URBAN DELIVERY INDUSTRY RESPONSE TO CORDON PRICING, TIME-DISTANCE PRICING, AND CARRIER-RECEIVER POLICIES

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ABSTRACT

The paper develops a set of analytical formulations to study the behavior of the urban delivery industry in response to cordon time-of-day pricing, time-distance pricing, and comprehensive financial policies targeting carriers and receivers. This is accomplished by modeling the behavior of receivers in response to financial incentives, and the ensuing behavior of the carrier in response to both pricing and the receiver decisions concerning off-hour deliveries. The analytical formulations consider both the base case condition, and a mixed operation with both regular hour and off-hour deliveries; two pricing schemes: cordon time of day, and time-distance pricing; two types of operations: single tour, and multi-tour carriers; and three different scenarios in terms of profitability of the carrier operation, which include an approximation to the best case, the expected value, and the worst case. The analyses, both theoretical and numerical, highlight the limitations of pricing-only approaches. In the case of cordon time of day pricing, the chief conclusion is that it is of limited use as a freight demand management tool because: (1) in a competitive market the cordon toll cannot be transferred to the receivers as it is part of the fixed costs; and (2) the structure of the cost function, that does not provide any incentive to the carrier to switch to the off-hours. The analyses of time-distance pricing clearly indicate that, though its tolls could be transferred to the receivers and provide an incentive for behavior change, the magnitude of the expected toll transfers under real life conditions are too small to have any meaningful impact on receivers choice of delivery times. In essence, the key policy implication is that in order to change the joint behavior of carrier and receivers, financial incentives should be provided to receivers in exchange for their commitment to do off-hour deliveries. As the paper proves, if a meaningful number of receivers switch to the off-hours, the carriers are likely to follow suit.

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1. INTRODUCTION

Walters's seminal publication (Walters, 1961) introduced the concept of road pricing, and identified its potential as a demand management tool that could lead to an optimal use of transportation facilities. Vastly influential, Walters' formulation was a natural progression in the field of welfare economics as it built upon the concept of the "Pigouvian tax" (Pigou, 1920). Soon after the publication of Walter's paper, a number of researchers (Nelson, 1962; Vickrey, 1963; Johnson, 1964; Beckman, 1965; Vickrey, 1969) contributed to create the foundations of modern road pricing. One of these researchers, W. Vickrey, would end up playing an influential role as a tireless advocate of road pricing, becoming so intrinsically associated with the concept that he is typically referred to as the "Father of Road Pricing."

Since these early days, a significant amount of research has been conducted on almost all relevant facets of the topic. This includes research on: behavioral responses to pricing (Adler et al., 2000; Cain et al., 2001; Supernak et al., 2002; Brownstone et al., 2003; Holguín-Veras et al., 2007c); policy and equity (Foster, 1974; Evans, 1992; Harrington et al., 2001; Eliasson and Mattsson, 2006; Holguín-Veras et al., 2006a); traffic impacts (Sullivan and Harake, 1998; Cain et al., 2001; Holguín-Veras et al., 2005; Ozbay et al., 2005a; Ozbay et al., 2005b); analytical formulations (Khajavi, 1981; Small and Gómez-Ibáñez, 1998; Verhoef and Small, 2004; De Palma et al., 2005; Holguín-Veras and Cetin, 2008); among others. This sample of publications, by no means comprehensive, provides an idea about the amount of the literature on the subject. For a comprehensive review the reader is referred elsewhere (Lindsey and Verhoef, 2001).

In spite of the voluminous body of research on pricing, only a handful of publications deal with the important area of freight road pricing. The first documents specifically focusing on freight (Hicks, 1977; Button, 1978; Button and Pearman, 1981) discussed the anticipated impacts of pricing without the benefit of solid data to support the analyses and verify the validity of the conclusions. Hicks (1977) did articulate some of the relevant questions pertaining to the effectiveness of freight road pricing, and briefly discussed congestion charges to the companies that generated the freight as an alternative based on a concept proposed elsewhere (Jacobi, 1973). A second group of publications with some empirical laid out basic behavioral hypotheses (New York State Thruway Authority, 1998; Vilain and Wolfrom, 2001).

The literature review revealed only one publication (Holguín-Veras et al., 2006c) focusing on the observed behavioral responses of urban carriers to cordon time-of-day pricing. The analyses of the behavioral data collected produced findings that challenge long-held assumptions. The data showed that: (1) the ability of carriers to unilaterally change delivery times is quite limited as it necessitates the concurrence of the receivers (which tend to prefer deliveries during the regular hours as they could take advantage of the staff at hand, as opposed to off-hour deliveries that may require extra staff, security, lighting, and other costs); and, (2) cordon tolls are not likely to be effective in inducing a switch to the off-hours, as most segments of the urban freight industry cannot pass toll costs to their customers depriving them of the price signal needed to effect a change. Further analyses (Holguín-Veras, 2008) concluded that the difficulties that carriers have to pass cordon time-of-day tolls to their customers reflect a highly competitive market with delivery rates equal to marginal costs. Since the cordon toll is a fixed cost—as it does not depend on the unit of output—it does not enter in the rates. The empirical data confirmed that only the market segments with market power (i.e., carriers of stone/concrete, wood/lumber, food, electronics, and beverages) could pass toll costs in a meaningful way (Holguín-Veras, 2008). The key insight is that, since the price signal only reaches the receivers in those cases where the carrier has market power (and in a diluted fashion because they allocate the toll costs among the multiple receivers in the tour), carrier centered pricing policies are not as effective as they should be because receivers have no incentive to change behavior. Since the consent of the receivers is needed for the carriers to change behavior, it follows that a new policy paradigm is needed. These new policies specifically target the receivers of the cargoes as well as the carriers, and are referred to as "carrier-receiver" policies. The goal here is to combine elements of carrier centered policies, e.g., freight road pricing, with receiver centered policies.

A number of carrier-receiver policies were designed and evaluated in a series of papers that: discussed constraints to implementation of off-hour deliveries (Holguín-Veras, 2006); analyzed the potential of the restaurant sector as a target for off-hour delivery programs (Holguín-Veras et al., 2006b); provided a framework for analyses of carrier-receiver interactions, and discussed the behavioral models estimated with stated preference data collected from receivers and carriers (Holguín-Veras et al., 2007a; Holguín-Veras et al., 2007b). These behavioral models clearly showed that: (1) receivers would be willing to switch to the off-hours in exchange for financial incentives; (2) all carriers are sensitive to requests from receivers; and, (3) only a handful of industry segments are sensitive to tolls (i.e., carriers of petroleum/coal, wood/lumber, food products, and textiles/clothing). The analyses clearly indicate that this type of policy will be supported by the carriers as delivering in the off-hours, in equality of conditions, is about 30% cheaper than delivering during the congested hours of the day (Holguín-Veras, 2006).

Taken together, the research on carrier-receiver policies has provided insight into their effectiveness, and the limitations of freight road pricing. However, in spite of the significant progress made towards understanding carrier-receiver interactions, and how they shape their joint response to pricing, there are still major knowledge gaps. One of the most important ones is the lack of analytical formulations to assess the effectiveness of various combinations of financial incentives to receivers, and toll surcharges targeting carriers. The techniques that have been used have some limitations. Using a sequence of discrete choice models, which was the first approach used (Holguín-Veras et al., 2007a; Holguín-Veras et al., 2008), cannot take important details (e.g., routing patterns, configuration of service areas) into account. This translates into a rather coarse way to estimate the joint response. Currently, the only way to study such operational aspects is with the use of micro-simulation techniques that replicate the behavior of individual receivers and carriers (Silas and Holguín-Veras, 2008). Although able to model the observed behavior in a fine level of detail, such simulations require a significant amount of data and calibration effort, which hampers their implementation. Having access to closed form models could simplify the analysis process significantly. Among other things, such formulations could provide insight into how effective cordon time-of-day pricing, time-distance pricing, and comprehensive carrier-receiver policies are for a variety of operational conditions.

The paper builds on the author's previous work (Holguín-Veras, 2008) that outlined the necessary conditions for such policies to succeed in inducing a shift of truck traffic to the off-hours. The main focus is on the development of analytical formulations to assess the impact of policies targeting receivers and carriers. The formulations are developed with the assistance of conceptualizations of the behavior of carriers and receivers. The resulting models are then used in numerical experiments to examine the impacts of off-hour deliveries on the industry.

The paper considers the case of a single carrier that is delivering goods to a set of receivers during the regular hours (base case conditions) from a location outside of the tolled area, i.e., the most typical case. It is also assumed that as a consequence of carrier-receiver policies, some or all receivers decide to receive goods during the off-hours, while others prefer receiving regular hour deliveries, and that no customers are lost because of the partition. Under these circumstances, the carrier would need to make two tours (i.e., regular and off-hours), and must to decide whether or not to conduct off-hour deliveries on the basis of the financial impacts associated with the resulting mixed operation. The formulations discussed in the paper are intended to help gain insight into the joint carrier-receiver response. (Although it is certainly possible that some carriers could do both regular and off-hour deliveries in the same tour by proper timing of the deliveries, or by waiting inside the tolled area, these cases are not considered here for the sake of brevity. This should be the subject of future research.)

The paper considers the case of independent carrier-receiver operations, and two different sub-cases of operational patterns (i.e., single, and multi-tour carriers). Independent carrier-receiver operations refer to the situation in which carrier and receiver are separate companies, each trying to maximize profits; as opposed to integrated carrier-receiver operations where both carrier and receiver belong to the same parent company. Since the latter case was sufficiently discussed in a previous publication (Holguín-Veras, 2008), there is no need to repeat the discussion here.

Two different toll schemes are considered. The first one is a cordon time of day system with a toll surcharge for travel during the regular hours, which is one of the most common road pricing schemes. Other schemes, e.g., the carrier only pays the toll surcharge once a day, could be accommodated by suitable adjustments to the toll surcharge. The second one is a time-distance tolling regime with tolls that are a function of time spent and distance traveled in the tolled area.

The paper has eight major chapters, in addition to the introduction. Chapter 2 introduces the notation used. Chapter 3 discusses carrier-receiver interactions. Chapter 4 focuses on receiver behavior. Chapters 5 and 6 analyze the joint behavior of carriers and receivers under cordon time of day pricing and time-distance pricing, respectively. Chapter 7 considers the second order effects on carrier and receivers. Chapter 8 analyzes policy implications. The final chapter, i.e., Conclusions, discusses the key findings.

2. NOTATION

To a great extent, the notation follows the author's previous work (Holguín-Veras, 2008). Throughout the paper, the subscripts i, and j refer to receiver i, and carrier j, respectively. Superscripts BC, R and O refer to base case, regular, and off-hour operations, respectively.

C_j^{BC} = Total cost of carrier *j*'s base case operations (no off-hour deliveries)

$C_j^M = C_j^R + C_j^O$ = Total cost of carrier *j*'s mixed operations (regular plus off-hour deliveries)

G_j^{BC}, G_j^M = Gross revenues (base case, mixed operation) to carrier *j*

C_j^R = Total cost of carrier *j* associated with regular deliveries in a mixed operation

C_j^O = Total cost of carrier *j* associated with off-hour deliveries in a mixed operation

ΔC_i = Incremental total costs to receiver *i* associated with switching to the off-hours

$\Delta C_j = C_j^M - C_j^{BC}$ = Incremental total costs to carrier *j*

$\Delta C_{F,j}$ = Incremental fixed costs to carrier *j*

$\Delta C_{D,j}$ = Incremental distance costs to carrier *j*

$\Delta C_{T,j}$ = Incremental time costs to carrier *j*

$\Delta C_{S,j}$ = Incremental toll costs to carrier *j*

C_{FC}^{BC}, C_{FC}^R, C_{FC}^O = Cost of trip to first customer (base case, regular, and off-hour operations)

C_{HB}^{BC}, C_{HB}^R, C_{HB}^O = Cost of returning to home base (base case, regular, and off-hour operations)

c_D^{BC}, c_D^R, c_D^O = Unit cost per distance traveled (base case, regular, and off-hour operations)

c_T^{BC}, c_T^R, c_T^O = Unit cost per time traveled (base case, regular, and off-hour operations)

D^{BC}, D^R, D^O = Tour distance (base case, regular, and off-hour operations)

T^{BC}, T^R, T^O = Tour time (base case, regular, and off-hour operations)

S^R = Toll surcharge to trucks traveling during regular hours as part of the cordon scheme

α_D^R, α_D^O = Distance based unit toll for distance traveled in tolled area (regular, and off-hours)

α_T^R, α_T^O = Time based unit toll for time spent in tolled area (regular, and off-hours)

$m_j^{N^R,S}$ = Marginal cost to carrier j associated with delivering to N^R receivers during the regular hours, under cordon time-of-day pricing

$m_j^{N^R,TDP}$ = Marginal cost to carrier j associated with delivering to N^R receivers during the regular hours, under time-distance pricing

m_i^O = Incremental cost per hour to receiver i associated with extending operations to off-hours

$\overline{m}^O$ = Average incremental cost per hour associated with extending operations to the off-hours

τ_i^O = Length of time during which off-hour deliveries are accepted by receiver i

$\tau_{\min}^O$ = Minimum amount of time required for off-hour deliveries

$\bar{\tau}^O$ = Average amount of time required to make one off-hour delivery

ϕ = Parameter of approximation model

A = service area, i.e., area of the minimum size rectangle that envelopes all customers

A^{BC}, A^R, A^O = service areas (base case, regular, and off-hour operations)

$N^{BC} = N^R + N^O$ = Total number of customers for base case conditions

N^R, N^O = Total number of customers during regular and off-hours (mixed operation)

K^{BC}, K^R, K^O = Number of trips made by multi-tour carriers (base case, regular, and off-hours)

u^R, u^O = Average travel speeds (regular and off-hours)

$\gamma = \frac{u^R}{u^O}$ = Ratio of average travel speeds

$\theta = \frac{c_T^O}{c_T^R}$ = Ratio of unit time costs

$\delta^{BC} = \frac{N^{BC}}{A^{BC}}$ = Customer density

$\Omega_j^{BC} = \Omega_j^R + \Omega_j^O$ = Original set of receivers during base case conditions, served by carrier *j*

Ω_j^R = Set of receivers, served by carrier *j*, that prefers regular hour deliveries

Ω_j^O = Set of receivers, served by carrier *j*, that decides to accept off-hour deliveries

$L_x^{\max}$ = Maximum separation along the x coordinate between receivers

$L_y^{\max}$ = Maximum separation along the y coordinate between receivers

$A = L_x^{\max} L_y^{\max}$ = Size of the actual service area

L_{ox} = X dimension of the rectangular service area

L_{oy} = Y dimension of the rectangular service area

$A_o = L_{ox} L_{oy}$ = Total area considered

Γ^O = set of carriers that do off-hour deliveries

F = Financial incentive provided to receivers for committing to accept off-hour deliveries

$P(F)$ = Probability that a receiver would commit to off-hour deliveries

F_{ij} = Incentive sent by the receiver to the carrier

3. CARRIER-RECEIVER INTERACTIONS

Conducting off-hour deliveries require the participation of different economic agents (e.g., shippers, carriers, warehouses, receivers). However, in terms of the role played in the decision concerning delivery times, receivers and carriers stand out. The reason is that shippers and warehouses can, in most cases, accommodate off-hour deliveries without too much trouble. Shippers could support off-hour deliveries by: ship goods late in the day to support night deliveries, or preload trucks for deliveries in the early hours of the day. Similarly, since most warehouses (that many identify as the source of most urban deliveries) are open at least partially during the off-hours, they could support off-hour deliveries with minimal inconvenience. These reasons suggest to focus on carriers and receivers (Ogden, 1992).

Consider a carrier and a receiver that are trying to decide on the delivery time (regular hours, or off-hours). In the case of independent carrier and receivers, which is the one discussed here, since each of them is trying to independently maximize its own profits, their interaction belongs to the class of non-cooperative (Nash) games. (Obviously, if carrier and receiver are part of the same company as in private carrier operations, the interaction reduces to the much simpler optimization problem of determining what is best for the joint operation.) To gain insight into the nature of their interactions, it is important to analyze the corresponding pay-off matrix, shown in Figure 1 (Holguín-Veras et al., 2007a).

Figure 1: Pay-off matrix

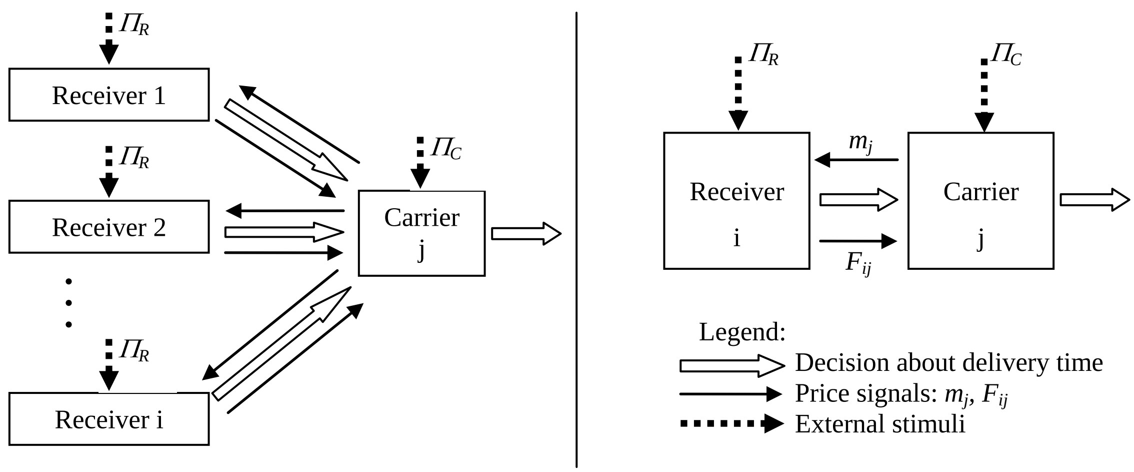
		Receiver	
	Strategy	Regular hours	Off-hours
Carrier	Regular hours	(−,+) (I)	(−,−) (II)
	Off-hours	(−,−) (III)	(+,−) (IV)

The four quadrants outline all the possibilities. Quadrants II and III represent the cases in which carrier and receiver do not agree on a delivery time. In such cases, both sides have negative payoffs (i.e., the receiver does not get its deliveries, and the carrier may be fired) so it is safe to assume that both of them would avoid the outcome. Obviously, if they cannot agree, they would part ways and the interaction would resume with a new set of agents until an agreement is found.

Quadrants I and IV represent the situations in which an agreement is reached on the delivery time. The solutions outlined in these quadrants have very different impacts. In the case of regular hour deliveries (quadrant I), the receiver benefits because it handles the deliveries when there is staff at hand at minimal extra cost; while the carrier has to contend with the lower productivity due to congestion. During the off-hours, the situation reverses as the receiver is the one facing a negative impact, i.e., the larger costs associated with extending operations to the off-hours; while the carrier benefits from the higher productivity associated with less congestion. This leads to a situation in which carrier and receiver favor different solutions. This situation corresponds to the "Battle of the Sexes" game (Rasmusen, 2001), which is known to have two Nash equilibria, i.e., quadrants I and IV, in which the final outcome is imposed by the player with most clout. Since the data show that the majority of deliveries are made during the regular hours (96% in New York City), it is obvious that receivers play the dominant role (Holguín-Veras et al., 2007a). This should not surprise anyone, since the carriers must be responsive to the wish of receivers—who are the customers—or running the risk of going out of business. It follows that, in order to induce the urban delivery industry to operate during the off-hours, appropriate policy stimuli must reach the receivers so that the equilibrium solution that they favor changes from the regular to the off-hours, i.e., quadrant IV. The recognition that receivers must be the target of policy making is front and center of the concepts discussed here.

The main thrust of the paper is on the study of carrier-receivers interactions, and how they shape the response to pricing policies. This requires a conceptual description of the interactions taking place between the carriers and all the receivers in a delivery tour. As shown in pane A of Figure 2, since the carrier interacts with all its receivers, its own response is shaped by what the receivers want. This is no trivial matter, as the data show that the number of receivers in a tour is large. In New York City, the average is 5.5 (Holguín-Veras, 2008), while in Denver is 5.6 receivers/tour (Holguín-Veras and Patil, 2005), though there are some carriers that may deliver 100 receivers in a tour, e.g., express deliveries. Schematically, one could depict the key interactions between carrier and receiver and the various policy stimuli with the assistance of Figure 2, that shows a schematic of the interactions between the carrier and a set of receivers.

Figure 2: Key interactions



A) Interaction between carrier and all receivers

B) Interaction between carrier and receiver i

In the case of carrier centered policies, e.g. freight road pricing, a policy stimuli Π_C is applied to the carrier. The fundamental assumption is that Π_C would prompt the carrier to send a price signal m_j to the receivers, i.e., the solid arrow from the carrier, that would induce them to switch to the off-hours. Once the receiver(s) make(s) its decision about off-hour deliveries, the carrier has to decide whether or not to do off-hour deliveries. Obviously, for carrier-centered policies to succeed: (1) carriers must be able to pass the toll cost m_j to all receivers; and, (2) m_j must be strong enough to induce all receivers (or at least a majority) to switch the off-hours. The paper tries to elucidate if this is likely to happen in competitive markets.

Receiver centered policies apply a stimulus Π_R to the receivers (e.g., incentives for participation in off-hour deliveries, or regulations like banning truck deliveries during the regular hours of the day). On the basis of such stimuli, the receivers decide how to respond and send a signal F_{ij} to the carrier, that then has to decide how to proceed. Carrier-receiver policies, as their name suggests, target both carriers and receivers by means of a duplet of stimuli (Π_C, Π_R) aimed at inducing a switch to the off-hours. This case obviously includes carrier centered, and receiver centered policies as extreme points.

The main objective of the paper is on assessing the impacts of such stimuli (Π_C, Π_R) on the joint behavior of carriers and receivers. In doing so, the paper considers the interactions shown in Figure 2. For simplicity of exposition, the formulations are obtained for carrier-receiver policies and the other two cases (i.e., carrier center, and receiver centered) are obtained as extreme points.

4. RECEIVER BEHAVIOR

This paper considers the case of N^{BC} receivers R_i that are served by a carrier j during the regular hours (base case conditions) such that $R_i \in \Omega_j^{BC}$. It is assumed that receivers: are randomly located over an urban area of rectangular shape, are observationally identical, and have a probability $P(R_i \in \Omega_j^O / F) = P(F)$ of participating in off-hour deliveries. This probability is a monotonic function of an external incentive, F, aimed at fostering off-hour deliveries such that $P(R_i \in \Omega_j^O / 0) = P(0) = p_0$ and $P(R_i \in \Omega_j^O / \infty) = P(\infty) = 1$. The probability p_0 represents the fraction of receivers that accept off-hour deliveries in the base case conditions, i.e., in absence of a financial incentive. This probability seems to be relatively small, e.g., 4% in New York City (Holguín-Veras et al., 2007a). For discussions on these incentives, the reader is referred elsewhere (Holguín-Veras et al., 2007a; Holguín-Veras et al., 2007b).

As a result of the incentive, some receivers may elect to accept off-hour deliveries, while others may choose to stay within the regular hours. In the most general case, this leads to a mixed operation in which the carrier has to deliver during both the regular and the off-hours, unless all receivers switch to the off-hours which leads to the elimination of the regular hours tour. Under these assumptions, the expected number of receivers willing to move to the off-hours is:

$$N^{0} = P(F)N^{BC} \qquad (1)$$

Assuming no loss of customers, the number of receivers in the regular hours is:

$$N^{R} = (1 - P(F))N^{BC} \qquad (2)$$

The distribution and location of the receivers that accept either regular or off-hour deliveries, have a significant impact on the carrier costs. Intuitively, one would expect that the tour length is a function of the service area so that the larger the area, the longer the tour and the corresponding delivery costs. Equally important for the carrier is that the delivery cost in a mixed operation, (i.e., with both regular and off-hour delivery service) depends on the combined impact of the service areas that arise after the receivers decide on the service they prefer. This highlights the need to study the relationship between the service area and the number of customers in it.

Consider an urban area with the shape of a unit square—which could be rescaled to any rectangular shape—in which receivers are randomly and uniformly located. The service area that would arise from a random realization is going to be a function of the maximum difference between the X and Y coordinates (i.e., $L_x^{\max}$ and $L_y^{\max}$) for any pair of receivers, such that:

$$A = L_x^{\max} L_y^{\max} \qquad (3)$$

Since the x and y coordinates are orthogonal, one could gain insight into the impacts of travel distance, and ultimately on costs, by studying the statistical patterns of the differences between locations along one of the coordinates. Consider a unit interval along one of the coordinates with random realizations of receiver locations, in which the receivers have been labeled in increasing order of distance from the origin. For any coordinate the expected value of the maximum separation between receivers, *E(L)*, is (Daganzo, 1984):

$$E(L) = E(|X_1 - X_{Nth}|) = \frac{N-1}{N+1} \qquad (4)$$

Numerical experiments suggest that equation (4) is quite good for even a small number of replications. The experiments show that five replications could lead to a Mean Absolute

Percentage Error of less than 10%. If instead of a unit square, the area of study is a rectangle of sides L_{ox} and L_{oy}, the service area for *N* customers randomly located would be equal to:

$$A = \left(\frac{N-1}{N+1}\right) L_{ox} \left(\frac{N-1}{N+1}\right) L_{oy} = \left(\frac{N-1}{N+1}\right)^2 L_{ox} L_{oy} = \left(\frac{N-1}{N+1}\right)^2 A_o \qquad (5)$$

Equation (5) is important as it turns out that the service area is correlated with the length of the optimal tour required to visit the *N* customers. This type of problem is studied with the use of approximation techniques to the probabilistic traveling salesman problem (TSP). This area of mathematics started with the work of Beardwood and his colleagues (Beardwood et al., 1959). They demonstrated that, for the probabilistic TSP, the ratio of the optimal tour length to the square root of the number of customers (*N*), when *N* tends to infinity, is equal to a constant that multiply the square root of the area, as shown in equation (6). The numerical experiments conducted (Chien, 1992; Robusté et al., 2004; Figliozzi, 2008) do suggest that these approximation techniques provide solid estimates of the optimal tour length. After reviewing this literature the original function proposed by Beardwood et al. (1959), was selected because it is simple, robust, and accurate enough for the purposes of the paper.

$$D = \phi \sqrt{AN} \qquad (6)$$

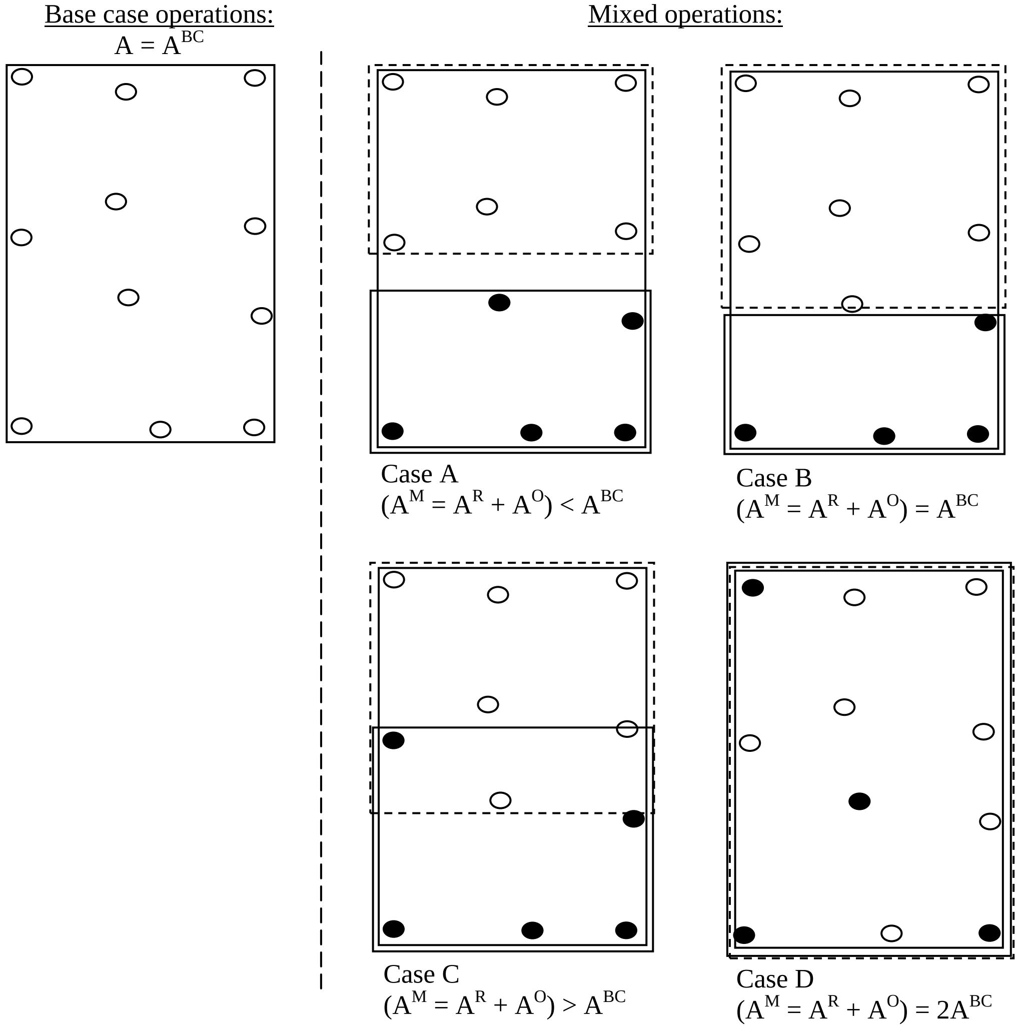
Where: *A* is the area of the minimum size rectangle that envelopes all stops (customers) to visit, and *N* is the number of stops (customers).

For the expected value case, substituting equation (5) in (6), and letting $A_0 = L_{ox} L_{oy}$, leads to:

$$D = \phi \left(\frac{N-1}{N+1}\right) \sqrt{A_o N} \qquad (7)$$

Because of the random nature of the underlying process, it is important to consider the range of configurations that could arise from the receivers' decisions. Consider the nine receivers shown under "Base Case" in Figure 3. Assume now that, as a consequence of a policy incentive, some of them decide to accept off-hour deliveries (solid circles), while others decide not to change (white circles). Cases A thru D represent some possible configurations. As a result of the partition, two new service areas for regular and off-hour operations arise, together with a combined service area for the resulting mixed operation. In cases A and B there is geographic segmentation of the market with regular hour receivers in one area, and off-hour receivers in the other. In contrast, in cases C and D there is little or no segmentation as their service areas overlap. In general, the service area for the mixed operation could be less than (Case A), equal to (Case B), or larger than (Cases C and D) the original service area. Case D is the upper bound of the service area for the mixed operation, in which regular and off-hour deliveries end up with service areas equal to the original one; while the lower bound is a variant of Case A.

Figure 3: Sample configurations of service areas resulting from partitioning



Note: A rectangle with dashed lines represent the service area for the customers denoted with white circles; while a rectangle with solid lines represents the same for the customers denoted by solid circles. To facilitate interpretation, the rectangles have been offset so that they do not overlap.

It should be pointed out that having geographically segmented sets of receivers in off-hours and regular hours could significantly increase the profitability of the mixed operation as it may lead to smaller combined service areas. This may be a good reason to provide incentive to receivers on a geographic basis, e.g., a downtown area, as doing so will make it easier for the carriers to benefit from the resulting mixed operation.

Due to its stochastic nature, it is not possible to make generalizations about the configuration of service areas that would arise in a particular instance. However, there are two exceptions: (1) non-overlapping service areas proportional to the number of customers in each group with a combined service area equal to the original one (a sub-case of B); and (2) perfectly overlapping service areas (Case D). The former case is referred as *perfectly complementary (PC) service areas*; and the latter as *perfectly overlapping (PO) service areas*. These cases, together with the expected value estimated using equation (4), describe the range of results. Mathematically:

A) Perfectly complementary (*PC*) service areas

$$A^{BC} = A^R + A^O = A \tag{8}$$

$$A^R = \frac{N^R}{N^{BC}} A^{BC} \tag{9}$$

$$A^O = \frac{N^O}{N^{BC}} A^{BC} \tag{10}$$

B) Perfectly overlapping (*PO*) service areas

$$A^R + A^O = 2A^{BC} \tag{11}$$

$$A^R = A^O = A^{BC} = A \tag{12}$$

Using equation (5), the expected value of the total area for the mixed operation becomes:

$$A^M = A^R + A^O = \left(\frac{N^R - 1}{N^R + 1}\right)^2 L_{ox} L_{oy} + \left(\frac{N^O - 1}{N^O + 1}\right)^2 L_{ox} L_{oy} = \left[\left(\frac{N^R - 1}{N^R + 1}\right)^2 + \left(\frac{N^O - 1}{N^O + 1}\right)^2\right] L_{ox} L_{oy} \tag{13}$$

$$A^{BC} = \left(\frac{N^{BC} - 1}{N^{BC} + 1}\right)^2 L_{ox} L_{oy} \tag{14}$$

As shown, there is a wide range of operational conditions that could arise. At one of the spectrum, the service area in the mixed operation could be smaller than in the base case (see

Case A of Figure 2); while at the other end it could double the size of the area under the base case conditions. However, the expected value indicate that in average an increase in the service area is likely, and that the maximum increase in the service area for the mixed operation would take place when the number of customers shifting to the off-hours is half the one in the base case. If only one customer is left in either the regular or off-hours, the service area would decrease for the mixed operation as one of the terms in equation (13) would vanish.

Having discussed how the receivers' decisions may impact the carriers' service areas and, ultimately, the carrier's decision it is important to analyze the fundamental aspects of carrier and receiver decision making under: cordon based time of day pricing, and time-distance based pricing. For brevity of exposition, derivations are provided only for the cordon time of day case.

5. CASE I: CARRIER-RECEIVER RESPONSE UNDER CORDON TIME OF DAY PRICING

This chapter considers the case in which there is a toll surcharge for truck travel during the regular hours that is assessed at a cordon surrounding the tolled area. This is the pricing scheme most frequently implemented (e.g., London, Singapore, and the Hudson River crossings in New York City). The popularity of cordon time of day pricing stems from its practicality as it reduces the number of tolling points, and the initial investment and disturbances to the traffic. It should be said that the scheme works quite well, particularly for passenger car demand management purposes. However, as discussed later in the paper, this scheme has significant limitations that hamper its effectiveness for freight demand management.

Two different cases of trucking operations (i.e., single and multi-tour carriers) are considered. The former case considers the situation in which the carrier only makes a single tour to the study area during the day, while the latter discusses the case in which multiple tours are made. Although the single tour is a particular instance of the multi-tour case, it provides a nice introduction to the most complex multi-tour case that leads to conclusions that, for the most part, carry over to multi-tour operations.

5.1 Single Tour Carriers Under Cordon Based Time of Day Pricing

This section considers a carrier *j* that is making a single delivery tour to a set Ω_j^{BC} of receivers *i* during the regular hours (base case conditions) such that $R_i \in \Omega_j^{BC}$. This is a key segment of the truck traffic as it represents a significant portion of the total truck traffic The analyses of data for New York City indicate that single tour carriers are about 40% of the total, while data from Denver suggest 72% (Holguín-Veras and Patil, 2005). Assume now that the carrier is considering doing off-hour deliveries in response to requests received from its customers. This leads to a situation in which the original set of customers is partitioned into a subset of receivers that prefers regular hour deliveries (Ω_j^R), and the receivers preferring off-hours (Ω_j^O). It is assumed that no customers are lost because of the partition.

Consider the expenditure function shown in equation (15), which represents the base case (*BC*) conditions. As shown, the total cost is a function of the fixed costs, distance and time to complete the tour, and a toll surcharge to be paid when traveling during the regular hours. The fixed cost has two components: the cost associated with traveling from the home base to the customers' location, and the cost of traveling back to the home base. The unit distance cost takes into account the expenditures associated with operating costs that depend on distance traveled; while the unit time cost includes time related items, most notably wages and cargo's time value.

$$C_j^{BC} = (C_{FC}^{BC} + C_{HB}^{BC}) + c_D^{BC} D^{BC} + c_T^{BC} T^{BC} + S^R \tag{15}$$

Consider now the case of a mixed operation (*M*) in which both regular and off-hour deliveries are conducted, i.e., $N^O < N^{BC}$. In this context, the total cost is comprised of the summation of the costs for regular and the off-hour operations (denoted by the superscripts *R* and *O*, respectively). Thus, the total cost for the mixed operation is:

$$C_j^M = C_j^R + C_j^O \tag{16}$$

$$C_j^M = \left[(C_{FC}^R + C_{HB}^R) + (C_{FC}^O + C_{HB}^O)\right] + \left[c_D^R D^R + c_D^O D^O\right] + \left[c_T^R T^R + c_T^O T^O\right] + S^R \tag{17}$$

The first term represents the total fixed cost associated with the mixed operation, i.e., the summation of the costs associated with the trip to reach the first customer and the return to the home base, during both the regular and the off-hours. The second and the third terms are the distance and time costs, respectively. The fourth term is the toll surcharge for regular hour travel.

As discussed elsewhere (Holguín-Veras, 2008), the mixed operation would be profitable to the carrier if its net profits are larger than the one for the base case. Mathematically:

$$G_j^M - C_j^M \geq G_j^{BC} - C_j^{BC} \tag{18}$$

Where: G_j^M and G_j^{BC} represent the gross revenues, and C_j^M and C_j^{BC} are the costs associated with the mixed and the base case operations, respectively.

Letting $\Delta G_j = G_j^M - G_j^{BC}$ and $\Delta C_j = C_j^M - C_j^{BC}$, leads to:

$$\Delta G_j \geq \Delta C_j \tag{19}$$

Substituting equations (15) and (17) in (19), simplifying, and grouping terms, one could obtain:

$$\begin{aligned}&\left[(C_{FC}^R + C_{HB}^R) + (C_{FC}^O + C_{HB}^O) - (C_{FC}^{BC} + C_{HB}^{BC})\right] + \left[c_D^R D^R + c_D^O D^O - c_D^{BC} D^{BC}\right] \\ &+ \left[c_T^R T^R + c_T^O T^O - c_T^{BC} T^{BC}\right] \leq \Delta G_j, \forall_{N^O < N^{BC}}\end{aligned} \tag{20}$$

Equation (20) captures the conditions that must be met for the carrier to participate in off-hour deliveries in terms of the cost components. The most striking feature of equation (20) is the absence of the toll surcharge, which disappears from the incremental cost because the carrier has to travel during both the regular and the off-hours. This implies that, for a sizable segment of the intended target, cordon time of day tolls do not play any role whatsoever in inducing the carriers to switch to the off-hours. In other words, increasing the tolls only reduces the carrier's profits. Not surprisingly, the carriers oppose such tolls which they, correctly it seems, call ineffective.

The only situation in which the cordon tolls play a role is when all receivers in the tour decide to switch to the off-hours. In this case, the necessary condition becomes:

$$\left[(C_{FC}^O + C_{HB}^O) + c_D^O D^O + c_T^O T^O\right] - \left[\left(C_{FC}^{BC} + C_{HB}^{BC}\right) + c_D^{BC} D^{BC} + c_T^{BC} T^{BC} + S^R\right] \leq \Delta G_j, \forall_{N^O = N^{BC}} \tag{21}$$

Equation (21) could be further simplified by pointing that both the fixed cost to travel to/from the tolled area, and the distance related costs during the off-hours are likely to be smaller than their counterparts in the base case. In the case of the fixed cost, this is due to faster travel during the off-hours that would lead to lower costs; while in the case of the distance cost is because delivering during the off-hours may enable carriers to re-optimize their routes without the constraints imposed by congestion. However, for simplicity sake, these effects are disregarded by assuming that both the fixed cost and the distance related costs in the off-hours are equal to the base case values. This leads to:

$$c_T^O T^O - c_T^{BC} T^{BC} - S^R \leq \Delta G_j \,, \forall_{N^O = N^{BC}} \tag{22}$$

Equations (20) and (22) indicate the existence of a policy paradox. Equation (20) clearly shows that unless all receivers switch to the off-hours, the toll surcharge plays no role in inducing the carrier to switch. However, equation (22) implies that as long as delivering in the off-hours is cheaper than during the regular hours (which is generally the case), the toll surcharge is not needed to induce the carriers to switch to the off-hours. To see why, it suffices to point out that the term $c_T^O T^O$ is likely to be smaller than $c_T^{BC} T^{BC}$, which leads to cost savings even if the toll surcharge is equal to zero. In other words, a cordon toll is not likely to be of any use for freight demand management purposes (though it could play an important revenue generation role). This is a paradox: cordon time of day tolls would only play a role when all receivers agree to off-hour deliveries; however, in such a condition the toll surcharge is not needed because the cost savings associated with the off-hour operation are likely to provide all the incentive needed for the carrier to switch to the off-hours. These results lead to question the use of cordon time-of-day pricing for freight demand management purposes.

The analyses that follow focus on the general case where the original receivers are split between the regular and the off-hours. At key places of the write up, the particular case where all receivers switch to the off-hours is discussed to provide a complete picture of the anticipated behavioral response. To facilitate the analyses, equation (20) has been transformed into equation (22) that expresses the incremental total cost as a function of the incremental fixed cost, incremental distance cost, incremental time cost, and incremental toll cost (that, unless all receivers switch to the off-hours, is equal to zero).

$$\Delta C_F + \Delta C_D + \Delta C_T + \Delta C_S \leq \Delta G_j \tag{23}$$

Incremental fixed costs

The incremental fixed cost (ΔC_F), shown in equations (24) and (25), represents the increase in fixed costs, i.e., the ones associated with traveling from the home base to the customers' location and back, between the mixed and base case operations. The reader shall notice that in most cases the fixed costs for both the base case and the regular hours of the mixed operation are likely to be very similar. In such a case, the incremental fixed cost could be approximated by equation (25) that shows that the incremental fixed cost is equal to the one associated with the off-hour deliveries. Obviously, if all the receivers switch to the off-hours the incremental fixed cost vanishes.

$$\Delta C_F = \left[(C_{FC}^R + C_{HB}^R) + (C_{FC}^O + C_{HB}^O) - (C_{FC}^{BC} + C_{HB}^{BC})\right] \quad (24)$$

$$\Delta C_F \cong \begin{cases} (C_{FC}^O + C_{HB}^O), \forall_{N^O < N^{BC}} \\ 0, \forall_{N^O = N^{BC}} \end{cases} \quad (25)$$

This result indicates that proximity to off-hour customers has a key role in determining the profitability of off-hour delivery operations as the farther a carrier is from its customers, the less profitable it is to diversify operations via an off-hour deliveries program. This is because the larger the incremental fixed cost the more difficult to meet the profitability constraint shown in equation (20). This finding is consistent with the discrete choice models estimated using stated preference data collected from a sample of carriers (Holguín-Veras, 2006).

Incremental distance costs

The incremental distance cost captures the additional distance related costs the carrier would incur if it decides to do off-hour deliveries. The paper assumes that the incremental distance cost for the situation in which all receivers are in the off-hours is equal to zero. Although, as noted before there could be cost savings, this effect is disregarded. Furthermore, since the unit distance costs are likely to be very similar (if not exactly the same), because they are determined by road conditions and other factors that are the same regardless of time of travel (Chesher and Harrison, 1987), one could obtain:

$$\Delta C_D = \begin{cases} c_D\left(D^R + D^O - D^{BC}\right), \forall_{N^O < N^{BC}} \\ 0, \forall_{N^O = N^{BC}} \end{cases} \quad (26)$$

To compute the travel distances, the approximation model discussed in the previous section is used. As a result, the incremental distance cost becomes:

$$\Delta C_D = \begin{cases} \phi c_D\left(\sqrt{A^R N^R} + \sqrt{A^O N^O} - \sqrt{A^{BC} N^{BC}}\right), \forall_{N^O < N^{BC}} \\ 0, \forall_{N^O = N^{BC}} \end{cases} \quad (27)$$

Equation (27) clearly suggests the potential benefits of geographic segmentation. A mixed operation in which A^R and A^O are relatively small compared to A^{BC} could lead to cost savings.

Since the net impact on distance traveled depends on the size of the service areas and the number of customers in each group, it is important to discuss, in addition to the expected values, the key cases that could arise from the partitioning of the original customers.

Assuming perfectly complementary service areas, and $N^O < N^{BC}$:

$$\Delta C_D = \phi c_D \sqrt{\frac{A^{BC}}{N^{BC}}}\left[N^R + N^O - N^{BC}\right] \tag{28}$$

Since $N^{BC} = N^R + N^O$

$$\Delta C_D = 0 \tag{29}$$

In other words, if the partition of customers conforms to perfectly complementary service areas, there is no change in the distance traveled between the base case and mixed operations. This implies that in cases where there is a pronounced geographic segmentation, e.g., Case A in Figure 3, the partition would lead to cost savings. If all receivers switch to the off-hours, the travel distance would be the same, which leads to $\Delta C_D = 0$.

For the expected value, the incremental distance cost is:

$$\Delta C_D = \begin{cases} \phi c_D \sqrt{L_{ox} L_{oy}}\left[\left(\frac{N^R - 1}{N^R + 1}\right)\sqrt{N^R} + \left(\frac{N^O - 1}{N^O + 1}\right)\sqrt{N^O} - \left(\frac{N^{BC} - 1}{N^{BC} + 1}\right)\sqrt{N^{BC}}\right], \forall_{N^O < N^{BC}} \\ 0, \forall_{N^O = N^{BC}} \end{cases} \tag{30}$$

Equation (30) suggests that an increase in travel distance is likely as the first two terms are likely to be larger than the third. The exceptions would be the case in which only one customer is in either the regular or the off-hours, because one of the first two terms would vanish, and those cases where there is a marked geographic segmentation of receivers (e.g., cases A and B).

In the case of perfectly overlapping service areas, the incremental distance cost becomes:

$$\Delta C_D = \begin{cases} c_D \sqrt{N^{BC} L_{ox} L_{oy}}\left[\frac{\sqrt{N^R} + \sqrt{N^O}}{\sqrt{N^{BC}}} - 1\right] = c_D\left[f_D^{'} - 1\right] D^{BC} \forall_{N^O < N^{BC}} \\ 0, \forall_{N^O = N^{BC}} \end{cases} \tag{31}$$

Where:

$$f_D^{'} = \frac{\sqrt{N^R} + \sqrt{N^O}}{\sqrt{N^{BC}}} \tag{32}$$

This means that the net impact on distance traveled only depends on the number of nodes assigned to each time period in relation to the total number of nodes in the base case. It is straightforward to show that the maximum value is $f_D^{'} = \sqrt{2}$. This implies that the contribution of ΔC_D to the total incremental cost is likely to be relatively small because of two reasons: (1) it is bound from above (by an average of 41%, i.e., the square root of two); and (2) c_D is relatively small when compared to c_T (typically one order of magnitude smaller).

Incremental time costs

The incremental time costs, that are estimated using the approximation model of equation (6) and average travel speeds for the regular and off-hours. This leads to:

$$\Delta C_T = \begin{cases} \left[c_T^R \frac{D^R}{u^R} + c_T^O \frac{D^O}{u^O} - c_T^{BC} \frac{D^{BC}}{u^{BC}} \right], \forall_{N^O < N^{BC}} \\ \left[c_T^O \frac{D^O}{u^O} - c_T^{BC} \frac{D^{BC}}{u^{BC}} \right], \forall_{N^O = N^{BC}} \end{cases} \tag{33}$$

Expressing: the travel speed during the off-hours as a function of the one for regular hours multiplied by a factor $\gamma > 1$, the unit time cost during the off-hours as a function of the unit time cost during the regular hours and a factor $\theta > 1$, and noting that $c_T^{BC} = c_T^R$:

$$\Delta C_T = \begin{cases} \frac{\phi}{u^R} \left[\sqrt{A^R N^R} + \frac{\theta}{\gamma} \sqrt{A^O N^O} - \sqrt{A^{BC} N^{BC}} \right] c_T^R, i\forall_{N^O < N^{BC}} \\ \frac{\phi}{u^R} \left[\frac{\theta}{\gamma} \sqrt{A^O N^O} - \sqrt{A^{BC} N^{BC}} \right] c_T^R, \forall_{N^O = N^{BC}} \end{cases} \tag{34}$$

In the case of perfectly complementary service areas, and denoting the customer density, δ^{BC}:

$$\Delta C_T = \frac{\phi}{u^R} \frac{N^O}{\sqrt{\delta^{BC}}} \left[\frac{\theta}{\gamma} - 1 \right] c_T^R, \forall_{N^O < N^{BC}} \tag{35}$$

This equation implies that there would be time cost savings as long as the increase in wages is less than the increase in travel speed, i.e., $\theta/\gamma < 1$. In other words, the more significant the difference between the travel speeds for the regular and off-hours, the more beneficial it is for the carriers to do off-hour deliveries.

The experience of Linens-N-Things provides an estimate of γ. Company executives, as part of an in-depth interview with the author, indicated they implemented off-hour deliveries before and during the Los Angeles Olympics in 1984, and found out that the travel speeds during the night hours averaged 34 miles per hour, compared to 17 miles per hour during the days hours ($\gamma = 2$) (Holguín-Veras, 2006). This implies that, even if the carrier had to pay premium wages (that according to industry sources could be in the range of 10-15%, i.e., $\theta \cong 1.10 - 1.15$), there will be savings in the time cost component. Another implication of equation (35) is that the incremental time costs are inversely related with the customer density. For that reason, the larger time savings would take place in areas with sparse customers.

In the expected value case, the incremental time cost is:

$$\Delta C_T = \begin{cases} \phi \dfrac{c_T^R}{u^R} \sqrt{A_o} \left[\left(\dfrac{N^R - 1}{N^R + 1} \right) \sqrt{N^R} + \dfrac{\theta}{\gamma} \left(\dfrac{N^O - 1}{N^O + 1} \right) \sqrt{N^O} - \left(\dfrac{N^{BC} - 1}{N^{BC} + 1} \right) \sqrt{N^{BC}} \right], \forall_{N^O < N^{BC}} \\ \phi \dfrac{c_T^R}{u^R} \sqrt{A_o N^{BC}} \left[\dfrac{\theta}{\gamma} - 1 \right] \left(\dfrac{N^{BC} - 1}{N^{BC} + 1} \right), \forall_{N^O = N^{BC}} \end{cases} \quad (36)$$

This suggests that carriers operating in congested urban areas are the ones that stand to gain the most from off-hour deliveries as in these cases the ratio of the speeds is the largest, leading to smaller values of the ratio θ / γ and larger savings.

In the case of perfectly overlapping service areas:

$$\Delta C_T = \begin{cases} \phi \dfrac{c_T^R}{u^R} \sqrt{AN^{BC}} \left[g_T^{'} - 1 \right], \forall_{N^O < N^{BC}} \\ \phi \dfrac{c_T^R}{u^R} \sqrt{AN^{BC}} \left[\dfrac{\theta}{\gamma} - 1 \right], \forall_{N^O = N^{BC}} \end{cases} \quad (37)$$

Where:

$$g_T^{'} = \frac{\sqrt{N^R} + \frac{\theta}{\gamma}\sqrt{N^O}}{\sqrt{N^R + N^O}} = \frac{\sqrt{N^R} + \frac{\theta}{\gamma}\sqrt{N^O}}{\sqrt{N^{BC}}} \tag{38}$$

These results are similar to the ones obtained before in that the time cost impacts are estimated as a function of the unit impact (term in brackets) multiplied by the total time traveled in the base case, though the multiplier θ / γ increases the comparative advantage of off-hour deliveries. The term $g_T^{'}$ captures the relative change in travel time with respect to the travel time in the base case. The sensitivity analyses showed that, in general, $g_T^{'}$ increases with the number of customers accepting off-hour deliveries up to a maximum of about 1.2, where it decreases. This was observed for the practical range of values of N^{BC} and N^{OP}.

Incremental toll costs

In the case of single-tour carriers, the incremental toll costs depend on whether or not the carrier could eliminate the regular hour tour. In the most general condition, where some receivers decide to stay during the regular hours, the incremental toll costs will be equal to zero. Only if all receivers switch to the off-hours, the carrier will save the of the toll (negative cost).

$$\Delta C_S = \begin{cases} 0, \forall_{N^O < N^{BC}} \\ -S^R, \forall_{N^O = N^{BC}} \end{cases} \tag{39}$$

The results discussed in this section indicate that neither the incremental fixed nor the incremental toll costs depend on the configuration of the service areas that arise after the receivers make their decisions regarding off-hour deliveries. In both cases, the incremental costs are determined by how many receivers decide to accept off-hour deliveries: if all of receivers are in the off-hours, the carrier could save the toll surcharge and the cost of the extra trip to the tolled area. Conversely, if not all receivers switch to the off-hours, the carrier cannot avoid the toll surcharge, and as a result, the toll plays no role in inducing a shift to the off-hours.

The derivations show that there could be significant differences in terms of the incremental distance and time costs. The formulations reveal that mixed operations are likely to lead to relatively small increases in incremental distance costs that is bounded from above by a factor of

$\sqrt{2}$, though there are cases in which it could be either zero (as in the perfectly complementary case) or even negative (leading to cost savings) as in Case A of Figure 3. The most important component of the incremental total cost is its time component. The results show that, at one end of the spectrum (perfectly complementary case), there would always be time cost savings as long as $\theta / \gamma < 1$, i.e., if the increase in wages is smaller than the increase in travel speed. At the other end (perfectly overlapping case), there could be cost increases though they are expected to be lower than 1.2 of base costs. The expected value depends on the number of receivers that decide to switch to the off-hours, i.e., the more receivers switch the off-hours the larger the savings. If all receivers switch the off-hours, the savings would amount to $(\theta / \gamma - 1)$ of base case costs, i.e., 57.5% for $\theta = 1.15$ and $\gamma = 2$ in the New York City case. In absolute value, these are significant savings given the high values of travel times observed in real life that sometimes exceeds \$60/hour (Holguín-Veras and Brom, 2008).

5.2 Case II: Multi-tour Carriers under Cordon Based Time of Day Pricing

This case considers carriers that make more than one delivery tour per unit time to the study area. The sparse data available on truck tours (Holguín-Veras and Patil, 2005; Holguín-Veras, 2008), indicate that multi-tour carriers represent between 28% to 60% of the total tours. As a consequence of their operational features, multi-tour carriers are likely to exhibit behavioral responses different than those exhibited by single tour carriers. Faced with the prospect of implementing a mixed operation with both regular hour and off-hour delivery tours, these carriers could rearrange, consolidate and modify tours at their convenience. Furthermore, since the number of stops per tour decreases with the number of tours per day (Holguín-Veras and Patil, 2005), multi-tour carriers may have an easier time doing off-hour deliveries because they have to coordinate with less customers per tour than single-tour carriers. As a result of this, multi-tour carriers have more flexibility than their counterparts.

This section assumes that: carrier j is making multiple delivery tours to the study area; receivers are only served by this carrier; and tours are relatively similar, in terms of the tour distance, time and number of stops. This is an acceptable assumption because truck dispatchers tend to balance service areas and number of customers to visit by each driver (Tang and Miller-Hooks, 2006). Under these assumptions, the average values (denoted by upper bars) may be assumed to provide a good way to assess the performance of the operation. The symbol K^{BC} denotes the number of tours in the base case conditions; while K^R, and K^O represent the number of tours for the regular and off-hours part of the mixed operation. The expenditure function becomes:

$$C_j^{BC} = \left((\overline{C}_{FC}^{BC} + \overline{C}_{HB}^{BC}) + c_D \overline{D}^{BC} + c_T^{BC} \overline{T}^{BC} + S^R \right) K^{BC} \tag{40}$$

For the case of a mixed operation (M) with both regular and off-hour deliveries:

$$C_j^{R} = \left((\overline{C}_{FC}^{R} + \overline{C}_{HB}^{R}) + c_D \overline{D}^{R} + c_T^{R} \overline{T}^{R} + S^R \right) K^{R} \tag{41}$$

and

$$C_j^{OP} = \left(\overline{C}_{FC}^{O} + \overline{C}_{HB}^{O} + c_D \overline{D}^{O} + c_T^{O} \overline{T}^{O} \right) K^{O} \tag{42}$$

Then, the total incremental cost could be obtained as:

$$\begin{aligned} \Delta C_j = & \left((\overline{C}_{FC}^{R} + \overline{C}_{HB}^{R}) K^R + (\overline{C}_{FC}^{O} + \overline{C}_{HB}^{O}) K^O - (\overline{C}_{FC}^{BC} + \overline{C}_{HB}^{BC}) K^{BC} \right) + \left(K^R - K^{BC} \right) S^R \\ & + \left(\overline{D}^R K^R + \overline{D}^O K^O - \overline{D}^{BC} K^{BC} \right) c_D + \left(c_T^R \overline{T}^R K^R + c_T^O \overline{T}^O K^O - c_T^{BC} \overline{T}^{BC} K^{BC} \right) \end{aligned} \tag{43}$$

Decomposing the incremental total cost into its key components:

$$\Delta C_j = \Delta C_F + \Delta C_D + \Delta C_T + \Delta C_S \tag{44}$$

Where:

$$\Delta C_F = \left((\overline{C}_{FC}^{R} + \overline{C}_{HB}^{R}) K^R + (\overline{C}_{FC}^{O} + \overline{C}_{HB}^{O}) K^O - (\overline{C}_{FC}^{BC} + \overline{C}_{HB}^{BC}) K^{BC} \right) \tag{45}$$

$$\Delta C_D = c_D \left(\overline{D}^R K^R + \overline{D}^O K^O - \overline{D}^{BC} K^{BC} \right) \tag{46}$$

$$\Delta C_T = \frac{c_T^R}{u^R} \left[\overline{D}^R K^R + \frac{\theta}{\gamma} \overline{D}^O K^O - \overline{D}^{BC} K^{BC} \right] \tag{47}$$

$$\Delta C_S = \left(K^R - K^{BC} \right) S^R \tag{48}$$

As shown, the incremental costs depend on how the carrier organizes its operations, in terms of the number of tours during the regular and the off-hours. Three different possibilities exist. The total number of tours in the mixed operation (K^M) could either be: smaller than, equal to, or higher than the number of tours in the base case (K^{BC}). However, for the reasons discussed elsewhere (Holguín-Veras, 2008) there are only two relevant cases, ($K^M = K^{BC}$, and $K^M = K^{BC}+1$).

However, since the formulations developed are able to accommodate all cases, only the case of $K^M = K^{BC}$ are discussed in detail. The reader shall notice that in the multi-tour case there is no need to discuss the sub-cases that arise if the number of receivers in the off-hours is less than or equal to the one in the case, as this is implicitly captured by the number of trips made.

For $K^M = K^{BC}$ and since $(\overline{C}_{FC}^{R} + \overline{C}_{HB}^{R}) \cong (\overline{C}_{FC}^{BC} + \overline{C}_{HB}^{BC})$, the incremental fixed cost (ΔC_F) is:

$$\Delta C_F \cong \left((\overline{C}_{FC}^{O} + \overline{C}_{HB}^{O}) - (\overline{C}_{FC}^{BC} + \overline{C}_{HB}^{BC}) \right) K^O \tag{49}$$

Equation (49) shows that the magnitude of the fixed cost depends on the relation between the fixed costs for the base case and the one for the off-hours. In cases where the customers accepting off-hour deliveries are closer to the carrier home base, than those receiving during regular hours there will be savings ($\Delta C_F < 0$); otherwise, higher costs would accrue.

The incremental distance cost shown in equation (50), captures the additional distance related costs the carrier would incur. In terms of the approximation model, for $K^M = K^{BC}$:

$$\Delta C_D = \phi c_D \left[(\sqrt{\overline{A}^R \overline{N}^R} - \sqrt{\overline{A}^{BC} \overline{N}^{BC}}) K^{BC} + (\sqrt{\overline{A}^O \overline{N}^O} - \sqrt{\overline{A}^R \overline{N}^R}) K^O \right] \tag{50}$$

Assuming $\sqrt{\overline{A}^R \overline{N}^R} \cong \sqrt{\overline{A}^{BC} \overline{N}^{BC}}$ leads to:

$$\Delta C_D \cong \phi c_D (\sqrt{\overline{A}^O \overline{N}^O} - \sqrt{\overline{A}^R \overline{N}^R}) K^O \tag{51}$$

Equation (51) shows that the incremental distance cost is a function of how compact the off-hour delivery tours are with respect to the tours in the regular hours. Off-hour delivery tours with customers relatively close together will require shorter travel distances and travel times, leading to cost savings. At the other end of the spectrum, off-hour delivery tours serving customers far away from each other would bring about significant cost increases. Again, this provides another indication of the potential benefits attributable to geographic segmentation of receivers.

The incremental time costs are for $K^M = K^{BC}$, and $K^R = K^{BC} - K^O$ equal to:

$$\Delta C_T = \phi \frac{c_T^R}{u^R} \left[\left\{ \sqrt{\overline{A}^R \overline{N}^R} - \sqrt{\overline{A}^{BC} \overline{N}^{BC}} \right\} K^{BC} + \left\{ \frac{\theta}{\gamma} \sqrt{\overline{A}^O \overline{N}^O} - \sqrt{\overline{A}^R \overline{N}^R} \right\} K^O \right] \tag{52}$$

For the case in which $\sqrt{\overline{A}^R \overline{N}^R} \cong \sqrt{\overline{A}^{BC} \overline{N}^{BC}}$:

$$\Delta C_T \cong \phi \frac{c_T^R}{u^R} \left[\frac{\theta}{\gamma} \sqrt{\overline{A}^O \overline{N}^O} - \sqrt{\overline{A}^R \overline{N}^R} \right] K^{OP} \quad (53)$$

As in the case of incremental distance cost, the incremental time cost depends on the difference between the time costs between the off and regular hour. Furthermore, since it is likely that $\theta / \gamma < 1$, the time related savings accrue faster than in the case of distance related savings.

The incremental toll cost, shown in equation (54), is equal to the amount of money saved by switching K^O trips to the off-hours. If $K^M = K^{BC}$, $K^R = K^{BC} - K^O$:

$$\Delta C_S = -K^{OP} S^R \quad (54)$$

In general terms, the results shown above are consistent with the ones for single-tour carriers. As in the previous case, and for similar reasons, the most important cost components are the incremental fixed costs, and the incremental time costs.

6. CASE II: CARRIER-RECEIVER RESPONSE UNDER TIME-DISTANCE PRICING

This chapter considers the case of a time-distance pricing scheme in which the toll to be paid is a function of the time spent and the distance traveled in the tolled area. Such toll regime is close to ideal as it may lead to the internalization of externalities that are a function of distance, e.g., pavement damage; as well as those that depend on the time spent in the area, e.g., pollution generated by idling trucks. To analyze the performance of such systems, the formulations obtained in the previous chapter were suitable modified. The following sections discuss the results for single and multi-tour carriers. For the sake of brevity, only final results are discussed.

6.1 Single tour carriers under time-distance pricing

Under a time-distance pricing scheme, the carrier would be charged a toll that is a function of the time and distance traveled during the regular and the off-hours. The corresponding incremental toll cost is shown below.

$$\Delta C_{TDP} = \begin{cases} \left[\alpha_T^R \left(T^R - T^{BC}\right) + \alpha_T^O T^O\right] + \left[\alpha_D^R \left(D^R - D^{BC}\right) + \alpha_D^O D^O\right], i\forall_{N^O < N^{BC}} \\ \left[\alpha_D^O T^O - \alpha_T^R T^{BC}\right] + \left[\alpha_D^O D^O - \alpha_D^R D^{BC}\right], \forall_{N^O = N^{BC}} \end{cases} \quad (55)$$

Where:

α_D^R, α_D^O = Distance based unit toll for distance traveled in tolled area (regular, and off-hours)

α_T^R, α_T^O = Time based unit toll for time spent in tolled area (regular, and off-hours)

Equation (55) indicates that, in sharp contrast with the cordon pricing case, the time-distance tolls do play a role in fostering off-hour deliveries. As shown, the higher the values of the unit charges and the time/distance switched to the off-hours, the stronger the incentive to do off-hour deliveries. To assess the impact of time-distance tolls, it is best to incorporate the incremental toll costs into the incremental fixed, distance, and time costs obtained before. This leads to:

$$\Delta C_{F,TDP} + \Delta C_{D,TDP} + \Delta C_{T,TDP} \le \Delta G_j \quad (56)$$

In mathematical terms:

$$\Delta C_{F,TDP} \cong \begin{cases} c_D\left(D_{FC}^O + D_{HB}^O\right) + c_T^O\left(T_{FC}^O + T_{HB}^O\right), \forall_{N^O < N^{BC}} \\ 0, i\forall_{N^O = N^{BC}} \end{cases} \quad (57)$$

$$\Delta C_{D,TDP} = \begin{cases} \left(c_D + \alpha_D^R\right)\left(D^R - D^{BC}\right) + \left(c_D + \alpha_D^O\right)D^O, \forall_{N^O < N^{BC}} \\ \left(\alpha_D^O - \alpha_D^R\right)D^{BC}, \forall_{N^O = N^{BC}} \end{cases} \quad (58)$$

$$\Delta C_{T,TDP} = \begin{cases} \left(c_T^R + \alpha_T^R\right)\left(T^R - T^{BC}\right) + \left(c_T^O + \alpha_T^O\right)T^O, \forall_{N^O < N^{BC}} \\ \left(c_T^O + \alpha_T^O\right)T^O - \left(c_T^R + \alpha_T^R\right)T^{BC}, \forall_{N^O = N^{BC}} \end{cases} \quad (59)$$

Equation (57) indicates that time-distance pricing does not impact the incremental fixed cost as the trip to and from the home base to the study area is not tolled. Equations (58) and (59) have very similar structures. The first terms in both equations reflect the reduction in regular hour travel costs due to the off-hour delivery operation; while the second terms capture the costs associated with off-hour deliveries. In both cases, the first terms are negative (cost savings) because $T^R < T^{BC}$ and $D^R < D^{BC}$, while their second terms are positive (cost increases). Furthermore, since the externalities produced by traveling during the regular hours are larger than the ones during the off-hours, one would expect that a sound pricing structure would lead to $\alpha_T^R >> \alpha_T^O$, and $\alpha_D^R >> \alpha_D^O$. This implies that the savings in time related costs (the first term) will increase with the magnitude of the unit distance-time tolls. Obviously, as the number of off-hour receivers increases the overall profitability also increases. These results stand in sharp contrast with the ones for cordon pricing, discussed in the previous chapter, in which it was proven that the tolls have no impact whatsoever in inducing a shift to the off-hours.

6.2 Multi tour carriers under time-distance pricing

It is straightforward to extend the results of the previous section to the case of multi-tour carriers. With proper manipulations, the following results can be found:

$$\Delta C_{F,TDP} \cong \left(c_D + \alpha_D^O - \beta_D^O\right)\left(\overline{D}_{FC}^O + \overline{D}_{HB}^O\right) + \left(c_T^O + \alpha_T^O - \beta_T^O\right)\left(\overline{T}_{FC}^O + \overline{T}_{HB}^O\right)K^O \quad (60)$$

$$\Delta C_{T,TDP} = \left(c_T^R + \alpha_T^R\right)\left(\overline{T}^R K^R - \overline{T}^{BC} K^{BC}\right) + \left(c_T^O + \alpha_T^O - \beta_T^O\right)\overline{T}^O K^O \quad (61)$$

$$\Delta C_{D,TDP} = \left(c_D + \alpha_D^R\right)\left(\overline{D}^R K^R - \overline{D}^{BC} K^{BC}\right) + \left(c_D + \alpha_D^O - \beta_D^O\right)\overline{D}^O K^O \quad (62)$$

In qualitative terms, these results imply that the number of tours transferred to the off-hours do matter, as it increases the fixed costs. In other words, the more tours are transferred to the off-hours, the larger the incremental distance and cost savings.

<u>Perfectly complementary service areas:</u>

$$\Delta C_{TDP} = \phi\sqrt{\frac{\overline{A}^{BC}}{\overline{N}^{BC}}}\left[\left(\alpha_D^R + \frac{\alpha_T^R}{u^R}\right)\left(\overline{N}^R K^R - \overline{N}^{BC} K^{BC}\right) + \left(\alpha_D^O + \frac{\alpha_T^O}{u^R}\right)\overline{N}^O K^O\right] \quad (63)$$

<u>Expected value:</u>

$$\Delta C_{TDP} = \phi\sqrt{\overline{A}_o}\left[\begin{array}{l}\left(\alpha_D^R + \frac{\alpha_T^R}{u^R}\right)\left(K^R\left(\frac{\overline{N}^R - 1}{\overline{N}^R + 1}\right)\sqrt{\overline{N}^R} - K^{BC}\left(\frac{\overline{N}^{BC} - 1}{N^{BC} + 1}\right)\sqrt{\overline{N}^{BC}}\right) \\ + \left(\alpha_D^O + \frac{\alpha_T^O}{u^R}\right)K^R\left(\frac{\overline{N}^O - 1}{\overline{N}^O + 1}\right)\sqrt{\overline{N}^O}\end{array}\right] \quad (64)$$

<u>Perfectly overlapping service areas:</u>

$$\Delta C_{D,TDP} = \phi\sqrt{\overline{A}^{BC}\,\overline{N}^{BC}}\left[\left(\alpha_D^R + \frac{\alpha_T^R}{u^R}\right)\left(K^R\sqrt{\frac{\overline{N}^R}{\overline{N}^{BC}}} - 1\right) + \left(\alpha_D^O + \frac{\alpha_T^O}{u^R}\right)K^O\sqrt{\frac{\overline{N}^O}{\overline{N}^{BC}}}\right] \quad (65)$$

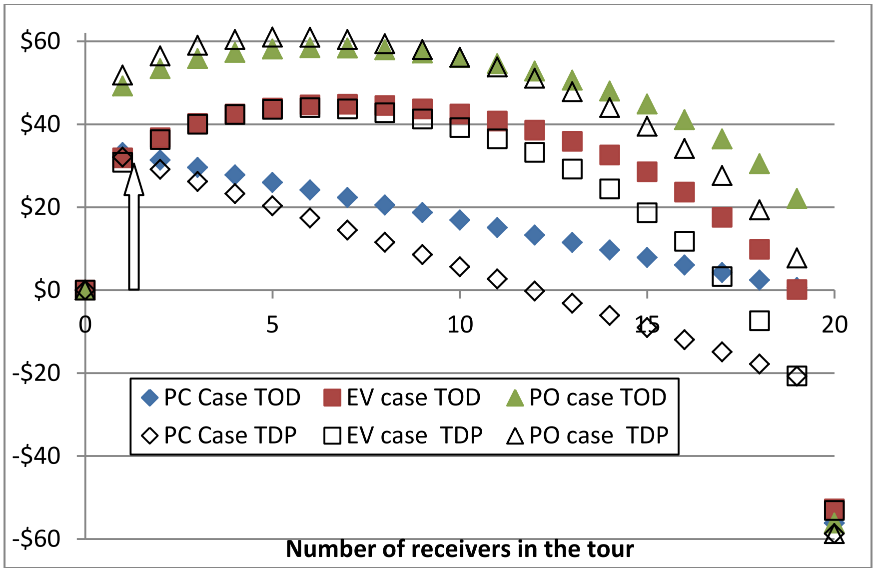
In order to provide a frame of reference, some numerical experiments were conducted to be discussed. The cases discussed are: perfectly overlapping (PO) service areas, which is the worst case scenario is terms of costs; perfectly complementary (PC) service areas, that is an approximation to the best case, and the expected value (EV) represents the “average” condition.

The analyses are based on a toll surcharge of $20, which is about what is typically charged to delivery vans for access to congested urban areas, e.g., New York City (Port Authority of New York and New Jersey, 2009). To ensure a fair comparison of results, the values of the cordon time-of-day surcharge and the unit distance and time tolls for time-distance pricing were selected so that both of them have approximately the same total impact in the costs. This was accomplished with α_D^R = $2/mile, α_D^O = $0.9/mile, α_T^R = $4/hour, and α_T^O = $2/hour, which were arbitrarily selected for illustration purposes. The numerical experiments in the paper, unless otherwise noted, correspond to: L_{ox} = 2 miles, L_{oy} = 11.5 miles, u^R = 10 miles per hour, c_D = $2/mile, c_T = $50/hour, and ϕ = 0.75. These values are what may be expected for Manhattan.

For the sake of brevity, the results shown correspond to a tour with twenty receivers. Figure 4 shows the total incremental costs for both cordon time-of-day and time-distance pricing. To facilitate understanding the results for cordon time-of-day are shown using solid bullets, and the ones for time-distance pricing using clear ones. As shown, implementing off-hour deliveries immediately increase the fixed cost (illustrated by an up arrow at N^O = 1).

In the case of cordon time-of-day pricing, increasing the number of off-hour deliveries increases total costs, in the PO and EV cases, up to a point where it starts to decrease. In the PC case, increasing the amount of off-hour deliveries always lead to cost reductions. In the PC and EV cases, the off-hour delivery operation is profitable if at least nineteen receivers agree to participate in off-hour deliveries. In contrast, the PO case requires full participation of the receivers for the off-hour deliveries to be profitable. The figure shows that time-distance pricing leads to small changes in incremental costs in the PO case, and a reduction in the breakeven number of receivers in both PC and EV cases.

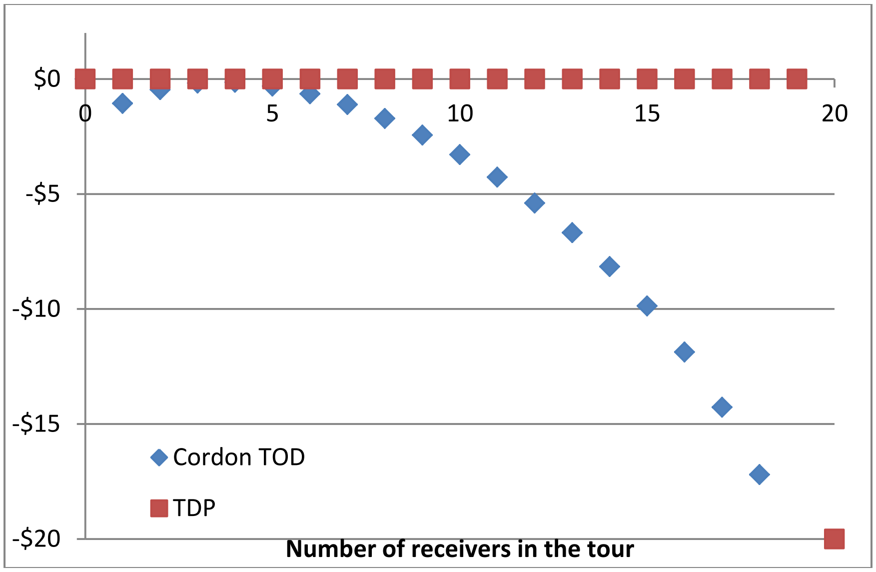
Figure 4: Incremental total costs for cordon time of day and time-distance pricing



Note: TOD refers to cordon time-of-day tolls, and TDP to time-distance pricing

A significant distinction between both pricing schemes is that while under time-distance pricing the larger the unit tolls the larger the impact, under cordon time-of-day the toll plays no role. This is because under time-distance pricing the carrier saves in tolls regardless of the number of off-hour customers, while under cordon time-of-day pricing, this only happens when all the customers are in the off-hours. This effect is clearly shown in Figure 5 that shows the incremental toll costs for both pricing schemes. As shown, under cordon time-of-day pricing the incremental toll costs are equal to zero, i.e., not providing an incentive, except when all receivers switch to the off-hours, which generates the spike in the incremental toll cost shown in the right end of the figure. In contrast, under time-distance pricing the carrier accrues cost savings from the start. As shown, if the number of receivers switching to the off-hours is low (in this case less than five) time-distance pricing does not have any noticeable impact.

Figure 5: Incremental toll costs Cordon pricing vs. Time-distance pricing



7. SECOND ORDER EFFECTS ON RECEIVERS AND CARRIERS

Throughout the discussions in the preceding chapters, the main focus has been on the direct (1^{st} order) effects that the pricing schemes and financial incentives have on carrier and receiver behavior. However, as outlined in Figure 2, a policy stimulus aimed at one agent could impact the other. This section discusses two such effects, which are the transfer of toll costs from carriers to receivers (m_j) and the transfer of financial incentives from receivers to carriers (F_{ij}).

7.1 Impacts of the transfer of toll costs on delivery rates

This section considers the impact that the pricing scheme has on delivery rates. The analyses assume a perfect competitive market with delivery rates equal to marginal costs. Although there are a number of different metrics that could be used as the unit of output, the paper uses the number of customers as it is directly tied to the models developed in the paper. In each case, the marginal costs are computed to gain insight into if, and how much of, the toll costs could be passed to receivers. This is an important policy question as, in order to induce a change in delivery times, a strong price signal must reach the receivers. There are two sub-cases worthy of discussion. The first one is when a receiver is transferred from a regular hour to an off-hour tour of the same carrier, leading to conservation of customers and a perfect inverse correlation between N^R and N^O. The second one is when the numbers of customers in each time period are not correlated, e.g., when a customer from another carrier is inserted in an existing tour.

In the most general case from the mathematical point of view, i.e., transfer of customers between tours belonging to the same carrier, the marginal cost under cordon time-of-day pricing could be obtained as the derivative with respect to N^R of equation (17). This leads to:

$$m_j^{N^R,S} = c_D \frac{\partial D^R}{\partial N^R} + c_T^R \frac{\partial T^R}{\partial N^R} + c_D \frac{\partial D^O}{\partial N^R} + c_T^O \frac{\partial T^O}{\partial N^R} \tag{66}$$

It should be highlighted that since D^O and T^O are functions of N^R as $N^O = N^B - N^R$, the derivatives with respect to N^R are different than zero. In contrast, if N^O and N^R are independent, the cross derivatives, i.e., the third and fourth terms, vanish. Equation (66) indicates that the delivery rate is equal to the monetized value of the additional distance and time required to make the deliveries in each time period, i.e., the marginal cost of inserting the customer in one tour and removing it from the other. Equation (66) implies that the delivery rate is not influenced by the toll surcharge used in cordon pricing. Obviously, since the toll signal does not reach the receivers, they will not switch to the off-hours. The only exception is when the addition of a customer produces an additional tour, as in this case, the surcharge could be transferred to receivers as it is part of the marginal cost of delivery.

Similar derivations for time-distance pricing lead to:

$$m_j^{N^R,TDP} = \left\{ \begin{array}{l} \left(c_D \frac{\partial D^R}{\partial N^R} + c_D \frac{\partial D^O}{\partial N^R} \right) + \left(c_T^R \frac{\partial T^R}{\partial N^R} + c_T^O \frac{\partial T^O)}{\partial N^R} \right) + \\ \left(\alpha_D^R \frac{\partial D^R}{\partial N^R} + \alpha_D^O \frac{\partial D^O}{\partial N^R} \right) + \left(\alpha_T^R \frac{\partial T^R}{\partial N^R} + \alpha_T^O \frac{\partial T^O}{\partial N^R} \right) \end{array} \right\} \tag{67}$$

As shown in equation (67), the marginal costs under time-distance pricing are equal to the summation of the monetized value of the additional distance and time required to make the deliveries during both regular and the off-hours, i.e., the base delivery rate, plus the associated time-distance tolls. In contrast with cordon time-of-day pricing, in time-distance pricing the tolls enter into the marginal costs implying that the carriers will be able to pass them to the receivers.

Using the approximation model for the expected value of the tour distance, one could compute an analytical expression to produce numerical results. Denoting:

$$D^R = D(N^R) = \phi\sqrt{A_o}\left(\frac{N^R - 1}{N^R + 1}\right)\sqrt{N^R} \tag{68}$$

$$D^O = D(N^O) = \phi\sqrt{A_o}\left(\frac{N^O - 1}{N^O + 1}\right)\sqrt{N^O} = \phi\sqrt{A_o}\left(\frac{N^B - N^R - 1}{N^B - N^R + 1}\right)\sqrt{N^B - N^R} \tag{69}$$

The marginal cost becomes:

$$m_j^{N^R,TDP} = \begin{Bmatrix} c_D\left(\frac{\partial D^R}{\partial N^R} + \frac{\partial D^O}{\partial N^R}\right) + \frac{c_T^R}{u^R}\left(\frac{\partial D^R}{\partial N^R} + \frac{\theta}{\gamma}\frac{\partial D^O}{\partial N^R}\right) + \\ \left(\alpha_D^R \frac{\partial D^R}{\partial N^R} + \alpha_D^O \frac{\partial D^O}{\partial N^R}\right) + \frac{1}{u^R}\left(\alpha_T^R \frac{\partial D^R}{\partial N^R} + \alpha_T^O \frac{1}{\gamma}\frac{\partial D^O)}{\partial N^R}\right) \end{Bmatrix} \tag{70}$$

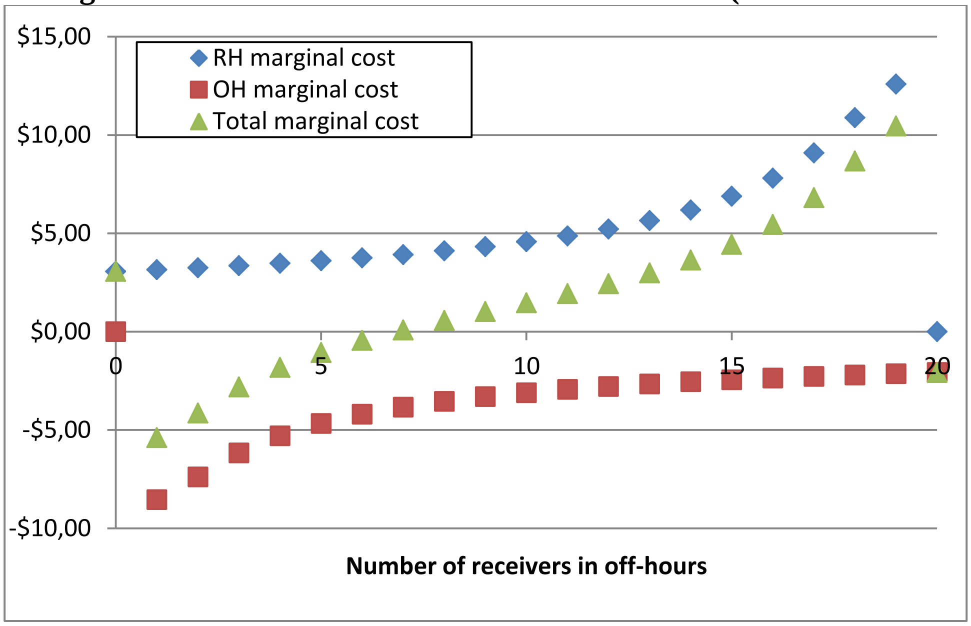
Where:

$$\frac{\partial D^R}{\partial N^R} = \frac{\phi\sqrt{A_o}}{(N^R + 1)^2\sqrt{N^R}}\left(\frac{(N^R)^2}{2} + 2N^R - \frac{1}{2}\right) \tag{71}$$

$$\frac{\partial D^O}{\partial N^R} = \frac{\phi\sqrt{A_o}}{(N^O + 1)^2\sqrt{N^O}}\left(-\frac{(N^O)^2}{2} - 2N^O + \frac{1}{2}\right) \tag{72}$$

Equations (70) thru (72) show that the marginal cost under time-distance pricing depends on the number of receivers and the time-distance unit tolls. The results also indicate that the marginal costs are a function of complex non-linear interactions (see Figure 6).

Figure 6: Marginal costs vs. Number of receivers in off-hours (20 receivers in the tour)



Having established that, in a competitive market, cordon time-of-day pricing will not lead to changes in behavior it is important to focus on time-distance pricing. The paper shows that time-distance pricing would enable carriers to transfer toll costs to receivers. However, the key question is whether or not this provides enough of an incentive for the receiver to switch to the off-hours. To answer it, one must compare the toll transfer from equation (67) to the incremental cost associated with a switch to the off-hours (Holguín-Veras, 2008).

The analysis takes into account that a receiver considering off-hours will face costs that depend on the amount of time it takes the deliveries to arrive during the off-hour period. Assuming that the goal is to induce all receivers in a tour to switch to the off-hours, the last receiver in the tour is going to accrue the costs associated with waiting for the delivery truck to travel to all previous customers, and make the corresponding deliveries. Mathematically, the cost for receiver $i=N^R$ is:

$$\Delta C_{i=N^R} = \overline{m}^O \left[T^R + \overline{\tau}^O N^R \right] \quad (73)$$

Where: T^R is the total tour time, $\overline{m}^O$ is the unit average cost of extending into the off-hours, and $\overline{\tau}^O$ is the average time spent actually doing a delivery.

For all receivers to switch to the off-hours, the toll component of the delivery rate (from equation 67) must be larger than the incremental cost associated with switching to the off-hours for the last receiver in the tour. This leads to:

$$\left(\alpha_D^R \frac{\partial D^R}{\partial N^R} + \alpha_D^O \frac{\partial D^O}{\partial N^R}\right) + \frac{1}{u^R}\left(\alpha_T^R \frac{\partial D^R}{\partial N^R} + \alpha_T^O \frac{1}{\gamma} \frac{\partial D^O)}{\partial N^R}\right) \geq \overline{m}^O \left[T^R + \overline{\tau}^O N^R\right] \tag{74}$$

Obviously, due to the number of unknowns, there is an infinite number of combinations of unit tolls that satisfy equation (74). In order to gain insight into the practicality of the tolls that arise from equation (74) one could focus on the case where the cross-derivatives are equal to zero as it provides a lower bound of the unit tolls. The reason is that, since the savings in distance and time accrued by removing the customer from another tour are not taken into account, the marginal distance and time included in the delivery rates are larger. As a result, the unit tolls required to meet equation (74) are lower than when these savings are included.

If the cross derivatives are equal to zero:

$$\left(\alpha_D^R + \frac{\alpha_T^R}{u^R}\right)\frac{\partial D^R}{\partial N^R} \geq \overline{m}^O \left[T^R + \overline{\tau}^O N^R\right] \tag{75}$$

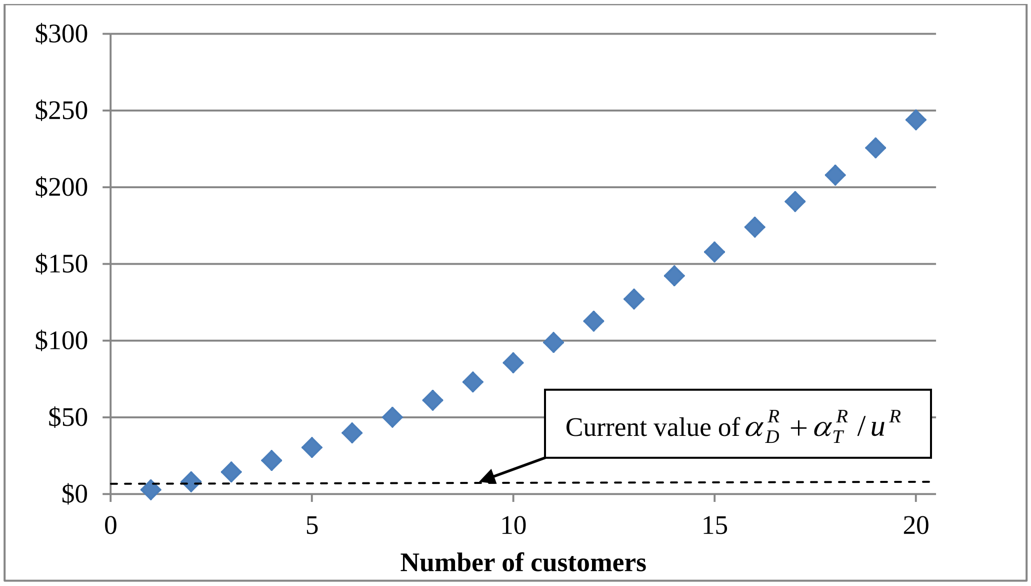
Consequently:

$$\left(\alpha_D^R + \frac{\alpha_T^R}{u^R}\right) \geq \frac{\overline{m}^O \left[T^R + \overline{\tau}^O N^R\right]}{\frac{\partial D^R}{\partial N^R}} \tag{76}$$

Equation (76) indicates that, in order for time-distance pricing (in isolation of other policies) to induce a switch to the off-hours, the unit tolls would have to be larger than the ratio of the expected incremental cost of switching to the off-hours to the marginal receiver (the numerator) and the expected marginal distance traveled (the denominator). Equation (76) indicates that while the expected incremental cost to the marginal receiver increases with the length of the tour (measured by N^R), the expected marginal distance traveled by the carrier decreases. As a result, the longer the tour, the higher the tolls required to induce the switch of all receivers.

To put things in perspective, numerical estimates have been produced with the data available for New York City. The in depth interviews conducted (Holguín-Veras, 2006) indicate that expanding hours of operation into the off-hours would cost the typical receiver in New York City between \$20 to \$100 for each additional hour in the off period. Figure 7 shows numerical estimates for different number of receivers. As shown, for a tour with only one customer the combined time-distance unit tolls, i.e., $(\alpha_D^R + \alpha_T^R / u^R)$, is about \$6; while for the average tour with five receivers is equal to \$30/mile. Regardless of how the \$30/mile are allocated between α_D^R and α_T^R, the author is doubtful that such tolls could be implemented in real life, as they are about five times larger than current base case costs. This implies that given the constraints imposed by the political realities, time-distance pricing may end up either not having any impact on carrier-receiver behavior, or only impacting the deliveries made using very short tour lengths.

Figure 7: Minimum time-distance unit tolls ($\alpha_D^R + \alpha_T^R / u^R$)



These considerations lead the author to believe that time-distance pricing by itself would only have a minor effect on inducing a switch of truck traffic to the off-hours. In other words, without the assistance of other policies that encourage receiver participation in off-hour deliveries, time-distance pricing is not likely to lead to a balanced distribution of truck traffic throughout the day.

7.2 Transfer of financial incentives to carriers

This section discusses the potential transfers of financial incentives from receivers to carriers (F_{ij} in Figure 2), e.g., higher rates during the off-hours. This takes into account that a receiver, faced with the prospect of not receiving the incentive because of the lack of a willing carrier, may decide to transfer part of the incentive F to the carrier. Assessing the likely role of F_{ij} is achieved by identifying the key cases.

Consider a situation in which the incentive F provided to the receivers is small so that only a small fraction of the receivers decide to accept off-hour deliveries. If the number of receivers willing to accept off-hour deliveries is small, the carrier will not agree either because the off-hour operation would not be profitable. Moreover, since the financial incentive is small, the receivers would not be able to cover their costs and share it with the carrier. In this situation, F_{ij} would be equal to zero. At the other end of the spectrum, a sufficiently large incentive F would lead all receivers in the tour to accept off-hour deliveries. However, if all receivers switch to the off-hours the carrier would switch without any external stimulus because the cost savings are enticing enough. Taking into account that receivers play the dominant role, and that carriers have an incentive to participate and therefore a weak negotiating position, it is likely that receivers would keep the financial incentive to themselves. In this case, F_{ij} would also be equal to zero.

F_{ij} could be expected to be different than zero at a very particular region in between these extremes, i.e., when the carrier's mixed operation is at the verge of profitability and the receivers have extra funds to share. Faced with the prospect of not receiving the incentive F, the receivers could transfer F_{ij} to the carrier and both of them would be better off. However, since the region in which F_{ij} could be different than zero is likely to be narrow, this author believes that the role of F_{ij} could be disregarded, as it is only active at the margins.

8. POLICY IMPLICATIONS AND CONCLUDING REMARKS

The paper has produced a number of important findings that provide insight for policy making. One of the key ones is that the receivers' decisions regarding whether or not to accept off-hour deliveries impact the carriers in different ways. The first and most obvious one, i.e., that the carrier cannot do off-hour deliveries without the concurrence of the receivers, was already identified in previous publications (Holguín-Veras et al., 2007a; Holguín-Veras, 2008; Holguín-Veras et al., 2008). A not so obvious way has to do with the service areas that arise from the receivers' decisions. This is important because the size of these service areas determine the distance and travel times, and the profitability for the carrier that would do the off-hour deliveries. In terms of carrier profitability, the paper identifies three configurations of service areas that correspond to: an approximation to the best case (perfectly complementary), the expected value condition, and the worst case scenario (perfectly overlapping).

The finding that off-hour deliveries would be more profitable when the service areas do not overlap highlight the benefits of implementing policies targeting receivers located at specific locations, e.g., downtown areas. Providing financial incentives for participation in off-hour deliveries to receivers located in a congested area are bound to be quite effective in enticing carrier participation. Equally important is that such approaches, by focusing on the congestion problem areas, could bring about significant reductions in both congestion and pollution.

The models show that the profitability of the mixed operation depends on the distance from the carrier's home base to the receivers. The farther the carrier is the less profitable the mixed operation: carriers located close to the study area should be the primary target of interest.

The numerical results suggest that, for a mixed operation to be profitable to the carrier, almost all receivers must agree to participate in off-hour deliveries. In all scenarios, the mixed operation is profitable if all the receivers in the tour switch to the off-hours. However, under the best case considered, i.e., perfectly complementary service areas, the breakeven number of receivers could be smaller than the expected value's; while in the worst case, the opposite is true.

The fact that carriers would do off-hour deliveries only if the majority of the receivers switch to the off-hours has important implications in terms of which segments of the industry would join off-hour deliveries. The first aspect to highlight is that due to the random nature of the receivers' response to an incentive, the probability of getting all receivers in the tour to agree to off-hour deliveries decreases geometrically with the number of receivers in the tour. This implies that carriers with short tours, i.e., small number of receivers visited, will have an easier time switching to the off-hours than carriers with long tours. Furthermore, even in cases where the carrier is able to pass toll costs as under a time-distance pricing regime, the magnitude of the tolls required to change the behavior of receivers grows exponentially with the tour length. Given that political considerations are bound to place a cap on the tolls, it follows that short tours would be the ones where the impact of time-distance pricing would be the highest and, therefore, the ones most likely to switch to the off-hours.

The paper also analyzed the performance of cordon time-of-day and time-distance pricing. The results produced have subtle and notable implications in terms of who would support the pricing scheme. In the case of cordon time-of-day pricing, since the carriers have great difficulties in passing the toll costs to receivers, most carriers have to absorb the toll costs. Under time-distance pricing, carriers would be able to pass toll costs to the receivers (though this may take time to allow for new contracts to be written) meaning that the price signals would reach the receivers. In essence, time-distance pricing transfers the toll burden from the carriers to the receivers.

All of this implies that the nature of the toll scheme determines which group would oppose it. While carriers are likely to oppose any cordon time-of-day pricing proposal, the receivers have nothing to fear because they would not be impacted. However, the situation reverses with time-distance pricing, as in this case the receivers would be impacted by the tolls; while the carriers would not. This conclusion is completely consistent with the public position of the American Trucking Associations (ATA) in support of an increase in the gas tax to finance transportation investments as opposed to time of day tolls (Nguyen, 2007); and with the fact that most contracts stipulate rates that are a function of distance traveled that provide no allowance for time of day tolls. The author's conjecture is that ATA has concluded that its members will be able to pass the gas tax increase to the customers, while the same cannot be said about cordon time of day tolls.

The analytical formulations provide insight into the effectiveness of pricing schemes as a freight demand management tool. Two results stand out. The first one is that cordon time-of-day pricing is of limited use for freight demand management purposes. This is because of: (1) in competitive markets carriers have great difficulties passing toll costs to receivers; and (2) the cordon toll—unless all receivers switch to the off-hours, which is the least likely case—plays no role in incenting the carrier to switch to the off-hours. It should not surprise anyone that cordon time-of-day pricing does not provide the intended effect.

The analyses conclusively show that—since time-distance tolls enter into the marginal costs—carriers should be able to pass them to the receivers. However, since in order to induce the receivers to switch to the off-hours, the price signal reaching them must be greater than the receivers' costs associated with extending operations to the off-hours, the required time-distance unit tolls are extremely high (estimated in an example as five times larger than current costs). Due to the political unfeasibility of such tolls, it is doubtful that time-distance pricing could play a primary role in freight demand management, though it could be a complementary policy.

The key implication of all of this is that achieving the goal of switching a meaningful portion the regular hour truck traffic to the off-hours requires providing financial incentives to the receivers. A voluntary program in which the receivers commit to off-hour deliveries in exchange for a financial incentive is likely to attract a meaningful number of receivers. Since the corresponding carriers are likely to benefit from the switch to the off-hours—because of the lower costs and higher productivity—it is likely that the carriers would follow suit.

This alternative is clearly superior to either forcing all receivers to do off-hour deliveries—as it is done in Beijing, China—because it would lead to widespread cost increases; or using road pricing approaches that charge tolls to the carriers in the hope that they would pass toll costs to the receivers, and that these would lead the receivers to switch to the off-hours. As shown in the paper, the latter is not likely to happen because either the carriers have difficulties passing costs to receivers (under cordon time-of-day tolls); or because the unit time-distance tolls required to induce a behavior change would have be so high that are not likely to be politically feasible.

Obviously, a paradigm shift is needed. Should transportation policy makers be willing to embrace the fundamental findings of this research, it could open the door to more cost effective freight demand management that would be embraced by both carriers and receivers. Such freight industry friendly approaches could be a welcomed addition to the transportation policy toolkit.

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