Modeling Impact of Technological Changes on Urban Commercial Trips by Commercial Activity Routing Type

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Several noteworthy developments in logistics practice have taken place without an equivalent and comprehensive development in urban freight transportation modeling. Part of the problem is the lack of deep understanding of the workings of distribution processes in relation to the generation of truck traffic. This study emphasizes the role and importance that distribution network size and information and communications technology have on the truck traffic flows that materialize as the supply chain flows over the public infrastructure. A concept is developed of commercial activity routing types that characterize the interplay between transportation demand requests and routing characteristics. This research contributes to the field by proposing a novel and detailed characterization of truck flows in a supply chain context. With well-known, yet simple, models and formulas from vehicle routing, operations research, and management science literature, behavioral insights are derived about distributors' and carriers' routing and order-sizing decisions, since routing constraints and second-order effects are important drivers of truck flows. The main contribution is to bring a new commercial activity-routing perspective and a deeper level of operational decision-making analysis to cope with the intricacies of freight transportation modeling.

Despite the critical role played by freight transportation in economic development and most economic activities, freight transportation modeling 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 (*1,* pp. 289–297; *2,* pp. 185–215). The accelerated pace of change in logistics practice with the advent of the information and communications technology (ICT) revolution has not improved the status quo.

An array of noteworthy developments in logistics practice have taken place without an equivalent and comprehensive development in freight transportation modeling. A short list of such logistics developments includes electronic data interchange (EDI) bar coding and more recently radio frequency identification (RFID), just-in-time (JIT) production systems, vendor-managed inventory (VMI), cross-docking, containerization, and electronic commerce. Despite the growing interest in considering and incorporating technological and behavioral elements into the freight transportation planning process, the goal remains elusive (*3*). The decision processes governing freight distribution and commercial truck 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 commercial truck traffic. It is widely accepted that the demand for freight transportation is a derived demand. This research accepts that assumption. However, the role and importance that distribution network size and technology may have on the truck traffic flows that "materialize" supply chain flows (demand) over the public infrastructure are emphasized.

This study develops the concept of commercial activity routing types that characterize the interplay between transportation demand requests and routing characteristics. The classification of commercial activity routing types is then used to model how technological changes may affect the generation of commercial truck flows. Once commercial activity has been disaggregated into significant routing types, it is possible to analyze how technological changes affect routing frequency, order size, and number of customers per route. From these route changes it is possible to infer how commercial activity truck flows may change. The focus here is only on commercial commodity truck flows. Detailed study of commercial service truck flows is left as a future research topic.

LITERATURE REVIEW

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 (*4*) report how JIT inventory and production systems and economic deregulation have affected 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 toward long-term contracting. A slightly different trend is reported by Lieb and Randall (*5*), who describe the trend, mainly among big companies, toward outsourcing transportation and logistics responsibilities to third-party logistics services. Crum and Allen (*6*), 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 cost-based procurement to collaboration-based procurement).

Technology has also spurred changes and transformation of transportation logistics procurement structures. Shortly after deregulation legislation was passed in the United States, EDI began to be available. Williams (*7*) studies and reports on how EDI facilitates and fosters a seamless integration between a shipper and a group of core carriers.

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Golob and Regan (*8*) studied carrier adoption of information technology tools, and Ng et al. (*9*) studied the type of information that carriers and drivers would like to receive from traveler information services. A survey study about the adoption and usage of Internet procurement tools by shippers was conducted by Lin et al. (*10*), which 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 employed some transportation online service (2001 data).

The literature mentioned thus far provides insight into trends or changes in supply chain relationships, technology adoption, or procurement strategies. Unfortunately, these studies are not useful from the freight modeler's 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. However, on the modeling side several efforts are under way to capture complex logistics relationships that are completely ignored in traditional four-stage approaches borrowed from the passenger modeling literature. Two innovative modeling approaches are in progress in the cities of Calgary, Australia, (*11*), and Los Angeles, California (*12*).

A different approach, from a multidisciplinary multiagent perspective, 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 governmental agencies. Taniguchi et al. (*13*) present a current review of the field and evaluate approaches that combine both optimization and simulation to predict the effect of policy measures. Hensher and Puckett (*14*) outline a general framework to study how supply agents interact by using stated-choice experiments, with a focus on collaboration or partnership formation as a tool to reduce traffic congestion.

A few research works emphasize the importance of network production–distribution details and costs in urban freight distribution flow patterns. Nemoto (*15*) 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. (*16*) discuss an analysis of how congestion created by small order sizes can negatively affect delivery times and inventory levels. The relation between lot sizes and traffic congestion on a common access road is studied with an inventory-queuing model. More recently, Sankaran et al. (*17*) performed a case study of congestion levels and replenishment order sizes in Auckland, New Zealand.

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 by taking advantage of transportation price structures. This industrial engineering literature modifies the original economic order quantity model to incorporate different transportation pricing methods. Pricing may profoundly affect order size. Quantity discounts in the case of less-than-truck-load (LTL) shipments and the number of truck loads affect delivery cost per unit and the optimal order size from the shipper's point of view (*18*). A further generalization of Lee's model is proposed by Swenseth and Godfrey (*19*), in which both vendor (warehouse) and buyer (retailer) are subject to a replenishment cost structure that includes a fixed cost plus a stepwise component. On the subject of behavioral freight demand modeling, the trade-off between ordering and transport costs and inventory has also been widely studied after the seminal contribution of Baumol and Vinod (*20*).

The current research differs from previous literature in two important aspects: (*a*) it attempts to model truck flows as a function of commodity–activity routing pairs and (*b*) it incorporates the transportation and distribution costs as a function of route and activities constraints. To the best of the author's knowledge, there is no research work or analytical model that incorporates these aspects. Furthermore, no research work has modeled the impact of technological changes and congestion on distribution systems at the route level.

COMMERCIAL ACTIVITY ROUTING TYPES

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 the distribution–service center solution to the particular 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.

In this section the concept of commercial activity routing type is developed, which characterizes the interplay between transportation demand requests and routing characteristics. Logistics strategies, including distribution, are designed to meet customer expectations (regarding the product or service required) in a cost-efficient manner. The commercial activity type reflects how the scheduling and routing of commercial vehicles (trucks) and people (drivers, service and repair personnel) materialize in the urban network. The relative importance of distribution and routing costs on the product or service offered has a decisive influence on the design and materialization of the distribution system.

The objectives and constraints utilized for the routing-distribution problem are determined by the commercial activity type, which determines the type of vehicle routing problem used. The conjunction of a vehicle routing problem and a specific set of demands or requests materializes or objectifies a supply–service chain activity into an observable set of parameters: number of customers per route, sequencing, time of service, vehicle used, distance, links traveled, and others.

The provision of a product or service is denoted here as a commercial activity or simply an activity. Two fundamental dimensions are used to discriminate between the effects of activities on routing: the time sensitivity of the activity and the value of the activity itself. In the case of products, value is an important determinant of production, inventory, and distribution strategies. In general, the value of activities is an important factor that determines how the logistics system design provides flexibility to meet the demand for speed, quick response, and consistency in deliveries.

Time-sensitive activities can originate in two ways: (*a*) the value of the activity itself decreases over time and (*b*) not having the activity at a given time disrupts the operation of a system or company. An example of the former is the provision of fresh vegetables or fresh bakery products; as the products get stale, their intrinsic value decreases considerably or even becomes zero (they must be discarded). An example of the latter is the provision of a JIT supply; the value of the supply product itself may not be too high (e.g., an LTL shipment of bolts for a specific car), but stopping the production line because of a late delivery carries a very high penalty for the consignee.

A simple classification of the activities according to their time sensitivity and value is presented in Table 1. The transportation decisions

TABLE 1 Routing Characteristics of Commodity or Service Activities According to Their Time Sensitivity and Value

Commodity or Service Value	Time Sensitivity High	Time Sensitivity Low
Low	(2) LTL delivery mostly Service trip chained Frequency determined by organizational issues, industry type, or product characteristics. Regular routes Usually time constrained only	(1) TL or LTL delivery Make to stock Trade-offs between Inventory/transport trade-off (EOQ) drives delivery frequency Regular routes Capacity or time constrained
High	(3) Package or direct delivery mostly Exclusive service trips Make to Order–JIT Delivery times or time windows drive routing decisions Irregular customers–routes	(4) Atypical combination

EOQ = estimated order quantity

associated with low-value, low-time-sensitive products [Table 1, (1)] are driven by trade-offs between inventory and transport or order costs. Examples of these kinds of products include the urban distribution of food products to supermarkets and fuel to service stations. Deliveries are made with truckload (TL) or LTL deliveries. It is the typical make-to-stock environment. Production, stocking, and distribution are done in anticipation of a future demand. Routes tend to be planned in advance. The distribution center influence area is divided into service areas (clusters) that can be attended to by a route (*21*). Capacity or route length constraints limit the number of customers that can be served in a given route.

The transportation decisions associated with low-value, high-time-sensitive products [Table 1, (2)] are driven by the necessary replenishment frequency. This frequency can be determined by organizational issues (personnel assigned to receive orders at a given time or on a given day), commercial activity (retailer's limited shelf space), or product characteristics (perishability). Examples of these kinds of activities include the urban distribution of newspapers, miscellaneous products to convenience stores, fresh-baked bread, garbage collection services, replenishment of vendor machines, regular repair crews, and so forth. Deliveries are typically made with LTL deliveries since the frequent delivery reduces the amount of the average order size. Routes tend to be planned in advance, and zoning or driver territory is also an important issue: Golden and Wasil report on the importance of clustering in the soft drink industry (*22*); Erkut et al. describe how Canada's largest publicly owned electric utility company redesigned its service-delivery network by clustering facilities into call pools (*23*). Route time length constraints usually limit the number of customers that can be served in a given route.

The transportation decisions associated with high-value, high-time-sensitive products [Table 1, (3)] are the most demanding activities in terms of transport service requirements. For products, order sizes are small and the most frequent delivery mode is package or direct delivery (courier) services. A make-to-order–JIT production fits in this category (e.g., Dell computers) as well as emergency repair work. In many cases routes cannot be planned in advance and delivery points change constantly. Unlike the two previous cases, there may be exclusive service trips for one stop or customer only. The penalties for late deliveries are high. Lieb and Millen found that companies that implement JIT production systems place a great emphasis on evaluating carrier responsiveness to unexpected service requests as well as on-time delivery performance (*24*). Speed and reliability are the key routing constraints.

The first two routing types, (1) and (2), are static and allow the dispatcher to plan ahead. In contrast, vehicle routing problems in the third type, (3), are dynamic, with requests that cannot always be foreseen. Part or all of the request information becomes available only during the day of operation.

The classification of commercial activity routing types is then used to model how technological changes may affect the generation of commercial truck flows. Once commercial activity has been disaggregated into significant routing types, it is possible to analyze how technological changes affect routing frequency, order size, and number of customers per route. From these route changes it is possible to infer how commercial activity truck flows may change.

MODELING FRAMEWORK, ASSUMPTIONS, AND NOTATION

This study focuses on one type of structure: a distribution or service center that provides for several retailers or customers. Within this basic distribution structure the number of retailers and customers in a given route can increase or decrease because of economic 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 or warehouses have one of the largest effects on vehicle miles traveled (VMT) in urban areas (*25*). On the service side, the commercial vehicles with the largest effect on VMT are business and personal service vehicles, rental cars, and public service vehicles (*25*), which mostly operate from a central depot. The one-to-many model not only is ubiquitous but also represents distribution activities of hypermarkets, distribution centers, producers, and repair service centers while keeping analytical complexity at a tractable level.

Since carriers' operational aspects and behavior have been mostly neglected in the freight modeling 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 into the model. It is assumed that retailers, customers, or specific business settings define the characteristics of the service such as order size, frequency, or time windows (the demand for freight transportation is a derived demand). Accordingly, routes are delineated in order to satisfy these requests by the central distribution or service center.

Given one vehicle and a set of customers, the routing problem in which one vehicle must visit each and every customer exactly once is denoted as the traveling salesman problem (TSP). This problem is notoriously difficult to solve optimally, that is, to find the best sequence to visit customers in order to minimize costs. However, if only the total distance traveled is needed (not the sequence information), fairly good approximations can be obtained with a simple formula. Several approximations have been proposed in the operations research literature (*26–28*).

Assuming that a set $R = \{\text{req}_1, \text{req}_2, \ldots, \text{req}_n\}$ of requests is randomly and independently dispersed over an area A and denoting the optimum traveling salesman tour length as $L(\mathrm{R}, A)$, for a reasonably compact and convex area, the following approximation formula is proposed by Larson and Odoni (*27*):

$$E\left[L(\mathrm{R},A)\right] \approx k\sqrt{nA} \tag{1}$$

where $k \approx 0.765$ and $n = |\mathrm{R}|$.

As long as feasibility is satisfied, economies of density are achieved because route length grows slower than the number of customer requests served. The same type of expression but with a different value of k can be obtained for the Manhatan, or L1, metric. More constrained problems have equal or larger solution costs as shown by Haimovich and Kan (*29*) for capacitated vehicle routing. Simulations performed by Chien (*30*) 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 Formula 1 is subadditive. This is reasonable because, all things being equal and without feasibility constraints, routing costs per customer tend to decrease on average since 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 modeling approach has been used to solve and gain insight into numerous logistics problems. A detailed compilation of such models is presented by Daganzo (*31*), who also presents an extensive analysis of approximation formulas for the TSP.

Summarizing, the following assumptions are made in this research:

- The cost formulation is for a generic multistop tour, delivering shipments from a single distribution or service center to several retailers or customers;
- Route distance is approximated with a routing cost formula similar to Expression 1;
- A single product or service is distributed;
- Delivery or service areas are fixed;
- Route and delivery or service frequency f is determined by the type of commodity or activity;
- The distributor or service center owns or operates the fleet (private carrier);
- A cluster-first, route-second method is used to divide distribution or service center influence area A into m delivery regions $\{A_1, \ldots, A_m\}$, where $A = (A_1 \cup A_2 \cup \ldots \cup A_m)$—the delivery regions' similar size and customer density;
- Customers and retailers are identical; and
- Truck deliveries are randomly scattered over the delivery region served.

Notation

A = area of generic area $A \in \mathrm{A}$ that has a set of customers R and a delivery route with $n = |\mathrm{R}|$ stops and each customer has demand d and order size q;
m = number of areas;
f = delivery or service frequency for area A;
r = line-haul distance from distribution center to A or vicinity of stops;
$\bar{r} = \dfrac{\sum_m r_m}{m}$ = average line-haul;
$\sum_n d_i = D$ = total demand in area $A \in \mathrm{A}$;
$\sum_n q_i = Q$ = total order size in area $A \in \mathrm{A}$;
$\mathrm{V} = \{v_1, v_2, \ldots, v_L\}$ = 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;
τ = time available for truck operations (i.e., driver maximum working hours per day minus lunch or mandatory breaks);
τ^{TW} = time available given by time window length (in general, time windows are more restrictive than working hours): $\tau^{\mathrm{TW}} < \tau$;
t_l = time to load a unit of product into truck;
t_u = time to unload a unit of product from truck (loading and unloading times are highly dependent on the loading and unloading equipment used—manual, forklift, conveyor, etc.—and on distance to and from truck to receiving area);
t_{or} = fixed time needed for order receiving during stop at retailer (includes order receiving, order checking and inspection, paperwork and documentation, etc.);
$c_d^d(v_l)$ = cost or distance for truck type v_l [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 or time on route (includes driver's time cost mostly; inventory in transit cost is not considered because of short journeys of urban deliveries);
c_o^d = distributor order preparation cost (includes preparation of route and shipping documents, notification of driver, etc.);
c_{ol}^d = distributor loading cost per unit of cargo (includes packing and loading truck costs during time t_l);
c_u = product unit cost for distributor and retailer (assumed in same company);
c_f^r = freight cost per order or stop, paid by 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 [includes employee time for clerical and administrative tasks plus 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 (includes employee time t_{or} per order receiving, checking and inspection, and paperwork and documentation); and
$h = h_i^r = h^d$ = inventory holding costs at retailer i or central distributor.

Basic Relationships

$T = mf$ = total number of trips per unit time and
$f = d/q$ = frequency for commodity-based cases (frequency given externally for services).

With Equation 1, the distance per route per unit time is the following:

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

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

The distance per unit of time per retailer is

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

Equation 2 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 center on urban traffic decreases, other things being equal. Conversely, as n and q decrease, the negative impact of the distribution center on urban traffic increases, other things being equal.

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

$$\sum_n q_i = Q \le \chi(v_l) \quad (3)$$

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

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 $C_d(v_l)$:

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

Expression 5 includes all distributors' costs since the truck is loaded and leaves the distribution center 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 total cost is

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

The cost per stop or customer is

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

$$= \frac{1}{n}C_d(v_l) + c_t^d t_u\left[q - \chi(v_l)/n\right] \quad (7)$$

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

Expressions 7 and 7′ are identical for a full truckload, which is a good approximation for high load factors. When this is the case, the value of q is close to $\chi(v_l)/n$. The only term in Expression 7 that depends on the order size is that which relates to unloading costs. The cost per unit per costumer also shows economies of scale (Equation 8). Hence, if Constraint 3 is satisfied, economies of scale can be achieved in Equation 8 for all three terms: distance, time, and order costs:

$$\frac{1}{qn}C_d(v_l,Q) = \frac{1}{q}\left\{c_d^d(v_l)\left(\frac{2r}{n} + k\sqrt{\frac{A}{n}}\right) + c_t^d\left[\frac{1}{s}\left(\frac{2r}{n} + k\sqrt{\frac{A}{n}}\right) + t_{\text{or}} + t_u q\right]\right\} \quad (8)$$

COMMERCIAL COMMODITY FLOWS

In this section, how logistics technology may affect commodity-based truck flows is reviewed. The study is undertaken by comparing two different technological scenarios for each of the three basic activity routing types described in the section on commercial activity routing types.

The two technological scenarios are (*a*) providing a set of retailers without advance shipping notification (ASN) and RFID and (*b*) providing a set of retailers with ASN, RFID, and VMI central inventory control. According to Piasecki (*32*),

> advanced shipment notifications are used to notify a customer of a shipment. ASNs will often include purchase order (PO) numbers, stock-keeping unit (SKU) numbers, lot numbers, quantity, pallet or container number, and carton number. ASNs may be paper based, however electronic notification is preferred. Advanced shipment notification systems are usually combined with bar coded compliance labeling that allows the customer to receive the shipment into inventory through the use of bar code scanners and automated data collection systems. (*32,* Glossary, p. 352)

Retailers and distributors are assumed to belong to the same company; however, in Scenario *a* retailers determine order sizes independently (i.e., only analyzing their own inventory transport trade-off). In Scenario *b* the central distributor determines the order size of the retailer taking into account systemwide inventory.

Low Value and Low Time Sensitivity

Independent Retailers Without ASN and RFID

In Scenario *a,* each retailer and the distributor are different profit-maximizing agents. Retailers' quantity and frequency (of orders) are set to minimize their purchase, inventory holding, and ordering costs. The costs incurred by retailer i per unit time can be expressed as the sum of purchase, holding, and ordering costs:

$$d\left(c_u + c_{\text{fu}}^r + c_{\text{ou}}^r\right) + \frac{qc_u h}{2} + \frac{d}{q}\left(c_o^r + c_f^r + c_{\text{or}}^r\right) =$$
$$d\left(c_u + c_t^d t_u + c_{\text{ou}}^r\right) + \frac{qc_u h}{2} + \frac{d}{q}\left[c_o^r + C_d\left(v_l\right)/n + c_{\text{or}}^r\right] \qquad (9)$$

where $c_f^r = (1/n)C_d(v_l)$, $c_{\text{fu}}^r = c_1^d t_u q$ from Expression 7′. Minimizing costs (Equation 9) over q,

$$q_{1a}^2 = \frac{2d_i\left[c_o^r + C_d\left(v_l\right)/n + c_{\text{or}}^r\right]}{hc_u} \qquad (10)$$

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

Under VMI: Centralized Ordering with ASN and RFID

Up to this point changes that can be brought about by technology have been ignored. ICT has a major impact on processes or transactions that can be accelerated or performed automatically. It also allows for efficient and economical transmission of information and centralized decision making. In this context, it is possible to set an ordering policy that takes 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, and therefore retailer ordering costs are eliminated.

If the distributor tries to minimize total system costs, the amount of inventory held at the distribution center must be taken into account also. This inventory is accounted for by using a multiplicative coefficient $\alpha \geq 1$ and includes the inventory held at the distributor because of the lack of coordination between inbound and outbound shipments that are arriving (leaving) to (from) the distribution center. With perfect coordination (efficient cross-docking, for example) the value of $\alpha = 1$. However, in other situations—the distributor holds the inventory (e.g., inbound order size is higher than outbound sizes), inbound and outbound schedules are uncoordinated, or the distributor is also a producer of the product—a value of $\alpha \geq 2$ is possible, as indicated by Burns et al. (*33*).

Tasks that mostly require data manipulation, verification, or updating are those that fall in a position to greatly benefit from ICT advances. In these kinds of tasks, denoted data-oriented tasks, human processing can be eliminated or greatly reduced, thus dramatically lowering execution times. However, 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 kinds of tasks are denoted physical tasks.

With 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 and delivery). Close to pickup and delivery time, an updated ASN is placed and the shipping and receiving departments can prepare to ship or receive the order (assign docking area, equipment, personnel, etc.). All these information processing and transmission tasks can be achieved without significant human intervention. When the carrier arrives, with RFID (or at least by scanning) the order received is matched against the purchase order and invoice reference; thus inspection and document processing time is saved.

Once the system is in place and working, the marginal costs of order processing can become negligible. The data-oriented costs that can be significantly reduced with VMI, EDI, ASN, and RFID are c_o^d (distributor order-preparation cost), c_o^r (retailer ordering cost), and c_{or}^r (retailer order-receiving cost). Once the systems are installed and fully operational, the ordering operating costs are assumed negligible. The time per stop is also reduced by elimination of the paperwork, and therefore the contribution of time t_{or} to the route costs is discounted. Systems costs can be expressed as follows:

$$n\left\{d\left(c_u + c_{\text{fu}}^r + c_{\text{ou}}^r\right) + \frac{\alpha qc_u h}{2} + \frac{d}{q}\left(C_d(v_l)/n - c_t^d t_{\text{or}}\right)\right\}$$

The order quantity that minimizes systems costs is

$$q_{1b}^2 = \frac{2d\left[C_d\left(v_l\right)/n - c_t^d\ t_{\text{or}}\right]}{\alpha hc_u} \qquad (11)$$

Order size $q_{1b}^2 < q_{1a}^2$ always; the numerator of Expression 10 is larger than the numerator of Equation 11, and the denominator of Expression 10 is smaller than the denominator of Equation 11. Therefore, truck traffic flows will increase when ordering and receiving tasks are performed automatically.

Second-Order Technological Effects

The technological improvement described in the previous section will bring not only 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 item is important since the number of stops can easily be in the dozens ($n \geq 25$) depending on the type of commercial activity. The vehicle routing literature reports that $n \approx 25$ is the median number of daily delivery services, for example, in the soft drink industry (*34*, p. 245–286). In order to get a sense of the savings, 5 min savings per stop in a route with 25 customers represents 26% of an 8-h driver working day.

For the sake of simplicity, it will be assumed that the fixed time due to order receiving can be eliminated as in Expression 11; however, the variable time and cost associated with the physical unloading of the cargo remain. 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 nor the route nor the customers have changed.

Ex ante (before introducing technological improvements), a rational distributor–carrier has chosen the truck type that minimizes costs with order size nq_{1a} per route. 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 subadditive, for any given truck size, costs are minimized while as many customers as possible are included per route. Hence, for any truck type, the carrier will add as many customers per route as possible until either Constraint 3 or 4 is binding. Two situations may arise: the original route was bounded by the capacity constraint (Equation 3) or the original route was bounded by the route time length constraint (Expression 4). These second-order effects are analyzed next.

If the original route was initially bounded by capacity constraints, after the introduction of technological improvements the capacity constraint is no longer binding. If the original route was at first 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.

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 $c_d^q(v_k) < c_d^q(v_l)$ 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; because of its subadditive 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 in order sizes and to a new constraint relaxation and so on until convergence is reached (ultimately, the downward spiral effect will be limited by available truck sizes or constant cost and distance 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

$$x_q^* \in \arg\max_{x \in N^+} n\, q_{1b}\left(1+x\right) \le \chi\left(v_l\right) \tag{12}$$

$$x_T^* \in \arg\max_{x \in N^+} \frac{1}{s}\left(2r + k\sqrt{\left(n+x\right)A\left(1+\frac{x}{n}\right)}\right) + t_u q_{1b}\left(n+x\right) \le \tau \tag{13}$$

where N^+ is the set of numbers that are positive integers.

Low Value and High Time Sensitivity

In this type of activity replenishment frequency is given by the commercial activity itself. With frequent replenishment, time length constraints are expected to be binding. The analysis is similar to the one already performed for the low-value, low-sensitivity activity type.

Ex ante (before introducing technological improvements), a rational distributor–carrier has chosen the truck type that minimizes costs and can serve as many customers as possible for the demanded frequency of delivery f. Ex post (after introducing technological improvements), a rational distributor–carrier will have reconsidered routes and tried to take advantage of the additional time. Since the cost of routing additional customer requests is subadditive, for any given truck size, costs are minimized while as many customers as possible are included per route. Hence, for any truck type, the carrier will tend to add as many customers per route as possible until Constraint 4 is binding.

If n increases, the distance per unit time per retailer decreases as indicated by Expression 2. This is a noteworthy outcome since the impact of technological changes has the opposite sign on the generation of truck flows.

It follows that the same technological changes have a beneficial or detrimental impact on the generation of truck flows depending on the activity routing type. As in the previous analysis, the magnitude of the change in truck flows will be influenced by the number of existing stops and the amount of time that can be saved with the introduction of new technologies. It still holds that for routes with $n \approx 25$, a savings of 5 min per stop represents a total time savings of approximately 26% of an 8-h driver working day. This saved time can be used to add more customers per route.

If the original route was at first 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 again.

If the original route was initially bounded by capacity constraints, the introduction of technological improvements alone will not lead to a higher number of customers per route. If capacity is binding, the carrier has two distinct options:

- Leave the routes intact and
- Increase the truck size of the fleet until a constraint is binding again; this option is based on the fact that since $c_d^q(v_k) < c_d^q(v_l)$ for any $v_k < v_l$, larger trucks will increase operational costs whereas more customers per route will decrease the distance traveled per unit time and customer (because of the subadditive property).

The trade-off between higher truck operating costs and savings due to decreased distance per customer determines if larger trucks are cost-effective (this is only relevant when capacity is binding in low-value, high-time-sensitivity activity routing).

As in activity routing with low value and low time sensitivity, the technological improvements may also bring about a reduction in distribution costs. However, the reduction is expected to be more significant when the binding constraint is only route length; more customers can be added without a required increase in truck size. Expressions 12 and 13 still apply but with the addition of the trade-off between truck operating costs and distance if the capacity constraint is binding. It follows that the same technological changes can have a different impact on truck flow generation depending not only on the activity routing type but also on the kind of constraint that is binding.

High Value and High Time Sensitivity

In high-value, high-time-sensitivity activities, routing is not constrained by capacity or route time length; rather it is constrained by tight time windows. Customer requests or delivery locations are not regularly scheduled but rather appear dynamically as carrier operations unfold (not all customers are visited in a regular basis or at regular times). Routes are changed or planned on a day-to-day basis or several times per day. The carrier's focus is on short delivery times or satisfying on-time delivery performance. Typical examples of this kind of activity are express package service and parcel pickups or deliveries. For example, next-day express deliveries usually require a time window determined by (*a*) the ending of hub sorting activities or earliest business (consignee) operating hours (whichever is the latest) and (*b*) the latest delivery time (usually before midday). Conversely, time windows for pickup operations are determined by (*a*) either the drop box, agent cutoff receiving time (usually around 5:00 p.m.) or the shipper pickup location (whichever is most constraining) and (*b*) the latest delivery time that will not delay hub sorting activities or interhub departing flights (*35*).

In general, time windows for high-value, high-time-sensitivity activities are more restrictive than working hours: $\tau^{TW} < \tau$. Two consequences of this higher level of temporal restrictions are that (*a*) the usually binding constraint is time windows rather than capacity and (*b*) the number of customers served per route tends to be smaller than in routes for Activity Routing Type 2 (Table 1). The latter easily follows from the analysis of Constraint 4. Other things being equal, the number of customers served in Activity Routing Type 3 is less than or at most equal to the number of customers served in Activity Routing Type 2 when $\tau^{TW} < \tau$.

The analysis of Activity Routing Type 2 with regard to route length and capacity relaxations applies to Activity Routing Type 3 but taking into account that $\tau^{TW} < \tau$. Therefore, in a deterministic setting an analysis similar to the one applied to Activity Routing Type 2 can be applied to Activity Routing Type 3. However, reliability, the most fundamental service dimension in this activity routing type, is missing in Expressions 12 and 13. This service dimension cannot be captured within the deterministic modeling framework presented in this research. The impact of variability and uncertainty on different routing types is analyzed in a companion paper (*36*).

DISCUSSION OF RESULTS

The effects of the analyzed technology on truck flows are dependent on the activity type and the route constraints. For low-value, low-time-sensitivity products, a reduction in order size will generate more truck flows per unit time, as shown in Expression 2. This finding agrees with the notion that as more industries move toward JIT environments (with smaller order sizes), there is an increase in the generation of truck flows. However, if the routes are mainly constrained in their time length, the reduction of delivery times will increase the number or customers per route and consequently decrease truck flows. This is also the case for frequency-driven low-value, high-time-sensitivity activities. For activities that are already operating in a JIT or make-to-order environment, speed in delivery is a key element. The studied technological effects may have already been incorporated in the operation of this type of production–distribution system.

Second-order effects can be staggered, which can make their measurement or detection difficult. Operational changes (route changes or drivers working extra hours) can be readily implemented. Tactical (change in vehicle size) or strategic (change in or addition of warehouse location) changes can take months or years to be fully implemented. Unfortunately, the intuition provided by the model is not readily confirmed or denied because of lack of data; in most countries, city logistics data collection is incomplete at best or simply inadequate (*37*).

One implication of this research on urban freight data collection efforts and modeling practices is the need to disaggregate the study and modeling of urban freight activities across relevant factors. This research provides an initial attempt to disaggregate by type of commercial activity, routing, and constraint characteristics. Further research is needed to elucidate a parsimonious list of factors and models that can accurately represent the different types of urban freight movements. The complexity of data collection and modeling in urban freight is a noteworthy issue, but it is beyond the scope of this research. A new level of urban freight data collection and modeling is necessary to understand the relationships between commercial activities, route designs, constraints, number of customers per route, and vehicle types.

Several assumptions were made in this research (see the section on modeling framework, assumptions, and notation). An effort was made to incorporate essential details of activity routing types and to limit the complexity of the modeling to allow the derivation and study of analytical expressions. A significant assumption in this research is the use of a deterministic modeling framework. Since not all urban distribution settings can be reasonably modeled without uncertainty or variability, the impact of variability and uncertainty on different routing types must be further analyzed.

CONCLUSIONS

This research contributes to the field by proposing a novel and detailed characterization of truck flows in a supply chain context. By using well-known yet simple models and formulas from vehicle routing, operations research, and management science literature, this research derives behavioral insights about distributors' and carriers' routing and order-sizing decisions. Routing constraints and second-order effects show strong evidence of being important drivers of truck flows, especially for low-value, low-time-sensitivity commodities.

The emphasis on understanding changes in truck flows in urban environments is novel. Despite the simplicity of the distribution model presented, important intuitive results can be obtained from its analysis. A detailed level of analysis of distribution costs and times is important when the effects of ICT technological advances are analyzed. Clearly, the reduction of order costs and fixed order receiving times can have an important effect on distribution systems, especially when routes already include a large number of customers. Equally important is the correct determination of the relevant commercial activity types.

The combination of routing constraints and second-order effects is a new insight and shows the complexity of the urban freight modeling task, even in a completely deterministic environment. 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 agent interaction in less restricted environments.

A large amount of research is needed to better understand freight and supply chain behavioral 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 behavioral 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 modeling.

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