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Approximation model to estimate joint market share in off-hour deliveries: William H. Hart Professor

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Abstract The main objective of this paper is to develop an approximation model to estimate the joint carrier–receiver response to off-hour delivery policies. The model's main intent is to bypass the need to use more complex approaches that require expensive data for model calibration. Having access to such approximation models would make it easier for transportation agencies and metropolitan planning organizations to analyze and design off-hour deliveries programs and policies. In its first part, the paper discusses carrier–receiver interactions concerning delivery time decisions and the conditions under which both carrier and receivers would agree to off-hour deliveries. Some of the key findings are that the typical receivers would participate only if provided with a financial incentive that covers the costs associated with the off-hour operations and that the carrier would find the off-hour delivery operation profitable if a large number of receivers switch to the off-hours. The latter provides an important piece of information to support the development of the approximation model introduced in the paper. The proposed model estimates the joint market share in off-hour deliveries by computing the joint probability that all receivers in a typical tour of length M agree to off-hour deliveries, the probability that the carrier operation is profitable, and finally the joint market share. The model's inputs are the probability that a typical receiver would participate in off-hour deliveries, the statistical distribution of tour lengths, and the probability that the carrier operation is profitable for a given number of receivers. The results indicate that the model provides the same results than other more complex methodologies for the practical range of values of receiver participation. For the high end of receiver participation (+80%), the formulation underestimates carrier participation. Because of its simplicity and practicality, the model provides an excellent way to estimate participation in off-hour delivery programs.

Keywords Freight pricing · Off-hour deliveries · City logistics

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1 Introduction

The combined pressures of global warming and climate change, aging infrastructure, and a looming funding crisis are bringing road pricing from the realm of academic discussions to the policy table. An example of such interest is manifested in the report produced by the National Surface Transportation Infrastructure Financing Commission set up by the United State Congress that discussed the role of pricing and other market-based mechanisms in infrastructure funding [17]. The reasons for such interests are obvious as the reductions in transportation demand brought about by road pricing could help ameliorate the negative externalities produced by transportation, while the revenues it generate could support both operation, renewal, and addition of infrastructure.

In terms of reduction in externalities, there is no doubt that reducing congestion could have a dramatic impact in sustainability. To start with, it is important to highlight that in the United States (US), for instance, the transportation sector consumes 29% of the total energy and 71% of the oil and produces 26% of the greenhouse gases, 50% of the carbon monoxide, 32% of the nitrogen oxide, and 22% of volatile organic compounds [2]. Adding to the problem, the urban freight system—which undoubtedly produces many benefits—also causes significant air pollution (local and transboundary) with significant health impacts. There is a statistical link between asthma rates and truck pollution [15], for example. This leads to large freight activity centers (e.g., terminals) becoming hot spots of environmental justice issues, as most are located in economically disadvantaged neighborhoods. The inefficiency of the urban freight system also aggravates the problem: about 25% of trucks are empty, and only 20% of their capacity is used [7]. Improving urban freight system will reduce environmental impacts, improve quality of life, help cities enhance their roles as economic drivers, and enhance environmental justice. For instance, reducing truck traffic in New York City (NYC) through off-hour deliveries by 25% will lead to reductions in carbon emissions of 279 tons/year, hydrocarbons of 62 tons/year, nitrogen oxides of 16.5 tons/year, and particulate matter of 198 pounds/year [10], and economic savings in the range of $100 million to $200 million per year in terms of productivity increase and travel time savings to all road users [11].

Thus, the surge of interest is a welcome, though not surprising, change. Although the benefits of road pricing have been known to academicians since the 1960s after a flurry of publications [18, 25, 27] set the foundations for road pricing, the first real-life implementations, that is, Singapore, came much later [16]. The benefits of road pricing have been documented, showing that road pricing could indeed lead to noticeable reductions in traffic and substantial toll revenues [5, 23]. However, significant differences have been noted between the observed impacts and behavioral responses of passengers and freight users [14]; while in the passenger case the observed response follows what expected by most analysts, the same does not happen in freight. The data collected on the freight industry's response to time-of-day pricing clearly indicate that urban delivery carriers cannot unilaterally change delivery times as this is opposed by most receivers, have major difficulties passing toll costs to the receivers (which deprives them of the price signal that could lead them to change behavior), and enact multi-dimensional responses involving complex combinations of productivity increasing measures, cost transfers, and to a lesser extent changes in facility usage [14]. This complex response was not anticipated by the handful of publications that have discussed freight road pricing [3, 4, 6, 26].

This seemingly puzzling behavior has been documented and explained in a sequence of papers that have highlighted the limitations of time-of-day pricing [14], identified the role played by receivers in setting delivery times and the need to use policies targeting both receivers and carriers [12, 13], identified the necessary conditions for carriers and receivers to change delivery times [8], and developed a formulation to estimate the impacts of cordon time-of-day and time–distance pricing on the joint carrier–receiver response [9]. It follows that, in order to induce truck traffic to switch to the off-hours, policies aimed at ensuring receivers' commitment to accept off-hour deliveries are required. This is a crucial component as research has shown that there is not much the carriers could do as pricing truck traffic is not likely to force the receivers to change behavior [8, 9].

The behavior observed from urban delivery carriers does seem in contradiction to what has been observed in other industry segments, most notably intercity freight carriers. As reported elsewhere [24], carriers using the Ohio Turnpike were able to change behavior, that is, switching routes to avoid the tolls. However, there is a major difference: while these carriers could switch routes and still satisfy the receivers' delivery constraints, urban delivery carriers can only change time of travel because most toll systems are designed to eliminate toll evasion by changing routes. Since most receivers oppose off-hour deliveries because of the extra costs, the carriers have no alternative than implementing productivity increases, and to a lesser extent pass the costs to someone else or reduce facility usage.

In spite of the significant amount of research that has been conducted on the subject, important questions remain unanswered. One of them is related to how to estimate the level of market penetration that off-hour deliveries could reach. Two different approaches have been used to assess the market share of off-hour deliveries. The first one relies on the use of discrete choice models to estimate the number of receivers that would decide to accept off-hour deliveries in exchange for a financial incentive and another set of discrete choice models that estimate the carrier's response given the receivers' decisions and the toll levels [12, 13]. Although useful and pragmatic, this approach has a number of limitations as it is not able to capture the effect of routing decisions, operational aspects, and other variables on the carrier's decision. The second approach entails the development of a behavioral micro-simulation (BMS) to represent the joint behavior of carriers and receivers when deciding whether or not to conduct off-hour deliveries [22]. The BMS—undoubtedly a step forward with respect to discrete choice models—is able to take into account operational elements, actual routing patterns, in a level of detail far beyond what could be accomplished with discrete choice models. However, the BMS has some limitations (e.g., data requirements, development, and programming time) that hamper its use for policy analysis. This is particularly important in urban areas that are considering implementing off-hour delivery policies and do not have access to the data required to use the BMS. Having access to simplified formulations to estimate participation in off-hour deliveries will facilitate analyses and design of off-hour delivery programs.

The main objective of this paper is to develop an approximation model to estimate the joint carrier–receiver response to off-hour delivery policies. The main intent here is to bypass the need for more complex approaches that require expensive data for model calibration. Having access to such models may make it easier for transportation agencies and metropolitan planning organizations to analyze and design off-hour deliveries programs and policies. The paper has five chapters in addition to this introduction. The chapters discuss, in sequence, the notation used in the paper, carrier–receiver interactions, minimum number of receivers for a profitable carrier operation, the approximation model developed, and then conclusions.

2 Notation

To a great extent, the notation follows the author's previous work [8, 9]. 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.

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

$\Delta G_j(\pi_C) = G_j^M - G_j^{BC}$ = Incremental gross revenues to carrier j associated with policy π_C

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)

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

$\Delta C_j(\pi_C) = C_j^M - C_j^{BC}$ = Incremental total costs to carrier j in response to policy π_C

$\Delta G_i(\pi_R) = G_i^M - G_i^{BC}$ = Incremental gross revenues to receiver i associated with policy π_R

$\Delta C_i(\pi_R) = C_i^M - C_i^{BC}$ = Incremental total costs to receiver i associated with switch to off-hours in response to policy π_R

$\Delta C_{F,j}$ = 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)

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)

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

ϕ = Parameter of approximation model

A = Service area, that is, area of the minimum size rectangle that envelops all customers

$A = L_x^{\max} L_y^{\max}$ = 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

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

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

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 prefer regular hour deliveries

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

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

3 Carrier–receiver interactions, necessary conditions, and impacts of pricing

The formulation of the approximation model at the heart of this paper requires taking advantage of a number of analytical developments that provide support to the assumptions used. Foremost in this list are the necessary conditions for carrier and receivers to switch to the off-hours [8], and the research conducted on the impacts of cordon time-of-day and time–distance pricing [9]. Because of their importance and relevance to this paper, these publications are discussed and used here.

The fundamental tenet of this research is that the interactions between carriers and receivers are what determine how they jointly respond to pricing. In this context, while carriers in equality of conditions prefer off-hour deliveries because of the higher productivity and lower delivery costs, most receivers favor regular hour deliveries because they could handle those with the staff at hand and without incurring in additional costs. This type of interaction is referred to as the Battle of the Sexes game [21] and is known to have two Nash equilibria, with the final outcome being imposed by the player with most clout. Since the data clearly show that the majority of deliveries are done in the off-hours [12], the unavoidable conclusion is that the receivers play the dominant role.

The explicit consideration of carrier and receivers as separate economic agents that interact when deciding on delivery times leads to a more realistic model of their joint response to pricing [9] that, more importantly, is able to adequately explain the observed behavioral response to pricing. Among other aspects that are explained with the aid of this new paradigm, the consideration of carrier–receiver interactions shed light into why the carriers interviewed after the Port Authority of New York and New Jersey's implementation of time-of-day pricing attempted to deal with the toll increases, primarily, by means of productivity increases, could pass the toll costs to their customers in only 9% of the cases, and when asked why they could not change behavior said "…customer requirements…" in 70% of the cases [14]. All these behaviors could only be explained once carrier–receiver interactions are accounted for in the context of a competitive market.

The consideration of carrier–receiver interactions leads to the realization that, in order for them to switch to the off-hours, both of them must be better off. In response to policies π_C and π_R targeting carrier and receivers, respectively, this condition could be represented mathematically [8] as:

$$\Delta G_i(\pi_R) \geq \Delta C_i(\pi_R) \quad \forall i \in \Omega_j^O \tag{1}$$

$$\Delta G_j(\pi_C) \geq \Delta C_j(\pi_C) \tag{2}$$

$$\tau_i^O \geq \tau_{\min}^O \quad \forall i \in \Omega_j^O \tag{3}$$

where, $\Delta G_i(\pi_R)$ and $\Delta C_i(\pi_R)$ are the incremental gross revenues and incremental costs to receiver i associated with the shift to the off-hours under policy π_R; $\Delta G_j(\pi_C)$ and $\Delta C_j(\pi_C)$ are the incremental gross revenues and incremental costs to carrier j associated with the shift to the off-hours under policy π_C; and τ_i^O is the delivery time for receiver i.

These equations provide the basis for the development of cost functions that capture the costs to the carriers associated with delivering to a set of N receivers that are divided among the regular and the off-hours. These cost functions, in turn, are used to estimate the delivery rates and consequently if, and how much of, the toll costs can be passed by the carrier to the receivers.

In a separate publication [9], the author studied the joint behavior of carrier and receivers in response to pricing and comprehensive carrier–receiver policies. The research revealed that in response to a financial incentive, some receivers may decide to switch to the off-hours, which leads to a situation in which the carrier has a mixed operation with both regular hour and off-hour deliveries. Holguín-Veras [9] identify three cases in terms of the profitability of the resulting operation: an approximation to the best case (termed here "quasi-best"), the expected value, and the worst case. The optimal tour distances are estimated with an approximation model for the Probabilistic Traveling Salesman Problem [1]. The analytical cost functions consider a fixed cost associated with traveling to/from the home base to the study area, and time, distance, and toll costs, for both cordon time-of-day and time–distance pricing. The results are shown in terms of the incremental costs to the carrier (negative if cost savings). The subscripts used are F (fixed cost), D (distance costs), T (time costs), S (toll costs under time-of-day pricing), and TDP (toll costs under time–distance pricing). The cost functions obtained for cordon time-of-day are shown in Eqs. 4 through 11.

3.1 Summary of results for cordon time-of-day pricing

All cases (quasi-best, expected value, and worst case):

$$\Delta C_{F,j} = \begin{cases} \left[(C_{FC}^R + C_{HB}^R) + (C_{FC}^O + C_{HB}^O) - (C_{FC}^{BC} + C_{HB}^{BC})\right] \cong (C_{FC}^O + C_{HB}^O), \forall_{N^O < N^{BC}} \\ 0, \forall_{N^O = N^{BC}} \end{cases} \tag{4}$$

$$\Delta C_{S,j} = \begin{cases} 0, \forall_{N^O < N^{BC}} \\ -S^R, \forall_{N^O = N^{BC}} \end{cases} \quad (5)$$

Quasi-best case:

$$\Delta C_{D,j} = 0, \forall_{N^O, N^{BC}} \quad (6)$$

$$\Delta C_{T,j} = \frac{\phi}{u^R} \frac{N^O}{\sqrt{\delta^{BC}}} \left[\frac{\theta}{\gamma} - 1\right] c_T^R, \forall_{N^O, N^{BC}} \quad (7)$$

Expected value case:

$$\Delta C_{D,j} = \begin{cases} \phi c_D \sqrt{L_{ox} L_{oy}} \left[\left(\frac{N^R-1}{N^R+1}\right)\sqrt{N^R} + \left(\frac{N^O-1}{N^O+1}\right)\sqrt{N^O} - \left(\frac{N^{BC}-1}{N^{BC}+1}\right)\sqrt{N^{BC}}\right], & \forall_{N^O < N^{BC}} \\ 0, & \forall_{N^O = N^{BC}} \end{cases} \quad (8)$$

$$\Delta C_{T,j} = \begin{cases} \phi \frac{c_T^R}{u^R} \sqrt{L_{ox} L_{oy}} \left[\left(\frac{N^R-1}{N^R+1}\right)\sqrt{N^R} + \frac{\theta}{\gamma}\left(\frac{N^O-1}{N^O+1}\right)\sqrt{N^O} - \left(\frac{N^{BC}-1}{N^{BC}+1}\right)\sqrt{N^{BC}}\right], & \forall_{N^O < N^{BC}} \\ \phi \frac{c_T^R}{u^R} \sqrt{N^{BC} L_{ox} L_{oy}} \left[\frac{\theta}{\gamma} - 1\right] \left(\frac{N^{BC}-1}{N^{BC}+1}\right), & \forall_{N^O = N^{BC}} \end{cases} \quad (9)$$

Worst case:

$$\Delta C_{D,j} = \begin{cases} \phi c_D \sqrt{N^{BC} L_{ox} L_{oy}} \left[\frac{\sqrt{N^R}+\sqrt{N^O}}{\sqrt{N^{BC}}} - 1\right] = c_D \left[f_D' - 1\right] D^{BC}, & \text{iff } N^O < N^{BC} \\ 0, & \text{iff } N^O = N^{BC} \end{cases} \quad (10)$$

$$\Delta C_{T,j} = \begin{cases} \phi \frac{c_T^R}{u^R} \sqrt{A N^{BC}} \left[\frac{\sqrt{N^R}+\frac{\theta}{\gamma}\sqrt{N^O}}{\sqrt{N^R+N^O}} - 1\right], & \text{iff } N^O < N^{BC} \\ \phi \frac{c_T^R}{u^R} \sqrt{A N^{BC}} \left[\frac{\theta}{\gamma} - 1\right] c_T^R, & \text{iff } N^O = N^{BC} \end{cases} \quad (11)$$

As shown, the incremental fixed costs are the same regardless of the case in question, while the incremental distance, time, and toll costs are not. Worthy of mention is that, in most cases, the costs exhibit a discontinuity when all receivers switch to the off-hours. In the case of the fixed cost, Eq. 4 clearly shows that there would be a fixed cost (associated with the extra trip during the off-hours) unless all receivers are in the off-hours, when the fixed costs would become zero. The fundamental implication of this finding is that the farther the carrier, the larger the incremental fixed cost, and the more difficult for the mixed operation to be profitable.

Equation 5 has important policy implications as it shows that the toll surcharge only provides an incentive to the carrier when all receivers are in the off-hours. This is because the carrier could have only one tour in the off-hours, thus avoiding the toll surcharge for regular hours travel. In all other conditions, the carrier has to travel during both regular and off-hours and has to pay the toll anyway. As a result, the incremental toll cost with respect to the base case is equal to zero, that is, it does not incentivize the carrier to switch to the off-hours. This calls into question the use of cordon time-of-day pricing for freight demand management purposes.

The analytical derivations by Holguín-Veras [9] indicate that the incremental distance and time costs depend on the case considered. In the quasi-best case, there would be cost savings in time and distance even if only a small number of receivers switch to the off-hours. As shown, the incremental distance cost is equal to zero (though more likely, the carrier would be able to re-optimize the tours in the absence of congestion), and the incremental time cost is negative from the start as long as $\theta/\gamma < 1$, which represent the ratio of the wage increase to the ratio of the speeds between off-hours and regular hours. In the expected value case, the quadratic nature of the problem leads to cost increases up to a point where they start to diminish, leading ultimately to cost savings when the number of receivers in the off-hours is large. In the worst case, there are distance and time cost increases almost always.

The analytical derivations for time–distance pricing indicate that the incremental fixed, distance, and time costs are exactly the same for cordon time-of-day pricing, which are shown in Eqs. 4–11. For brevity sake, these are not repeated here. The key difference is on the incremental toll costs that are shown below.

3.2 Summary of results for time–distance pricing

Quasi-best case:

$$\Delta C_{TDP,j} = \phi\sqrt{\frac{A^{BC}}{N^{BC}}}\left[\left(\alpha_D^R + \frac{\alpha_T^R}{u^R}\right)(N^R - N^{BC}) + \left(\alpha_D^O + \frac{\alpha_T^O}{u^R}\right)N^O\right] \tag{12}$$

Expected value case:

$$\Delta C_{TDP,j} = \phi\sqrt{L_{ox}L_{oy}}\left[\begin{array}{r}\left(\alpha_D^R + \frac{\alpha_T^R}{u^R}\right)\left(\left(\frac{N^R-1}{N^R+1}\right)\sqrt{N^R} - \left(\frac{N^{BC}-1}{N^{BC}+1}\right)\sqrt{N^{BC}}\right)\\ +\left(\alpha_D^O + \frac{\alpha_T^O}{u^R}\right)\left(\frac{N^O-1}{N^O+1}\right)\sqrt{N^O}\end{array}\right] \tag{13}$$

Worst case:

$$\Delta C_{TDP,j} = \phi\sqrt{A^{BC}N^{BC}}\left[\left(\alpha_D^R + \frac{\alpha_T^R}{u^R}\right)\left(\sqrt{\frac{N^R}{N^{BC}}} - 1\right) + \left(\alpha_D^O + \frac{\alpha_T^O}{u^R}\right)\sqrt{\frac{N^O}{N^{BC}}}\right] \tag{14}$$

The first and most obvious feature of these results is that, in all cases, time–distance pricing does provide an incentive for the carrier to switch to the off-hours as the unit distance tolls enter into the incremental toll costs. The results also indicate that a sound pricing policy with $\alpha_D^R > \alpha_D^O$ and $\alpha_T^R > \alpha_T^O$ would also lead to cost savings to the carrier, regardless of how many receivers are in the off-hours. Equally important is that the larger the difference between the unit tolls for the regular and the off-hours, the larger the incentive to the carrier. This stands in sharp contrast with the results for cordon time-of-day pricing where the toll surcharge would only play when all receivers switch to the off-hours.

4 Minimum number of receivers for a profitable mixed operation

The results obtained for cordon time-of-day and time–distance pricing suggests that off-hour deliveries would cause increases in some components of the incremental costs, and reductions in others. This leads to a situation in which the profitability of the mixed operation (with both regular and off-hour deliveries) depends on how many receivers decide to switch to the off-hours. If the number of off-hour receivers is "small," it is likely that the carrier would face cost increases and refuse to do off-hour deliveries. If, at the other end, the number of receivers in the off-hours is "large," there would be cost savings and the carrier would participate. Then, the key challenge is how to ensure that a "large" number of receivers are in the off-hours. Three possibilities exist: using freight road pricing, regulation, and providing incentives to the receivers in exchange for their commitment to do off-hours. It is important to discuss them in some detail.

Although appealing, both empirical evidence and theory suggest that pricing truck traffic will not lead to substantial changes in the behavior of receivers. In the case of cordon time-of-day pricing under a competitive market, the carriers cannot pass the toll costs to their customers [8, 9] because the toll cost is part of the fixed cost. The theoretical findings are confirmed by the empirical evidence as only the carriers with market power were able to pass toll costs to receivers in a meaningful way [8, 9, 14]. In contrast, under time–distance pricing, the carriers should be able to pass the toll costs to the receivers. However, the analyses made clearly indicate that in order for the tolls to induce the receivers to change behavior, the unit tolls would have to be about six times larger than current operating costs. Such tolls are politically unacceptable [9].

The second alternative entails the use of regulatory approaches, such as banning regular hour deliveries as done in Beijing, China. However, this is likely to lead to massive protests from the business sector and widespread cost increases as all receivers would face increasing operating costs. The experience of Los Angeles in the 1980s clearly indicates that the business sector will vigorously fight such measures [19].

The approach suggested in this paper consists of providing incentives to receivers for participation in off-hour deliveries. This concept has a number of advantages as it (1) is a voluntary program that leads to increases in the receivers' welfare because only those that stands to benefit from the incentive would join, (2) could lead to a substantial shift of delivery operations to the off-hours, for example, 20% for a tax deduction to receivers of food, (3) would reduce congestion and pollution in urban areas, thus improving quality of life, (4) would increase the productivity of urban delivery operations via the congestion reductions, (5) will enjoy the enthusiastic support of the carriers as delivering in the off-hours is 30% cheaper than in the regular hours, and (6) would increase the competitiveness of the urban areas via the increases in productivity and quality of life.

The research conducted clearly supports giving incentives to receivers in exchange for their participation in off-hour deliveries. However, a fundamental question remains concerning what is the minimum number of receivers required for the carrier operation to be profitable.

To answer this question, the cost functions shown in Eqs. 5 through 14 are used. 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, for example, New York City [20]. To ensure a fair comparison, 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 $\alpha_D^R = \$2$/mile, $\alpha_D^O = \$0.9$/mile, $\alpha_T^R = \$4$/h, and $\alpha_T^O = \$2$/h, which were arbitrarily selected. The results correspond to $L_{ox} = 2$ miles, $L_{oy} = 11.5$ miles, $u^R = 10$ miles per hour, $c_D = \$2$/mile, $c_T = \$50$/h, and $\phi = 0.75$. These values are what may be expected for Manhattan. Typical results are shown in Fig. 1 for a tour with 20 receivers, after Holguín-Veras [9]. Solid bullets are used to represent cordon time-of-day, and clear ones for time–distance pricing.

The results shown in the Fig. 1, for the expected case, illustrate a number of key features. The impact of the fixed cost associated with the extra trip is obvious (marked by an up arrow at $N^O = 1$). As shown, there are cost increases if the number of receivers in the off-hours is "small" and cost savings if this number is "large." Obviously, this also depends on the pricing regime. The results also show the superiority of time–distance pricing as it increases the profitability of the mixed delivery operation. As shown, while under cordon time-of-day pricing a minimum number of 19 receivers are required for a profitable operation, only 16 receivers are needed under time-of-day pricing. The numerical experiments conducted produced similar results for other tour lengths and cases (i.e., worst and quasi-best).

5 Approximation model

The results discussed in previous sections indicate that (1) delivering during the off-hours is cheaper than during the

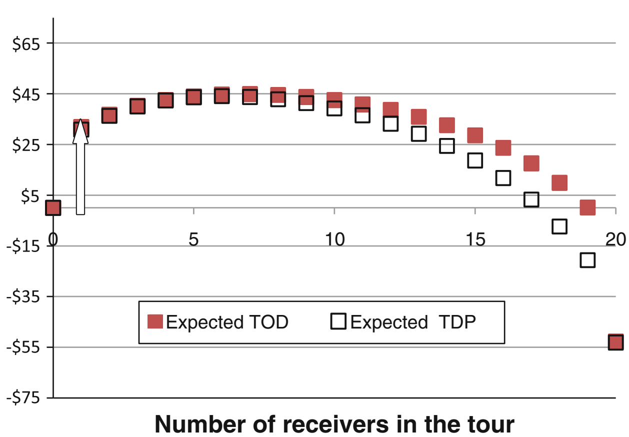


Fig. 1 Incremental costs for a tour with twenty receivers

regular hours and (2) if all receivers decide to accept off-hour deliveries, the carrier is likely to follow suit as it will save money. These observations provide the basis for an approximation model that provides a lower bound of the joint market share for carrier–receiver participation in off-hour deliveries. This lower bound assumes that (1) the receivers are observationally identical and independent, (2) the carrier will switch to the off-hours, if and only if, all receivers agree to the switch, and (3) there are no other policies, for example, time–distance pricing, that provide an external stimulus to the carrier. The second assumption is not problematic as this is expected to hold in all congested areas where delivering in the off-hours is cheaper than in regular hours. The second and third assumptions imply that if the carrier decides to do off-hour deliveries—even when not all receivers agree or if there are other external stimuli impacting the carrier—that the actual joint response may be larger than the one estimated by the model.

Consider now that carrier j has a number of customers R_i receiving regular hour deliveries as part of the base case conditions, $R_i \in \Omega_j^{BC}$. Assume that, as a consequence of a given financial incentive F, the receivers have a probability $P(R_i \in \Omega_j^O) = P(F)$ of accepting off-hour deliveries. Since the receivers in the delivery tour can be assumed to make independent decisions, the probability that all of them agree to off-hour deliveries (and therefore belong to the set with off-hour customers Ω_j^O) is then:

$$P(R_1 \in \Omega_j^O \cap R_2 \in \Omega_j^O \cap R_3 \in \Omega_j^O \cap \ldots R_M \in \Omega_j^O / M' = \left|\Omega_j^{BC}\right|) = [P(F)]^{M'} \tag{15}$$

where, M' is the cardinality of the set Ω_j^{BC}.

Defining Γ^O as the set of carriers that do off-hour deliveries, the probability that carrier j would do off-hour deliveries is equal to the joint probability that all its receivers agree and that the resulting operation with m receivers is profitable, denoted by the probability $P(G_M > C_M/M)$:

$$P(j \in \Gamma^O) = [P(F)]^M P(G_M > C_M/M) \tag{16}$$

Letting Q_M be the total number of tours with M delivery stops, the expected value of the number of tours that would be switched to the off-hours in response to an incentive F is:

$$E(Q) = \sum_{M=1}^{M^*} Q_M [P(F)]^M \tag{17}$$

where, M^* is the upper bound of the number of delivery stops per tour expected in the area.

Defining $Q_* = \sum_{M=1}^{M^*} Q_M$ and $f_M = \frac{Q_M}{Q_*}$ as the relative frequency a tour with M delivery stops, then the market share of off-hour tours is:

$$MS^O = \sum_{M=1}^{M^*} f_M [P(F)]^M \quad (18)$$

Equation 18 has interesting implications related to what segments of the industry are likely to participate in off-hour deliveries. Since the term $[P(F)]^M$ decreases geometrically with M (tour length), Eq. 18 implies that the bulk of the tours that would participate in off-hour deliveries are the ones with short tour lengths, particularly those with one and two stops with proportions f_1 and f_2. In other words, cities with distribution patterns characterized by "large" proportions of "short" tours are likely to achieve larger share of off-hour deliveries than cities with predominantly "long" tours. Although it seems natural to think that the market share would be related to the average tour length, the reality is that it is not. To illustrate why, consider the case of following two urban areas. In the first case, there are 50% of deliveries with one stop and the remainder 50% with ten stops, while in the second, there are 50% of tours with four stops and the other 50% with seven stops. In both cases, the average number of stops is the same (5.5 stops/tour), but the market shares are very different. Assuming a probability of receiver participation of 50%, the market share in the first case is 25.05% ($0.5 \times 0.5^1 + 0.5(0.5)^{10}$), and in the second only 3.5% ($0.5 \times 0.5^4 + 0.5(0.5)^7$).

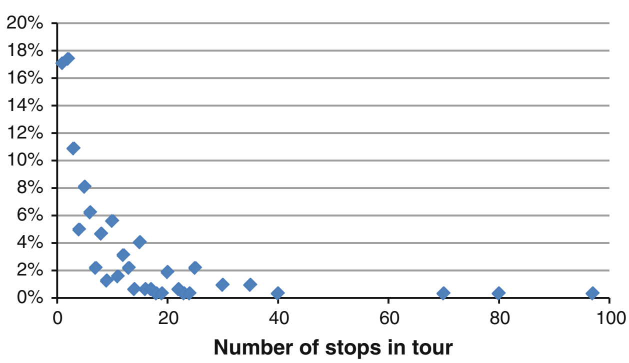


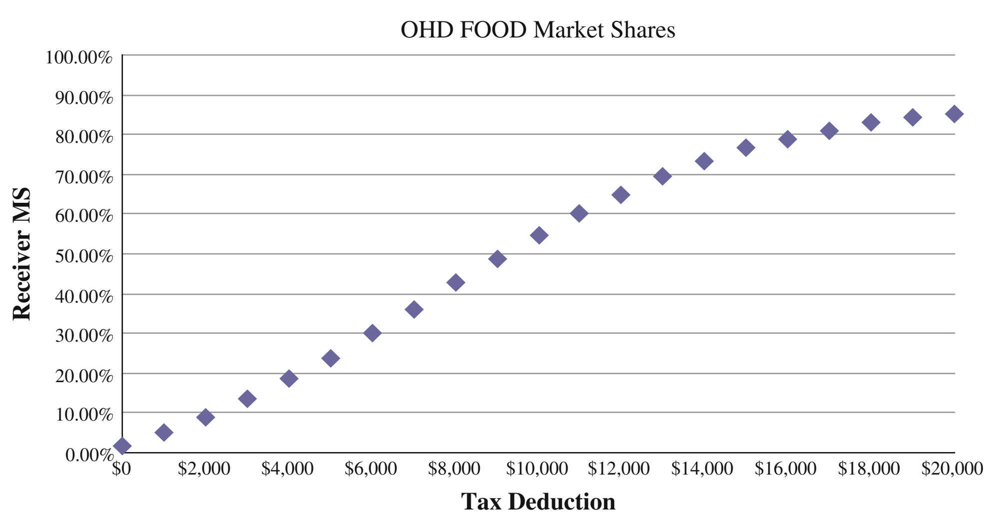
Fig. 2 Frequency distribution of number of delivery stops per tour

In order to produce numerical estimates, the data for New York City were analyzed to estimate the frequency distribution of the number of stops. Figure 2 shows the values obtained. As shown, although the vast majority of tours have less than five stops, there is a wide range of values with some tours with more than 90 stops. The average number of stops is 6.8 stops/tour. Information about $P(F)$ is available from the behavioral research conducted by the author and his colleagues [12]. Figure 3 shows the market shares estimated for food receivers as a function of tax deduction in exchange for their commitment to accept off-hour deliveries. As shown, a tax deduction of $10,000 per year would lead to 50% participation.

In order to assess the performance of Eq. 18, the formulation developed was applied to the different industry segments studied using the BMS [22]. In general, the results exhibit similar patterns to that of Fig. 4 that shows the estimates produced with the assistance of the BMS and the ones produced by the approximation model [22]. The results labeled "MS" correspond to the approximation model presented in this chapter, while the ones labeled "BMS" represent the ones produced by the behavioral micro-simulation.

Figure 4 shows that the approximation model performs remarkably well as long as $P(F)$ is less than 80%. After this value, the magnitude of the underestimation is significant. This seems to be a consequence of assuming that the off-hour delivery tour is profitable if and only if all receivers agree to it. It is entirely possible that, for instance, a tour in which nine out of ten receivers agree to off-hour deliveries is profitable to the carrier, which is a possibility not considered by the lower bound. If $P(F)$ is small, the probability

Fig. 3 Food receiver participation in off-hour deliveries



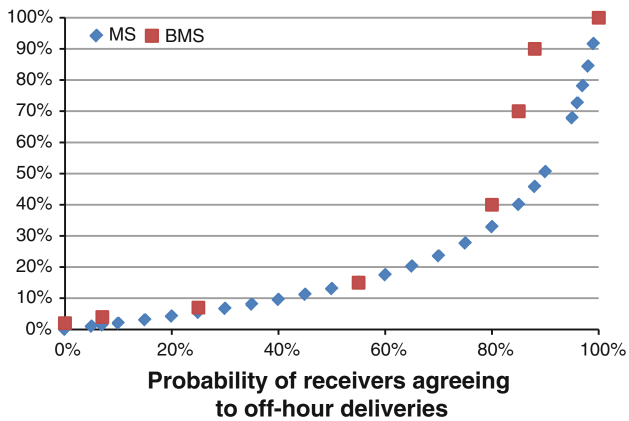


Fig. 4 Expected market shares of off-hour deliveries

of finding such cases is negligible. However, as $P(F)$ increases, the number of cases in which almost all receivers agree, and the operation is profitable to the carrier, increases. Since the lower bound does not consider such cases, it underestimates the actual market share for high values of $P(F)$.

Equation 18 does provide a convenient way to produce quick estimates of the potential participation in off-hour deliveries as it only requires an estimate of receiver participation in response to a given policy and basic data about the number of stops in the delivery tours. These estimates could be readily obtained from consultations with industry representatives.

6 Conclusions

The research conducted on the impacts of pricing on urban deliveries has highlighted that delivery time decisions are jointly made between carriers and receivers. In this interaction, the carriers prefer off-hour deliveries, while the receivers favor regular hour deliveries. Because of this mismatch, the outcome that materializes is the one favored by the agent with the most clout. In the case of urban deliveries, where the vast majority of deliveries are made in the regular hours, it is obvious that receivers play the dominant role, and where without receivers' consent, off-hour deliveries cannot take place.

The paper discusses different approaches to ensure participation of receivers, pricing, regulation, and financial incentives, and reaches the conclusion that the latter alternative is the only practical alternative. The analyses indicate that pricing the carriers is not likely to lead to changes in receivers' behavior because either the carriers have great difficulties passing the tolls to the receivers (the case of cordon time-of-day pricing) or the toll charges would have to be huge to have any effect (in time–distance pricing). Using regulation, for example, banning regular hour deliveries, would impose significant costs in the entire business sector as they would have to switch the entire operations to the off-hours. This is bound to generate massive opposition from the private sector, as the unsuccessful attempt to ban regular hour deliveries at Los Angeles in the 1980s demonstrates [19]. In contrast, the proposed financial incentives would (1) increase receivers' welfare because only those that stand to benefit from the incentive would join, (2) shift a significant number of deliveries to the off-hours, (3) reduce congestion and pollution, (4) increase the productivity of urban deliveries, (5) enjoy the enthusiastic support of the carriers as delivering in the off-hours is 30% cheaper than in the regular hours, and (6) increase the competitiveness of the urban areas.

The analyses in the paper also indicate that, from the carrier standpoint, that a large number of receivers are needed for a profitable operation. These conclusions were reached with the use of analytical cost functions that capture the incremental costs to the carriers associated with a mixed operation with and off-hour deliveries. In general, the mixed operation leads to increases in operational cost to the carriers if the number of receivers in the off-hours is small.

In its final section, the paper introduces a formulation to estimate the joint market share (receivers and carriers) in off-hour deliveries. This formulation builds on the insight gained from the analyses with the cost functions and is based on the following assumptions: (1) the carrier would participate in off-hour deliveries if and only if all the receivers in the tour are in the off-hours; (2) there are no external incentives that could impact the carrier's decisions; and (3) receivers are observationally random, make independent decisions, and have a known probability to participate in off-hour deliveries. The model computes the joint probability that all receivers agree to accept off-hour deliveries, and with the assistance of the tour length distribution, it computes the market shares.

The approximation model clearly indicates that, for a given probability of receiver participation in off-hour deliveries, the joint market share is going to be determined primarily by the proportion of "short" tours as the probability of all receivers agreeing to off-hour deliveries geometrically decreases with tour length. This implies that policies aimed at increasing delivery payloads could play a role in fostering off-hour deliveries as they would incentivize the carrier to convert "long" tours into "short" ones.

The results provided by the model were compared with the results from a behavioral micro-simulation [22]. The analyses indicate that the approximation model is very accurate as long as the probability of receiver participation is less than 80%. Beyond this value, the approximation model underestimates the market share. The reason for this underestimation seems that be related to the assumption that the carrier operation would be profitable only if all receivers are in the off-hours.

In terms of practicality, the approximation model is clearly superior to any of the available techniques as it only requires an estimate of the probability of receiver participation in off-hour deliveries and the tour length distribution. These pieces of information could be easily estimated from surveys or interviews with industry representatives.

The research conducted enhances the transportation community's understanding of the potential market shares that off-hour deliveries could reach. More importantly, by providing easy to use mathematical models—that bypass the need for more complex approaches—this research is contributing to the implementation of off-hour delivery programs in the world's congested urban areas.

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