

# A framework to understand the impacts of logistics trends and cost variations on commodity based urban truck flows

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## 1 Introduction

Despite the critical role played by freight transportation in economic development and most economic activities, freight transportation modelling is not yet a mature field. Undoubtedly, freight transportation traffic and demand models have received far less attention than passenger models. This underdevelopment has been widely recognized (Mahmassani, 2001, Regan and Garrido, 2001). The accelerated pace of change in logistics practices with the advent of the information and communication technology (ICT) revolution has not improved the status quo.

An array of noteworthy developments in logistics practice has taken place without an equivalent and comprehensive development in freight transportation modelling. A short list of such logistics developments includes EDI<sup>1</sup>, bar coding and more recently RFID, JIT, VMI<sup>2</sup>, cross docking, containerization, and electronic commerce. Despite the growing interest in considering and incorporating technological and behavioural elements into the freight transportation planning processes, the goal remains elusive (Golob and Regan, 2001). The decision processes governing freight distribution and traffic are not yet well understood.

This research proposes that part of the problem is the lack of deep understanding of the workings of distribution processes in relation to the generation of truck traffic. It is widely accepted that the demand for freight transportation is a derived demand. This research accepts this assumption. However, in this paper it is emphasized the role and importance that distribution network size, technology, and congestion have on the truck traffic flows that “materialize” supply chain flows over the public infrastructure.

This research focuses on one type of distribution structure: a distribution centre that provides one commodity to several retailers or customers (one to many). Within this basic distribution structure the number of retailers/customers in a given route can increase or decrease due to economical or technological factors. The factors discussed in this paper include: ownership (independent retailers vs. central inventory control), technology (order policy with and without VMI, ASN, and RFID technologies), second order technological effects, congestion, and toll effects. It is assumed throughout the paper that the joint minimization of distribution and inventory costs is the main behavioural driver. Other behavioural drivers are discussed in a companion paper (Figliozzi, 2005b).

The paper is organized as follows: section 2 reviews literature related to the impact of logistics trend and technological changes in the industry. Section 3 defines terminology and notation used in the paper. Section 4 studies how truck flows are affected by changes in the distribution system. Section 5 discusses some implications of the results obtained in section 4. The paper ends with conclusions in section 6.

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<sup>1</sup> EDI: Electronic Data Interchange

<sup>2</sup> RFID: Radio Frequency Identification, JIT: Just-in-Time (production system), VMI: Vendor Managed Inventory

## **2 Literature Review: Technological Advances, Logistics Trends, and Truck Flows**

The changes and trends in shipper-carrier procurement strategies have received a great deal of attention in the transportation and logistics academic literature, mostly through published survey results. For example Crum and Allen (1991) report how Just In Time (JIT) inventory and production systems and economic deregulation have impacted carrier-shipper relations. These authors use survey data to demonstrate trends indicating a reduction in the number of motor carriers utilized by individual shippers and a move towards long term contracting. A slightly different trend is reported by Lieb and Randall (1996). These authors report a trend, mainly among big companies, towards outsourcing transportation and logistics responsibilities to 3PLs. Crum and Allen (1997), after comparing survey data taken in 1990 and 1996, conclude that the trend in carrier-shipper relationships continues to move away from a transactional framework to a relational one (from a cost based procurement to a collaboration based procurement)

Technology has also spurred changes and transformation of transportation-logistics procurement structures. Shortly after deregulation legislation was passed in the USA, Electronic Data Interchange (EDI) began to be available. Williams (1994) studies and reports how EDI facilitates and fosters a seamless integration between a shipper and group of core carriers. Golob and Regan (2002) studied how carriers adopting information technology tools and Ng et al. studies (1995) the type of information that carriers and drivers would like to receive from traveller information services. A survey study about the adoption and usage of Internet procurement tools by shippers was conducted by Lin et al. (2002). That survey indicated that 60% of the shippers use the internet to procure transportation services (phone usage was tallied at 90%). Load matching and transportation auctions were used by 15% of the shippers that used some transportation online service (2001 data).

The references mentioned thus far provide insight into trends or changes in supply chain relationships, technology adoption, or procurement strategies. Unfortunately, they are not very useful from the freight modeller point of view since they provide little insight into how the knowledge acquired in the surveys can be translated into parameters of freight or urban transportation models. A more practical approach is being adopted by the relatively novel field of "city logistics". Focusing in urban environments, city logistics aims at optimizing logistics operations in an urban environment taking into account benefits and costs for all stakeholders: shippers, freight operators, urban residents, and the governmental agencies. Taniguchi et al. (2003) present a current review of the field and review approaches that combine both optimization and simulation to predict the effect of policy measures. Hensher and Puckett (2004) present a general framework to study how supply agents interact using stated choice experiments, with a focus on collaboration or partnership formation as a tool to reduce traffic congestion.

A higher emphasis on distribution details and costs is presented by the work of Nemoto (1997), who presents a detailed traffic and cost analysis of a freight consolidation scheme aimed at reducing the negative impact of a high number of frequent and small sized shipments in the city of Fukuoka, Japan. Moinzadeh et al. (1997) presents an analysis of how congestion created by small order sizes can negatively impact delivery times and inventory levels. The relation between lot sizes and traffic congestion on a common access road is studied by using an inventory-queuing model. More recently Sankaran et al. (2004) performed a case study between congestion levels and replenishment order sizes in Auckland, New Zealand. These authors report that in the city of Auckland even as congestion level raise, quantity orders decrease. This phenomenon has not taken place across the board. A company did experience during the same period a reduction in delivery frequency and larger order sizes.

Another stream of research comes from the industrial/production engineering literature. Given that transportation can account for up to 50% of total logistics costs, different methods

have been proposed to reduce logistics costs taking advantage of transportation price structures. This literature modifies the original economic order quantity (EOQ) model to incorporate different transportation pricing methods. Pricing may profoundly affect order size since quantity discounts in the case of less-than-truck-load (LTL) and the integer number of carloads/truckloads in the case of truck-loads (TL) affect delivery cost per unit (Lee, 1986). A further generalization of Lee's model is studied by Swenseth and Godfrey (2002), where both vendor (warehouse) and buyer (retailer) are subject to a replenishment cost structure that includes a fixed cost plus a stepwise component. However, there is no incorporation of transportation costs as a function of route characteristics or routing constraints.

To the best of the author's knowledge, there is no research work or analytical model that incorporates routing costs and constraints into the EOQ analysis. This research focuses on the distribution of a commodity. The concept of commercial activity routing types that characterize the interplay between transportation demand requests and routing characteristics is further developed by Figliozzi (2005b). The impacts of congestion and travel time variability are further analysed in (Figliozzi, 2005a) and (Figliozzi, 2005c) respectively.

### **3 Modelling Framework, Assumptions, and Notation**

This paper focuses on one type of distribution structure: a distribution centre that provides to several retailers. Within this basic distribution structure the number of retailers in a given route can increase or decrease due to economical or technological reasons. This configuration has been chosen because recent studies in urban areas in the United States have shown that deliveries from distribution centers (DC) or warehouses have one of the largest impacts on vehicle miles travelled (VMT) in urban areas (Outwater et al., 2005). The one to many model is not only ubiquitous but also represents distribution activities of hypermarkets, distribution centres, and producers while keeping analytical complexity at a tractable level.

Since carriers' operational aspects and behaviour have been mostly neglected in the freight modelling literature, this work emphasizes the role and importance of routing. Therefore, cost, capacity, and time elements that condition and constrain carriers' routing decisions are explicitly incorporated in the model. It is assumed that retailers, or the distributor, define order size and frequency (the demand for freight transportation is a derived demand). Accordingly, routes are delineated in order to satisfy these freight transport requests. The importance of routes and vehicle routing decisions stems from the fact that the assignment of trucks to the public network is ultimately determined by a carrier's solution to his or her vehicle routing problem. Routing is understood as the process that carriers use to "materialize" supply chain flows over the public infrastructure. The movement of a truck over a network generates the traffic flow associated with that truck in that network. Therefore, truck flows are the materialization needed to satisfy the spatial dimension of customer requests in a supply chain.

Given one vehicle and a set of customers, the routing problem where one vehicle must visit each and every customer exactly once is denoted the travelling salesman problem (TSP). This problem is notoriously difficult to solve optimally, i.e. to find the best sequence to visit customers in order to minimize costs. However, if only the total distance travelled is needed (not the sequence information), fairly good approximations can be obtained with a simple formula.

Assuming that a set  $R = \{req_1, req_2, \dots, req_n\}$  of requests is randomly and independently dispersed over an area  $A$  and denoting the optimum travelling salesman tour length as  $L(R, A)$ , this limit holds (Bearwood et al., 1959):

$$\lim_{|R| \rightarrow \infty} \frac{E[L(R,A)]}{\sqrt{A}} = k\sqrt{A}$$

For reasonably compact and convex area, the limit converges rapidly. The following approximation formula is proposed by Larson and Odoni (1981) with  $k \approx 0.765$  and  $n = |R|$ :

$$E[L(R, A)] \approx k\sqrt{nA} \quad (1)$$

This formula requires a Euclidean travel metric or  $L_1$  metric. Jaillet (1988) estimated the constant  $k \approx 0.97$  for Manhattan travel metric or  $L_2$  metric. As long as feasibility is satisfied, economies of density are achieved because distance grows slower than the number of customer requests served. More constrained problems have equal or larger solution costs as shown by Haimovich and Kan (1985) for the capacitated vehicle routing. Simulations performed by Chien (1992) show that expression (1) is a robust and accurate approximation to the length of a TSP.

Without feasibility constraints, the cost of routing customer requests as expressed in expression (1) is sub-additive. This is reasonable because, all things being equal and without feasibility constraints, routing cost per customer tend to decrease on average as more customers can be included in a given route and area. Expression (1) is used in this research as a continuous approximation of the length of TSP tours in order to analytically determine how technological changes and trade-offs between transport and inventory costs affect the demand for transport. A similar modelling approach has been used to solve and gain insight into numerous logistics problems, a detailed compilation of such models is presented by Daganzo (1991).

Summarizing, the following assumptions are made in this paper:

- The cost formulation is for a generic multi-stop tour, delivering shipments from a single distribution centre to several retailers/customers;
- Route distance is approximated with a routing cost expression similar to (1);
- A single product (commodity) is distributed;
- Delivery or service areas are fixed;
- Route and delivery/service frequency  $f$  is determined by the type of commodity or activity;
- The distributor/service centre owns/operates the fleet (private carrier);
- A cluster first, route second method is used to divide distribution/service centre influence area  $A$  into  $m$  delivery regions  $\{A_1, \dots, A_m\}$  where  $A = (A_1 \cup A_2 \cup \dots \cup A_m)$  -- the delivery regions similar size and customer density;
- The number of retailers/customers in a given route can increase or decrease due to economical or technological factors;
- The joint minimization of distribution and inventory costs is the main behavioural driver;
- Customers/retailers are identical; and
- Truck deliveries are randomly scattered over the delivery region served.

### 3.1 Notation

$A$  = Area of a generic area  $A \in \mathcal{A}$  that has a set of costumers  $R$  and a delivery route with  $n = |R|$  stops, each customer has a demand  $d$  and an order size  $q$ .

$$\sum_n d_i = D \text{ and } \sum_n q_i = Q$$

$m$  = Number of areas.

$f$  = delivery/service frequency for area  $A$  .

$r$  = Line-haul distance from the distribution centre to  $A$  or the vicinity of the stops.

$$\bar{r} = \frac{\sum r_m}{m} = \text{Average line-haul.}$$

$V = \{v_1, v_2, \dots, v_L\}$  = Ordered set of possible vehicle sizes

$\chi(v_l)$  = Truck capacity for type  $v_l$ , with  $\chi(v_k) < \chi(v_l)$  for any  $v_k < v_l$

$s(v_l) = s$  = Average truck speed for any type of truck  $v_l$

$\tau$  = Time available for truck operations (i.e. driver maximum working hours per day minus lunch or mandatory breaks)

$t_l$  = Time to load a unit of product into the truck

$t_u$  = Time to unload a unit of product from the truck

Loading/unloading times are highly dependent on the loading/unloading equipment used (manual, forklift, conveyor, etc) and the distance to/from the truck to the receiving area

$t_{or}$  = Fixed time needed for order receiving when stopping at the retailers (this time includes order receiving, order checking/inspection, paperwork and documentation, etc)

$c_d^d(v_l)$  = Cost/distance when using truck type  $v_l$ , this cost includes variable costs like fuel, maintenance or tires, with  $c_d^d(v_k) < c_d^d(v_l)$  for any  $v_k < v_l$

$c_t^d$  = Cost/time on the route, this time includes driver's time cost mostly. Inventory in transit cost is not considered due to the short journeys of urban deliveries

$c_o^d$  = Distributor order preparation cost, this cost includes preparation of route and shipping documents, notify driver, etc.

$c_{ol}^d$  = Distributor loading cost per unit of cargo, this cost includes packing and loading truck costs during time  $t_l$  .

$c_u^d$  = Product unit cost for the distributor

$c_f^r$  = Freight cost per order/stop, paid by the retailer (transportation cost only)

$c_{fu}^r$  = Freight cost per unit of product delivered, paid by the retailer (transportation cost only)

$c_o^r$  = Fixed cost per order placed paid by the retailer, this cost includes employee time for clerical and administrative tasks plus the cost of order submission (phone, fax, EDI, email, etc).

$c_{ou}^r$  = Cost per unloading, handling, and storing each unit of product during time  $t_u$  .

$c_{or}^r$  = Fixed cost per order receiving which includes employee time ( $t_{or}$ ) per order receiving, checking/inspection, paperwork and documentation

$c_u^r$  = Product unit cost for the retailer

$h = h_i^r = h^d$  = Inventory holding costs at retailer  $i$  or central distributor

The superscripts  $r$  and  $d$  are used to denote costs incurred by the retailer or the distributor respectively.

## Basic Relationships

$T = M f =$  Total number of trips per unit time.

$f = \frac{d}{q} =$  Frequency for commodity based cases (frequency is given externally for services).

Using equation (1), the distance per route per unit time is the following:

$$z = \frac{d}{q} 2r + \frac{d}{q} k \sqrt{nA} = \text{total distance per unit time area } A \in A.$$

$$Z = \sum_m z_m = \frac{md}{q} 2\bar{r} + \frac{md}{q} k \sqrt{nA} = \text{total system distance.}$$

The distance per unit of time per retailer is equal to:

$$\frac{Z}{mn} = \frac{md}{mnq} 2\bar{r} + \frac{md}{mnq} k \sqrt{nA} = \frac{d}{nq} 2\bar{r} + \frac{d}{q} k \sqrt{\frac{A}{n}} \quad (2)$$

This is a measure of the efficiency of the distribution system. As the number of customers per route  $n$  increases, the distance per unit of time per customer decreases (economies of scope). As the order size  $q$  increases the distance per unit time per customer decreases (economies of scale). Therefore, as  $n$  and  $q$  increase the negative impact of the distribution centre on urban traffic *decreases ceteris paribus*. Conversely, as  $n$  and  $q$  decrease the negative impact of the distribution centre on urban traffic *increases ceteris paribus*.

As mentioned in the previous section, a route can be constrained or unconstrained. In the latter case, typical constraints present in urban operations are capacity and route length constraints. Using previous notation these constraints can be expressed as:

$$\sum_n q_i = Q \leq c(v_l) \quad (3)$$

$$\frac{1}{s} (2r + k \sqrt{nA}) + nt_{or} + t_u Q \leq \tau \quad (4)$$

Total costs per full truck type  $v_l$ , per route, for the  $n$  customers in the area  $A$  can be expressed as  $C_d(v_l, \chi(v_l))$  or simply as  $C_d(v_l)$ :

$$C_d(v_l) = c_d^d(v_l) (2r + k \sqrt{nA}) + c_i^d \left( \frac{1}{s} (2r + k \sqrt{nA}) + nt_{or} + t_u \chi(v_l) \right) \quad (5)$$

Expression (5) includes all distributors' costs since the truck is loaded and leaves the DC fully loaded until it comes back empty after serving  $n$  customers. For a variable cargo size  $Q < \chi(v_l)$ , per route, for the  $n$  customers in the area  $A$  is:

$$C_d(v_l, Q) = [c_d^d(v_l) (2r + k \sqrt{nA}) + c_i^d \left( \frac{1}{s} (2r + k \sqrt{nA}) + nt_{or} + t_u Q \right)] \quad (6)$$

The cost per stop or customer is:

$$\begin{aligned} \frac{1}{n} C_d(v_l, Q) &= [c_d^d(v_l) \left( \frac{2r}{n} + k\sqrt{\frac{A}{n}} \right) + c_i^d \left( \frac{1}{s} \left( \frac{2r}{n} + k\sqrt{\frac{A}{n}} \right) + t_{or} + t_u q \right)] \\ &= \frac{1}{n} C_d(v_l) + c_i^d t_u (q - \chi(v_l) / n) \end{aligned} \quad (7)$$

$$\approx \frac{1}{n} C_d(v_l) \quad (7')$$

The expressions (7) and (7') are identical for a full truck load, which is a good approximation for high load factors. The only term in (7) that depends on the order size is that which relates to unloading costs. The cost per unit per customer also shows economies of scale (7''). Hence, if constraint (3) is satisfied, economies of scale can be achieved in expression (7'') for all three terms: distance, time, and order costs.

$$\frac{1}{qn} C_d(v_l, Q) = \frac{1}{q} [c_d^d(v_l) \left( \frac{2r}{n} + k\sqrt{\frac{A}{n}} \right) + c_i^d \left( \frac{1}{s} \left( \frac{2r}{n} + k\sqrt{\frac{A}{n}} \right) + t_{or} + t_u q \right)] \quad (7'')$$

#### 4 Distribution System Performance

This section studies how changes in technology and congestion may affect the efficiency of truck flows. The study is undergone comparing six different scenarios: a) independent retailers, b) central inventory control, c) Order policy with VMI, ASN, and RFID technologies d) second order technological effects, e) congestion, and f) toll effects.

##### a. Independent Retailers

In this scenario, each retailer and the distributor are different profit maximizing agents. Retailers order quantity and frequency is set to minimize their purchase, inventory holding, and ordering costs. Two different sub-scenarios are going to be analysed: a.1) constant transport costs, and a.2.) variable transports costs.

##### a.1 Constant transport costs

The costs incurred by retailer  $i$  per unit time can be expressed as the sum of purchase, holding, and ordering costs:

$$C_i^{a1} = c_u^r d_i + \frac{q_i c_u^r h}{2} + \frac{d_i}{q_i} (c_o^r + c_f^r + c_{or}^r) + c_{ou}^r d_i$$

Then, the order size  $q_i$  that minimizes retailer costs is determined by the classic EOQ formula:

$$q_i^2 = \frac{2d_i(c_o^r + c_f^r + c_{or}^r)}{\beta h c_u^d} = \frac{2d_i(c_o^r + C_d(v_l) / n + c_{or}^r)}{\beta h c_u^d}$$

It is assumed that freight cost charged by the distributor can be approximated by:

$$c_f^r = \frac{C_d(v_l)}{n}$$

If  $\beta$  is the cost mark-up from distributor to retailer (which must cover at least distributor's costs), then retailer's cost per unit is:

$$c_u^r = \beta c_u^d$$

Assuming that all retailers face the same demand rate  $d_i = D/n$ , then:

$$q_i^2 = \frac{2D/n(c_o^r + C_d(v_l)/n + c_{or}^r)}{\beta h c_u^d} = \frac{2D(c_o^r + C_d(v_l)/n + c_{or}^r)}{n\beta h c_u^d}$$

Taking the square root on both sides and multiplying by  $n$ :

$$Q^{a1} = nq_i = n\sqrt{\frac{2D(c_o^r + C_d(v_l)/n + c_{or}^r)}{n\beta h c_u^d}} = \sqrt{N} \sqrt{\frac{2D}{\beta h c_u^d}} \sqrt{(c_o^r + C_d(v_l)/n + c_{or}^r)}$$

$$Q^{a1} = \sqrt{\frac{2D}{\beta h c_u^d}} \sqrt{(n(c_o^r + c_{or}^r) + C_d(v_l))} \quad (8)$$

The optimal order size is denoted  $Q^{a.1}$  in case a.1. Truck flows decrease as the order size increases. Higher truck flows are expected for expensive products or when distribution and ordering costs are relatively inexpensive.

## a.2) variable transport costs

If the distributor charges a cost per unit delivered to the retailer, freight cost per unit charged by the distributor can be approximated using:

$$c_{fu}^r(q) = \frac{C_d(v_l)}{\mu c(v_l)n} \quad n/c_l(v_l) \leq \mu \leq 1$$

where  $\mu$  is the truck loading factor employed by the distributor to approximate per unit delivery costs. With this assumption, the costs incurred by retailer  $i$  per unit time can be expressed as:

$$C_i^{a2} = c_u^r d_i + \frac{q_i c_u^r h}{2} + \frac{d_i}{q_i} (c_o^r + c_{or}^r) + c_{ou}^r d_i + d_i c_{fu}^r$$

The optimal order size,  $Q^{a.2}$ , in case a.2 is

$$Q^{a2} = \sqrt{\frac{2D}{\beta h c_u^d}} \sqrt{n(c_o^r + c_{or}^r)} \quad (9)$$

Changing the way transportation is paid profoundly affects order size. When delivery cost per unit is constant (no economies of scale) order size decreases. With small order costs,  $(c_o^r + c_{ou}^r)$ , the order size per retailer can be one; which completely minimizes cycle inventory costs. In general, truck flows increase by a factor:

$$\frac{Q^{a1}}{Q^{a2}} = \min\left\{\sqrt{\frac{n(c_o^r + c_{or}^r) + C_d(v_l)}{n(c_o^r + c_{or}^r)}}, \frac{Q^{a1}}{n}\right\} \quad (10)$$

If retailers are charged a fixed cost per delivery plus an amount that depends on the order quantity, the fixed cost per delivery is included as in expression (8).

### **b. Two echelon inventory control under VMI**

This case analyses the influence of setting the ordering policy taking into account the distributor and retailer echelons simultaneously. If the distributor owns the retailers, the distributor tries to minimize total system distribution and inventory holding costs. Furthermore, under VMI policies the distributor or manufacturer is responsible for inventory decisions at the retailer level, therefore retailer ordering costs are eliminated. System costs can be expressed as:

$$\frac{D}{Q} [c_d^d(v_l)(2r_0 + k\sqrt{nA}) + c_i^d (\frac{1}{s(v_l)}(2r_0 + k\sqrt{nA}) + nt_o + t_u Q) + c_o^d + c_{or}^r] + \frac{c_u^d h Q}{2} \alpha + D(c_{ol}^d + c_{ou}^r)$$

In this case  $1 \leq \alpha$  is a coefficient that accounts for the inventory held at the distributor due to the lack of coordination between inbound/outbound shipments that are arriving (leaving) to (from) the distribution centre. With perfect coordination (efficient cross-docking for example) the value of  $\alpha = 1$ . However, for other settings such as: a) the distributor holds inventory (e.g. inbound order size higher than outbound sizes), b) inbound/outbound schedules are uncoordinated, or c) inventory hold at the factory, a value of  $\alpha \geq 2$  is possible as indicated by Burns et al. (1985). The order quantity that minimizes systems costs is:

$$(Q^b)^2 = \frac{2D}{\alpha c_u^d h} [c_d^d(2r_0 + k\sqrt{nA}) + c_i^d (\frac{1}{s(v_l)}(2r_0 + k\sqrt{nA}) + nt_o) + c_o^d + c_{or}^r]$$

The term in brackets is similar to the route cost given in (7) but with the exclusion of unloading time costs: given by  $c_i^d t_u Q$ .

$$Q^b = \sqrt{\frac{2D}{\alpha c_u^d h} [C_d(v_l) - c_i^d t_u c_l(v_l) + c_o^d + c_{or}^r]} = \sqrt{\frac{2D}{\alpha c_u^d h}} \sqrt{C_d(v_l) - c_i^d t_u c_l(v_l) + c_o^d + c_{or}^r}$$

Then, the relationship between the two order sizes is:

$$\frac{Q^{1,a}}{Q^b} = \sqrt{\frac{n(c_o^r + c_{or}^r) + C_d(v_l)}{c_o^d + c_{or}^r + C_d(v_l) - c_i^d t_u c_l(v_l)}} \sqrt{\frac{\alpha}{\beta}} \quad (10)$$

The first term in (10) is always larger than one as long as:

$$(n-1)(c_o^r + c_{or}^r) + c_i^d t_u c_l(v_l) > (c_o^d - c_o^r)$$

which is easily satisfied for 2 or more retailers since order preparation costs are usually of the same order of magnitude  $c_o^d \approx c_o^r$ .

The second term in (10) depends on the ratio  $\alpha/\beta$ . For values of  $\alpha \geq 2$  and small mark-ups the increase in truck traffic is  $\approx 41\%$ . This is a typical case where optimizing the system distribution costs, by means of including all relevant cycle inventory, can significantly increase the number of truck trips.

### **c. Ordering with VMI, EDI, ASN, and RFID**

Up to this point changes that can be brought about by technology have been ignored. Information and communication technologies (ICT) have a major impact on processes or transactions that can be sped up or performed automatically. Tasks that mostly require data manipulations, verification, or updating are the tasks in a position to greatly benefit from ICT advances. In these kinds of tasks, denoted *data oriented*, human processing can be eliminated or greatly reduced thus dramatically lowering execution times. On the other hand, for tasks that mostly depend on physical manipulation of the cargo or products, the benefits of ICT are obtained indirectly through better system coordination or incremental improvements in handling processing techniques or equipment. The latter kind of tasks are denoted as *physical tasks*.

Using EDI or a web based system a retailer can place an electronic order directly into the distributor's system. The distributor's system electronically confirms the order and transmits information about the order to the distributor's shipping and accounting departments as well as to the carrier. The carrier's system electronically confirms the pickup and provides the distributor and retailer with pickup and delivery information respectively (information includes date, time, and other details of the upcoming pickup/delivery). Close to pickup/delivery time an updated ASN is placed and the shipping/receiving departments can prepare to ship/receive the order (assign docking area, equipment, personnel, etc.). All these information processing and transmission tasks can be achieved without any significant human intervention. When the carrier arrives, using RFID (or at least scanning) the order received is matched against the purchase order and invoice reference, thus saving inspection and document processing time. Once the system is in place and working the marginal costs of order processing can become negligible.

The data oriented costs can be significantly reduced using VMI, EDI, ASN, and RFID are:  $c_o^d$  (distributor order preparation cost),  $c_o^r$  (retailer ordering cost),  $c_{or}^r$  (retailer order receiving cost). If these costs are assumed negligible, the expression for the optimal order size in case c) is reduced to:

$$Q^c = \sqrt{\frac{2D}{\alpha c_u^d h}} \sqrt{C_d(v_l) - c_t^d t_u c_l(v_l)} \quad (11)$$

The order size is smaller than the previous size orders  $Q^a$  and  $Q^b$ ; therefore truck traffic flows will increase when ordering/receiving tasks are performed automatically.

#### **d. Second order technological effects**

The technological improvement described in part c. will not only bring cost reductions but also important savings in time. The fixed time for order receiving,  $t_{or}$ , can be significantly reduced with ASN and RFID technologies. In urban deliveries this is an important item since the number of stops can easily be in the dozens ( $n > 25$ ). The vehicle routing literature report that  $n \geq 25$  is the median in a number of daily delivery services such as dairy products, food products, drinks, and supermarket replenishments (Golden et al., 2001). In order to get a sense of the savings, 5' savings per stop in a route with 25 customers represent 26% of an 8 hours driver working day.

For the sake of simplicity, it will be assumed that the fixed time due to order receiving can be eliminated. Then, expression (11) becomes:

$$Q^{d1} = \sqrt{\frac{2D}{\alpha c_u^d h}} \sqrt{C_d(v_l) - c_t^d t_u c_l(v_l) - c_t^d n t_{or}} \quad (12)$$

Reducing delivery times reduces delivery costs; which in turn results in smaller order sizes and more truck traffic. Technological improvements (VMI, EDI, ASN, and RFID) have led to a simultaneous reduction in order size, costs, and route time length. However, neither the fleet size, nor truck type, nor route, nor customers have changed.

Ex-ante (before introducing technological improvements), a rational distributor/carrier has chosen the truck type that minimizes costs with order size  $Q^a$  or  $Q^b$ . Ex-post (after introducing technological improvements), a rational distributor/carrier will reconsider routes and truck sizes. Since the cost of routing additional customer requests is sub-additive, for any given truck size, costs are minimized while including as many customers as possible per route. Hence, for any truck type, the carrier will add as many customers per route as possible until either constraint (5) or (6) is binding. Two situations may arise: 1) the original route was bounded by the capacity constraint (5), or 2) the original route was bounded by route time length constraint (6).

#### **d.1) capacity constraint**

If the original route was initially bounded by capacity constraints, after the introduction of technological improvements the capacity constraint is no longer binding. The carrier has two distinct options:

- Leave the routes intact and decrease the truck size of the fleet until a constraint is binding again; since  $c_d^d(v_k) < c_d^d(v_l)$  for any  $v_k < v_l$ , smaller trucks will decrease operational costs and transportation cost per customer
- Leave the original trucks but increase the number of customers served per route (if possible) until a constraint is binding again; due to its sub-additive property transportation costs per customer are going to decrease if more customers are added to the route.

In either case the decrease in transportation costs will lead to a decrease of order sizes and to a new constraint relaxation and so on. Ultimately, the spiral down effect will be limited by available truck sizes,  $Q \geq n$ , or constant cost elements such as  $r$ .

The maximum number of extra customers  $x^* = \min(x_T^*, x_Q^*)$  that *can be added* to the route is determined by:

$$x_Q^* \in \arg \max_{x \in \mathbb{N}} Q^d (1 + x/n) \leq \chi(v_l)$$

$$x_T^* \in \arg \max_{x \in \mathbb{N}} \frac{1}{s} (2r + k\sqrt{(n+x)A(1+x/n)} + t_u Q^d (1 + x/n)) \leq \tau$$

#### **d.2) route time length constraint**

If the original route was originally bounded by time length, after the introduction of technological improvements the length constraint is no longer binding. In this case, the carrier can serve more customers along the route until the constraint is binding as analysed in point d.1.

#### **e. Congestion effects**

If congestion in the area  $A$  increases, average delivery speed will decrease. Congestion will not only increase routing costs but also possibly violate route time length constraints. If the congested speed is  $s^e < s$  the first order effect of congestion is to increase delivery costs by an amount:

$$c_t^d \left( \frac{1}{s^e} - \frac{1}{s} \right) (2r + k\sqrt{nA})$$

The new order size will be higher than in case d), which will decrease truck traffic flows:

$$Q^e = \sqrt{\frac{2D}{\alpha c_u^d h}} \sqrt{C_d(v_l) - c_t^d t_u c_l(v_l) - c_t^d n t_{or} + c_t^d \left( \frac{1}{s^e} - \frac{1}{s} \right) (2r + k\sqrt{nA})} \quad (13)$$

If either route length or capacity constraints are now violated two options are possible:

- If the route length constraint is violated the number of customers per route must be decreased until constraints are satisfied again. Decreasing the number of customers per route will increase delivery costs, which will in turn increase order size even further (second order effect).
- If the capacity constraint is violated, a larger truck can be used. However, a larger truck will increase operating costs. However, for a constant demand delivery frequency will decrease.

In the first case, the increase in transit time will lead shorter routes. The number of extra customers  $x^* = \max(x_T^*, x_Q^*)$  that must be *taken out* of the route to obtain feasibility is determined by:

$$x_Q^* \in \arg \max_{x \in \mathbb{N}} Q^d (1 - x/n) \leq \chi(v_l)$$

and

$$x_T^* \in \arg \max_{x \in \mathbb{N}} \frac{1}{s^e} (2r + k\sqrt{(n-x)A(1-x/n)}) + t_u Q^d (1 - x/n) \leq \tau$$

#### **f. Toll Road Effects**

If toll roads are added to the network, the distributor will use the new toll road if savings in travel time or distance compensate for the cost paid in tolls. Alternatively, faster travel speeds may allow for the relaxation of a route time length constraint, which may allow more customers per route. Additional customers, in a given route, decrease distribution costs per customer. In either case, if the distributor finds it beneficial to use the toll roads a reduction in delivery size is expected as well as an increase in truck flows. First order and second order effects are expected as described in part c. and d.

## **5 Discussion**

This research draws from widely accepted concepts and models that have been developed in the Vehicle Routing and Management Science literature, though the emphasis on understanding changes in truck flows in urban environments is novel. Despite the simplicity of the distribution model presented in section four, important intuitive results can be obtained from its analysis. Points 4.a.1 and 4.a.2 suggest that transport payment structure can have an important impact on order size and retailer behaviour. Surprisingly, this aspect has not been thoroughly studied in the freight transport modelling literature.

Ownership and relationships in the supply chain also have important effects on order size. Clearly, optimization/coordination of 2 or more supply chain echelons may not contribute to the reduction of truck flows. This finding is consistent with the findings of Moinzadeh et al. (1997), who have shown how the individual optimization of JIT supply chains can lead to higher congestion in access roads and eventually to a situation where all firms are worse-off.

Metaphorically, this class of situation is a tragedy of the commons where the common resource is the public road space.

The detailed level of analysis of distribution costs and times is important when analysing the effects of ICT technological advances in section 4.3. Clearly, the reduction of order costs and fix order receiving times can have an important effect on distribution systems, especially where  $n$  is already a large number. Specifically in manufacturing distribution systems, the combination of JIT setup/order time/cost reductions and distribution order time/cost reductions can have a significant effect on order size and generation of truck flows.

The main result of this research is the fact that changes in truck flows will be influenced by what is the decision variable that carriers (or distributors) are adjusting to minimize delivery costs and what are the constraints of the problem. The combination of routing constraints and second order effects is a novel insight and shows the complexity of the urban freight modelling task, even in a completely deterministic environment. Second order effects can be staggered what makes their measurement or detection difficult. Operational changes (routes changes or driver working extra hours) can be readily implemented. Tactical (change vehicle size) or strategic (change/add warehouse location) changes can take months or years to be fully implemented. The findings regarding the influence of congestion and toll road are novel in their second order effect regarding changes in fleet size/vehicle type and number of customers per route. Unfortunately, the intuition provided by the model is not readily confirmed or denied due to lack of data; in most countries city logistics data collection is incomplete at best or simply inadequate (OECD, 2003)

Important assumptions are made about the distribution system including one commodity type, constant deterministic travel times and demand rates, and lack of time windows. Further research is needed to understand supply chain agents interaction in less restricted environments.

## **6 Conclusions**

This research contributes to the field proposing a novel and detailed characterization of truck flows in a supply chain context. Using well-known yet simple models and formulas from vehicle routing, operations research, and management science literature, this research derives behavioural insights about distributors and carriers' routing and order sizing decisions. Routing constraints and second order effects seem to be important drivers of truck flows.

A large amount of research is needed to better understand freight and supply chain behavioural aspects in the urban environment. Given the optimization driven approach that prevails in supply chain operations, contributions from the vehicle routing, operations research, and management science literature need to be incorporated into freight behavioural models and analysis. The main contribution of this research is to bring a new perspective and deeper level of operational decision-making analysis to cope with the intricacies of freight transportation modelling.

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