study.

First, some revealed or stated data from the region of study should be obtained to estimate models on the demand side: shipment bundling model (Equation (1)) and carrier selection model (Equations (2) to (4). A shipment bundling model estimated using local data would permit the identification of the impact of local freight poles in the process of bundling shipments. Likewise, a carrier selection model estimated using local data would incorporate local weights for the importance of carriers' level of service. Stated preference data may be a good alternative for data collection.

Second, cost parameters should also be obtained to represent the behavior of the supply side in FREMIS. Some publications provide information about trucking cost parameters such as the "Operating Costs of Trucks in Canada" published annually by Transport Canada.

Third, carrier level of service and the values of its attributes should be analyzed in the region of study. As a consequence, a survey should be implemented to collect the values of carrier attributes (e.g. travel time reliability) in the region and to find the relationship between these attributes and transportation network characteristics (e.g. travel time variability). Identification of this relationship will permit the evaluation of the impact of changes in the transportation network using FREMIS outputs.

Fourth, information about the characteristics of shippers and carriers in the region has to be obtained. This information is mainly the number of shippers and carriers, number of vehicles by type, and resources owned by the companies (warehouses, distribution centers). Number of shippers and carriers can be obtained from institutions that merchandise company lists (e.g. InfoCanada or InfoUSA) and number of vehicles can be inferred from surveys such as the Canadian Vehicle Survey conducted by Statistics Canada or the US Motor Carrier Financial and Operating Statistics.

4. Conclusion

This paper represents a contribution to a subject that is still in its early stages of knowledge. Current freight modeling approaches are not able to represent the complexities of actual freight markets. Since the characteristics of freight markets directly influence vehicle flows, current freight modeling approaches may not be able to accurately predict the impacts of transportation policies in freight movements. To improve this situation, a new framework is presented in this paper.

The proposed framework, FREMIS, permits the simulation of freight markets using agent-based approaches. These approaches do not require any assumption of equilibrium [16]. As a consequence, they permit the analysis of the conditions upon which complex economic markets (e.g. freight markets) converge or not to one or more equilibrium points [8]. Another contribution of this framework is that current agent-approaches for freight markets do not explicitly consider agent interactions. Hence, many common situations in a freight market (e.g. competition, failure of companies) cannot be represented using these approaches. The framework proposed in this paper can represent the competition between carriers in the freight market. Since carriers' behavior is developed using profit functions, the framework can also simulate the failure or establishment of new carriers in the market (firmography processes).

Since FREMIS is a framework for the simulation of freight markets, it can be used in many different situations by different users. The main expected application of FREMIS is the evaluation of public policies which directly impact a freight market. For instance, the construction or expansion of freight infrastructure (e.g. seaport) may generate many diverse externalities (positive and negative) in the local freight market, and an agent-based freight market simulation framework would permit a representation of the behavior of freight agents in the face of the new policy. Other possible applications of FREMIS include market simulations to assist freight agents (shippers and carriers) in their strategic decision process to define, for instance, location of facilities (plants, distribution centers, warehouses).

One of the main obstacles in the development of a feasible framework for an agent-based simulation of a freight market is the availability of data. FREMIS was developed using data from an interactive stated preference questionnaire which created realistic representations of freight market scenarios. This questionnaire was implemented in a web survey conducted recently with company managers (shippers and carriers) in the Greater Toronto Area and Hamilton, see Cavalcante and Roorda [17]. Pilot tests were conducted during the design of this web survey to identify the most viable data collection framework for estimating parameters in Equations (1) to (4) for FREMIS implementation in a freight market.

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