# THE IMPACTS OF CONGESTION ON COMMERCIAL VEHICLE TOUR CHARACTERISTICS AND COSTS

**Miguel Andres Figliozzi**

Department of Civil and Environmental Engineering

Maseeh College of Engineering and Computer Science

Portland State University

figliozzi@pdx.edu

**ABSTRACT**

Analytical modeling and insights, numerical experiments, and real-world tour data are used to understand the impact of congestion on urban tour characteristics, carriers' costs, and distance/time traveled. This paper categorizes tours into three classes based on their tour efficiency and variable costs structure. Travel time/distance between customers and depot is found to be a crucial factor that exacerbates the negative impacts of congestion. Travel time variability is a significant factor only when travel time between depot and customers is considerable in relation to the maximum tour duration. For each customer, it is possible to define a dimensionless coefficient that provides an indication of the relative impact of congestion on routing constraints. Congestion also affects carriers' cost structure, as congestion worsens the relative weight of wages and overtime escalates and the relative weight of distance related costs decrease.

KEYWORDS: Congestion Modeling, Carrier Costs, Urban Freight, City Logistics

## 1. Introduction

Increased travel times and the uncertainty brought about by congestion impacts the efficiency of logistics operations. Direct and indirect costs associated with congestion have been widely studied and reported. Most of the studies have focused on passengers' value of travel time, shippers' value of time and market access costs, production costs, and labor productivity costs (Weisbrod et al., 2001). However, the modeling and study of the specific impacts of urban congestion on commercial vehicle tours have received scant attention. The lack of studies is largely explained by lack of disaggregated and comprehensive commercial vehicle data, which due to privacy or competitive reasons, is expensive to collect or unattainable at the desired level of detail.

This research studies the impact of congestion on commercial vehicle tours in an urban area. It contributes to the understanding of the impacts of congestion on commercial vehicle tours. The specific contributions of this research are threefold: a) it analytical approximations and empirical data to study and describe the impact of congestion on tour characteristics, b) it discusses congestion costs from a carrier's perspective, c) it uses a novel and intuitive classification of urban distribution tours according to their efficiency and susceptibility to congestion. Empirical or real-world disaggregated tour data is also analyzed to validate analytical insights of the model.

Recent studies indicate that a high proportion of urban commercial vehicle kilometers traveled (VKT) originate at distribution centers (DC), warehouses, or depots (Cambridge Systematics, 2003, Outwater et al., 2005) and constitute trip-chains or multi-stop tours. Multi-stop commercial vehicle tours are ubiquitous in urban areas; for example, in Denver approximately 50% of single and combination truck tours include 5 to 23 stops per tour (Holguin-Veras and Patil, 2005). The terms "route", "tour", and "trip-chain" are used interchangeably in this research to designate the activity of a commercial vehicle that starts at a depot, visits one or more customers, and then returns to the depot; for the sake of brevity the word tour is used herein.

The research is organized as follows: section two provides a literature review of congestion impacts on carrier operations and costs. Section three introduces a model to analyze the impacts of congestion on commercial vehicle tours. Section four presents analytical insights for time constrained tours. Section five contains a numerical analysis and discusses tour efficiency. Section six discusses the impact of congestion on carriers' costs. Section seven examines empirical tour data; it also proposes a classification of tours based on their efficiency and vulnerability to congestion. Section eight ends with conclusions.

## 2. Literature Review

It is widely recognized that congestion seriously affects logistics operations. McKinnon (1999) presents the results of in-depth interviews with DC managers and discusses the negative effects of congestion on logistics operations. Direct and indirect costs of congestion on passengers' travel time, shippers' travel time and market access, production, and labor productivity have been widely studied and reported. For a systematic review of this congestion literature the reader is referred to the work of Weisbrod et al. (2001). Sizeable progress has been made in the development of econometric techniques to study the joint behavior of carriers and shippers in regards to congestion (Hensher and Puckett, 2005).

Survey results suggest that the type of freight operation has a significant influence on how congestion affects carriers' operations and costs. Data from a California survey indicate that congestion is perceived as a serious problem for companies specializing in LTL (less-than-truckload), refrigerated, and intermodal cargo (Golob and Regan, 2001). In addition, Golob and Regan (2003) found a positive relationship between the level of local congestion and the purchase of routing software. Carriers that do not follow regular routes, e.g. for-hire carriers, tend to place a higher value on the usage of real-time information to mitigate the effects of congestion (Golob and Regan, 2005).

Another branch of the literature models the relationship between industrial/commercial procurement and congestion. The impact of just-in-time (JIT) production systems, i.e. more trips with smaller shipment sizes, on vehicle trip generation has been analyzed and modeled (Rao et al., 1991, Moinzadeh et al., 1997). Using data from Auckland, New Zealand, Sankaran et al (2005) study the impact of congestion and replenishment order sizes on carriers with time-definite deliveries. Sankaran and Wood (2007) continues this work and presents a model using Daganzo's (1984, 1991) approximations to routing problems. For problems where routes have 10 or more deliveries Sankaran and Wood (2007) indicate that congestion costs increase with the average number of rounds per day and decrease with the workday duration, the square root of the number of deliveries, and that congestion is invariant with fixed or variable stop times.

Routing constraints limit the number and characteristics of the feasible set of tours that carriers can use to meet customer demand. Figliozzi (2006) models tour constraints using Daganzo's (1991) approximations to routing problems and analyzes how constraints and customer service time affect trip generation using a tour classification based on supply chain characteristics and route constraints. Building on this work, Figliozzi (2007) proposes an analytical framework to study the impact of policy or network changes on urban freight VKT; the model shows that a decrease in travel speed severely affects tours with time window constraints while capacity constrained tours are less affected. Figliozzi (Figliozzi, 2007) also indicates that changes in both VKT and vehicle hours traveled (VHT) differ by type of tour and routing constraint. This work links the dominant tour constraints to the time sensitivity of the commercial activity and the value of the activity itself in relation to the cost of transport to define four tour types: (1) capacity constrained tours, (2) frequency of service constrained tours, (3) tour duration constrained tours, and (4) time window constrained tours. It is established that tour duration and time window constrained tours are the most affected by congestion.

Confidentiality issues are usually an insurmountable barrier that precludes the collection of detailed and complete freight data. To the best of the author's knowledge, all freight congestion studies present aggregated tour data with the exception of Figliozzi et al. (2007) and Greaves and Figliozzi (2008). In these two studies detailed truck activity was analyzed and disaggregated tour data was used to reveal tour characteristics, speed variability, and data collection challenges. More recently, an analytical model to determine the impact of time windows on vehicle routing tour was developed (Figliozzi, 2008b). To the best of the author's knowledge, there is no research whose major focus is on the impact of congestion on vehicle routing tours costs and structure.

Transportation agencies are increasingly using travel time reliability as a congestion measure (Chen et al., 2003); reliability is often associated to a "buffer time index" (Lomax et al., 2003, Bremmer et al., 2004). The buffer time index represents the extra time a traveler needs to allow in order to arrive on time 95% of the time. Carriers also use buffers to mitigate the effects of travel time or demand variability. Reliability as a constraint or objective has also been incorporated in operations research models where routes and service areas are designed using continuous approximations (Erera, 2000, Novaes et al., 2000) or on stochastic programming (Laporte and Louveaux, 1993, Kenyon and Morton, 2003). In particular, Erera (2000) proposes continuous approximations to estimate expected detour and distances in a stochastic version of the capacitated vehicle routing problem. To the best of the author's knowledge, no model has been developed to study the impacts of congestion on tour characteristics, costs, and VKT/VHT.

## 3. The Tour Model

This research considers a system with one DC or depot and $n$ customers. A tour is defined as the closed path that a truck follows from its depot to visit one or more customers in a sequence before returning to its depot during a single driver shift. A tour is comprised of several trips; a trip is defined by its origin and destination and characterized by its distance and travel time attributes. A seminal contribution to the estimation of the length of a shortest closed path or tour through a set of points was established by Beardwood et al. (1959) . Daganzo (1984) proposed a simple and intuitive formula for the capacitated vehicle routing problem (CVRP) length when the depot is not necessarily located in the area that contains the customers:

$$l(n) = 2\overline{r}\, n / Q + 0.57\sqrt{an}$$

In this expression $l(n)$ is the total length of the CVRP problem serving $n$ customers, the average distance between the customers and the depot is $\overline{r}$ , the area that contains the customers is $a$, and the maximum number of customers that can be served per vehicle is $Q$ . Daganzo's approximation can be interpreted as having: (a) a term related to the distance between the depot and customers and (b) a term related to the distance between customers. An approximation to the average length of vehicle routing problems to serve $n$ customers for different values of $m$ is:

$$l(n) = 2\overline{r}m + k_l \frac{n-m}{n}\sqrt{an} \quad (1)$$

where:

$l(n)$: the total length of the tours needed to serve $n$ customers

$n$ : the number of stops or customers

$m$ : the number of routes

$k_l$: coefficient to be estimated by linear regression

$a$ : the extent of the area of service comprised by the $n$ customers

$\overline{r}$ : the average distance from the depot to the $n$ customers

Expression (1) is a robust approximation to predict the average length of tours in a diverse set of randomly generated instances and empirical or real-world urban networks (Figliozzi, 2008c). This expression has been tested in compact square areas with different patterns of customer spatial distribution, time windows, customer demands, and depot locations. The fit of expression (1) to simulated and empirical data is high with a r-square of 0.96 to 0.99 and a mean absolute percentage error (MAPE) of less than 5%. The value of the coefficient $k_l$ is determined by linear regression and captures the influence of factors such as spatial customer distribution, depot location, and time windows. Expression (1) is minimized when $m=1$, i.e. one route serves *all* customers, and maximized when $m=n$, i.e. one route per customer.

Let customer $i, i \in I = \{1,....,n\}$ have a location $x_i$ and a distance $r_i$ to the depot; $d_{ij}$ represents the distance between customers $i, j \in I$. The set of tours to serve all customers in $I$ is denoted $R = \{1,....,m\}$, where $m$ indicates the number of routes or service regions and $n_r$ is the number of customers in route $r \in R$. Any given route $r \in R$ is formed by a set of $n_r + 1$ links denoted $L_r$, where $|L_r| = n_r + 1$. Let:

$t_u =$ Time to load/unload a unit of product

$t_o =$ Fixed time when stopping at a customer

$t_l =$ Average travel time in link $l$

$t_l^f =$ Free-flow travel time in link $l$

$s_l = d_l / t_l =$ Average travel speed in link $l$

$s_l^f =$ Free-flow travel speed in link $l$

$\alpha =$ Congestion increase coefficient

$\overline{s} =$ Average travel speed in any given route $r$

$\sigma_l =$ Standard deviation of the travel time in link $l$

$\upsilon_l = \sigma_l / t_l =$ Coefficient of variation in link $l$

$\rho_{kl} =$ Correlation between the distributions of travel time in links $k$ and $l$

$w =$ Tour duration constraint

$b =$ Vehicle capacity

$q_i =$ Amount delivered at customer $i, i \in I = \{1,....,n\}$

$\overline{q}_r =$ Average amount delivered per customer in route $r$, such that $n_r \overline{q}_r \le b$

The units associated with each mathematical element are clearly determined by their physical meaning, i.g. distance, time, area, speed, etc. Coefficients are simply dimensionless or have dimensions that are determined by the other elements in the mathematical expression, e.g. $k_l$ in expression (1).

There are several constraints associated with the operation of an urban commercial vehicle fleet: the type and capacity of the vehicles, drivers' working hours or maximum tour durations, service time, and the design of balanced tours (Bodin et al., 2003). For a given set of customer requests, the fleet operator delineates tours that satisfy these requests and constraints. In urban tours, commonly binding constraints for service, package delivery, and LTL[1] tours are service time (morning/afternoon customer visits) and tour duration. A common assumption when continuous approximations are utilized is that routes are balanced, i.e. routes have a similar number of customers (Daganzo, 1984, Daganzo, 1991). Assuming balanced routes, the binding constraint for each route with an average of $n/m$ customers and average speed $\bar{s}$ can be expressed as:

$$\frac{1}{\bar{s}}(2\bar{r} + k_l \frac{n-m}{nm}\sqrt{an}) + \frac{n}{m}t_o + t_u \frac{n}{m}\bar{q} \le w \quad (2)$$

Although in practice commercial vehicles do not experience the same levels of congestion at all points in a route, an average speed $\bar{s}$ is assumed for the sake of analytical tractability. The tour duration can be limited by one or several constraints such as: a) service considerations, e.g. tour durations of less than eight hours to ensure deliveries during normal business hours, b) driver working hours, e.g. by country or state law the number of consecutive hours that a truck driver can drive is restricted, usually the threshold is between 10 and 12 consecutive hours, and c) cost considerations, e.g. after a certain number of hours the carrier must pay overtime, which can be a significant cost in congested areas as discussed in Section 6. The tour effective speed, which also takes into account the time spent at customers, is defined as:

[1] LTL stands for less-than-truckload

$$\bar{s}_e = \frac{2\bar{r} + k_l \frac{n-m}{nm}\sqrt{an}}{\frac{1}{\bar{s}}(2\bar{r} + k_l \frac{n-m}{nm}\sqrt{an}) + \frac{n}{m}t_o + t_u \frac{n}{m}\bar{q}}$$

## 4. Analysis of the Impact of Congestion on Duration Constrained Tours

To facilitate the analysis of congestion impacts, tours are broken down into three cases: (a) the increase in average travel time, (b) the increase in travel time variability, and (c) the interaction effect between a simultaneous increase in average travel time and variability. Practically, the latter and most complicated case is usually the most relevant. However, simpler cases are analyzed firstly for the sake of presentation efficiency.

### 4.1. Increase in average travel time – no uncertainty

An increase in average travel time can be expressed by the coefficient $\alpha \geq 1$ that reflects the travel time increase with respect to the free-flow travel time:

$$t_l = \alpha\, t_l^f \quad \text{and} \quad s_l = \frac{1}{\alpha} s_l^f \tag{3}$$

By using this coefficient, expression (2) can be restated as:

$$\frac{\alpha}{\bar{s}_f}(2\bar{r} + k_l \frac{n-m}{nm}\sqrt{an}) + \frac{n}{m}t_o + t_u \frac{n}{m}\bar{q} \leq w \tag{4}$$

If travel time increases and the tour duration constraint (4) is violated, the number of routes, $m$, increases to restore feasibility. Since the definition of VHT includes only time spent on the road network, i.e. VHT does not include time spent at the customers, an increase in average travel time increases not only driving time but may also increase the number of tours and the total distance traveled. Therefore, the direct impact on VHT alone is insufficient to describe the effects of congestion; the impact on VKT must also be considered. For any given $\alpha > 1$, the percentage-wise increase in VHT is, on average, always larger than the percentage-wise increase in VKT. If percentage time driving is calculated as the ratio between time driving and tour duration, then an increase in average travel time increases the percentage time driving whereas the customer time, i.e. time spent at the customers, is unaffected.

### 4.2. Increase in travel time variability

If the travel times are not constant, the buffer $\sigma_r z$ must be added to (2) in order to guarantee a customer service level:

$$\frac{1}{\bar{s}}(2\bar{r} + k_l \frac{n-m}{nm}\sqrt{an}) + \frac{n}{m}t_o + t_u \frac{n}{m}\bar{q} \leq w - \sigma_r z \quad (5)$$

Assuming normally distributed travel times, the coefficient $z$ is related to the probability of completing the tour within the allowed tour duration. The route travel time standard deviation can be expressed as:

$$\sigma_r = \sqrt{\sum_{k \in L_r} \sigma_k^2 + \sum_{k=1}^{n_r} \sum_{l=k+1}^{n_r} \rho_{kl} \sigma_k \sigma_l} \qquad l = k+1 \qquad k, l \in L_r \quad (6)$$

Unlike previous studies and modeling approaches, the correlation between travel times is included because empirical data suggests that a positive correlation may not be negligible (Figliozzi et al., 2007). To minimize costs, a carrier will reduce the number of vehicles needed as well as the total route length-duration without violating customer service constraints. For a given set of customers and depots, this is equivalent to minimizing the number of routes subject to constraint (5).

The route travel time standard deviation, expression (6), grows with the number of customers per route or with an increase in variability (variances are non-negative numbers). An increase in travel time variability affects the right-hand term of expression (5) which is decreased by the term $\sigma_r z$. This may lead to a violation of the constraint and therefore $m$ must increase in order to restore feasibility. Total route duration variability increases with respect to case (a) but average route durations decrease when the buffer increase makes expression (5) binding and $m$ increases. Hence, on average, route durations shorten but the sum of the route duration plus the buffer tends to remain constant. Unlike case (a), only when $m$ increases there is an increase in distance traveled, time driving, and percentage time driving. Average driving speed does not change. However, effective tour speed, $\overline{s}_e$, increases as the number of stops per tour decreases.

**4.3. Interaction effect between a simultaneous increase in travel time and variability**

If there is an increase in congestion and average travel time increases while the coefficient of variation remains constant the impact of congestion is amplified. A widespread approach to indicate the degree of uncertainty in the distribution of a random variable is to calculate the coefficient of variation. Using coefficients of variation $\upsilon$, expression (6) can be restated as:

$$\sigma_r = \sqrt{\sum_{k \in L_r} (\upsilon_k\, t_k)^2 + \sum_{k=1}^{n_r} \sum_{l=k+1}^{n_r} \rho_{kl} \upsilon_k t_k \upsilon_l t_l} \qquad l = k+1 \quad k,l \in L_r$$

Although in practice commercial vehicles do not experience the same levels of travel time variability at all points in a route, a constant coefficient of variation is assumed for the sake of analytical tractability. Assuming a constant coefficient of variation, $\upsilon = \upsilon_k = \upsilon_l \quad \forall k,l \in L_r$, then:

$$\sigma_r = \upsilon \sqrt{\sum_{k \in L_r} t_k^2 + \sum_{k=1}^{n_r} \sum_{l=k+1}^{n_r} \rho_{kl} t_k t_l} \qquad l = k+1 \quad k,l \in L_r \tag{7}$$

Expressing the travel time using the free-flow travel times, $t_l = \alpha\, t_l^f$

$$\sigma_r = \upsilon \alpha \sqrt{\sum_{k \in L_r} (t_k^f)^2 + \sum_{k=1}^{n_r} \sum_{l=k+1}^{n_r} \rho_{kl} t_k^f t_l^f} \qquad l = k+1 \quad k,l \in L_r \tag{8}$$

Denoting $\sigma_r^f$ as the "free-flow" standard deviation of the route travel time in route $r$

$$\sigma_r^f = \sqrt{\sum_{k \in L_r} (t_k^f)^2 + \sum_{k=1}^{n_r} \sum_{l=k+1}^{n_r} \rho_{kl} t_k^f t_l^f} \qquad l = k+1 \quad k, l \in L_r \tag{9}$$

$$\sigma_r = \upsilon \alpha \, \sigma_r^f \tag{10}$$

Assuming normal distributions:

$$\frac{\alpha}{\overline{s}_f}(2\overline{r} + k_l \frac{n-m}{nm} \sqrt{an}) + \frac{n}{m} t_o + t_u \frac{n}{m} \overline{q} \le w - \upsilon \alpha \sigma_r^f z \tag{11}$$

Due to the central-limit-theorem, the assumption regarding normal distributions is crucial only when $n_r$ is small. There is a multiplicative interaction between $\upsilon$ and $\alpha$ which affects the right-hand term of expression (11). Since $\upsilon$ and $\alpha$ are non-negative a simultaneous increase in travel time and variability can have a large impact on the buffer size. A decrease in travel speed increases the average time to complete the route, as seen in the left-hand term of (11) . A decrease also increases the required buffer, as seen in the right-hand term of (11). In all cases, as the number of tours increases, the average number of customers decreases, and the distance per tour decreases. However, the absolute rate of decrease in the average distance per tour is always less than the rate of increase in the average number of tours.

Links with long travel times have a significant contribution on the final value of $\sigma_r^f$ as shown in (9). In tours with a long travel time from a DC to a service area that is followed by short inter-customer trips, the value of the standard deviation is determined by the round trip from/to the depot.

### 4.4. Constraint Coefficient

For each customer it is possible to define a dimensionless coefficient $\phi$ that can provide an indication of the relative impact of congestion on routing constraints for each customer.

$$\phi_i(\alpha, \upsilon) = \frac{\alpha 2 r_i / \overline{s}_f + t_o + t_u q_i}{w - \upsilon \alpha \sigma_i^f z} \tag{12}$$

Where the time standard deviation for the round trip from the depot to customer $i$ is defined as:

$$\sigma_i^f = \sqrt{(t_i^f)^2(2+\rho)}$$

Congestion has a distinct impact on each customer due to its location and service characteristics. When $\phi_i$ reaches the value of one, it is infeasible to serve customer $i$ with the desired level of service $z$.

## 5. Sensitivity Analysis

To illustrate how changes in travel time affect tour characteristics as well as VHT/VKT, a sensitivity analysis based on a real-world situation[2] and tour data reported in the literature is performed. Tour data from different cities indicate that the average number of stops per tour in urban areas is equal or greater than 5 stops per tour: approximately 6 in Calgary (Hunt and Stefan, 2005), 5.6 in Denver (Holguin-Veras and Patil, 2005), and 6.2 in Amsterdam (Vleugel and Janic, 2004). Customer service is highly related to the number of operations to be performed and the number of pallets/packages to be loaded/unloaded; service time can be as short as a few minutes (package delivery). In Amsterdam, unloading/loading time per stop is 21 minutes on average; LTL data from Sydney indicate a median stop time 30 minutes and an average time of approximately 40 minutes (Figliozzi et al., 2007).

Routing scenarios were constructed assuming a service area of 39.5 square kilometers containing 30 customers, a maximum tour duration of eight hours ($w = 8$), three different round trip distances to the depot ($2\overline{r}$ = 25, 50, and 75 kilometers), four different coefficient of variations ($\upsilon$ = 0.0, 0.2, 0.4, and 0.6), and four customer service times ranging from 15 to 60 minutes ($t_o + t_u\overline{q}$ =15, 30, and 45 minutes). The coefficient $z$ was set to a 1.64 value. Tours were designed using a construction and improvement routing heuristics for three average speeds: 50, 25 and 12.5 km/hr. When congestion sets in, routes must be redesigned to satisfy tour duration constraints as indicated by expressions (4), (5), and (11). Routes

[2] Tour characteristics and scenarios are based on data presented in Figliozzi et al. (2007). The service area represents the industrial district of Bankstown in the city of Sydney, Australia.

were built using a VRP construction and improvement heuristic that provides solutions within 3% of the best solutions for standard benchmark VRP instances with time window constraint (Figliozzi, 2008a). Using linear regression expression (1) was estimated and the regression fit was $R^2 = 0.97$.

<< Insert Table 1 Here >>

The sensitivity to congestion as a function of customer service time is presented in Table 1. A tour starts at a depot, visits one or more customers, and then returns to the depot. Table 1 does not present the number of tours but the average[3] increase factors with respect to free-flow speed and assuming $2\overline{r}$ = 25 km, $\overline{s} = 50$, and a constant service time per customer. For example, keeping the service time constant, $t_c$ = 45 min, but reducing the speed by half ($\overline{s} = 25$km/hr), the number of tours needed is 1.25 times larger than the number of tours needed when $\overline{s} = 50$ km/hr. A reduction of travel speed has a significant effect on VKT and VHT. The impact of congestion on VKT and VHT is higher when customers have longer service times. The corresponding constraint coefficients follow a similar trend as shown in Table 2.

<< Insert Table 2 Here >>

The sensitivity to congestion as a function of distance to the depot is presented in

Table 3; this table is organized by the three return distances (25, 50, 75 km) to depot $2\overline{r}$ . Each of the sections contains the average[4] increase factors with respect to free-flow speed and no variability, i.e. $\overline{s}$ =

[3] The average among the three variability factors: 0.2, 0.4, and 0.6

[4] The average among three customer times $t_c$ : 15, 30, and 45 minutes

50, $\upsilon = 0.0$, and for a given return distance to depot $2\overline{r}$. For example, by setting $2\overline{r} = 50$km, the number of tours needed when speed is halved ($\overline{s} = 25$km/hr) and variability increases from $\upsilon = 0.0$ to $\upsilon = 0.6$ is 1.60 times larger than the number of tours needed when $\overline{s} = 50$ km/hr, and $\upsilon = 0.0$.

<< Insert Table 3 Here >>

Several observations can be made from the analysis of

Table 3: (a) round trip distance to the depot is a crucial factor. The impact of congestion is amplified as the depot moves further away from its customers; (b) variability is an important factor for travel times that are relatively long with respect to the tour duration. For short average distances to/from the depot and high speeds the "buffer" is too small with respect to $w$ and the impact of variability is negligible; (c) when congestion is high, i.e. low speeds and high variability, it becomes infeasible to serve more distant customers with a high service level; (d) in all cases, the increase in the number of tours is greater than the increase in total distance traveled. Hence, the distance per tour decreases as congestion increases, i.e. tours become shorter on average; and (e) as congestion increases, the number of tours needed increases and with it the percentage of time driving and the average distance per customer. The corresponding constraint coefficients follow a similar trend as shown in Table 4.

<< Insert Table 4 Here >>

As shown in Table 2 and Table 4, the analysis of the constraint coefficients $\phi_i$ is a fast and effective proxy to study the sensitivity of tours to changes in congestion levels.

Conceptually, the impact of congestion on VKT/VHT can be analyzed as a function of the customer distance to the depot and the level of the constraint coefficient $\phi_i$, see Table 5. When congestion is such that the constraint coefficients are close to or above one and customer service level has to be maintained, new depots are required or the service of customers located far away from the depot must be transferred to another transport provider, for example a third party logistics company (3PL).

<< Insert Table 5 Here >>

## 6. Impact on Costs

In transport or highway planning studies, commuter/passenger congestion costs are traditionally estimated as the sum of three different components: 1) the product of the travel time delays and the value of time per vehicle-driver, 2) a cost due to travel time unreliability, and 3) higher operating and environmental costs. Carriers' costs are harder to quantify; the impact of congestion is heavily dependent on network (e.g. depot location), route type (e.g. number of stops and its density) and customer service characteristics (e.g. time windows) that may greatly vary among carriers.

Congestion not only increases carriers' costs but also changes the relative weight of daily operational costs such as fuel and labor needed per customer. Table 6 presents congestion related fuel and wage increases as a function of travel speed and its coefficient of variation. The column named "total increase factor" shows the total cost increase using as a base scenario a travel time of 50 km/h and no travel speed variation. The columns named “service time”, “driving time”, and “fuel” respectively indicate their share as a percentage of the total fuel plus labor costs[5].

<< Insert Table 6 Here >>

For a given number of customers served, total customer service time is not affected by congestion – i.e. time spent at the customers’ locations does not change – whereas fuel and wages are directly affected by the amount of VHT and VKT. As congestion increases, labor and fuel costs related to time and distance driven become dominant. From a carrier’s perspective, the ultimate monetary impact of congestion depends on how much a carrier can charge customers or pass on congestion costs along the supply chain. If direct distance between distribution center and customer location is the main basis to price transport services, carriers cannot readily and transparently transfer the costs brought about by congestion.

Table 6 does not include costs associated with the increases in fleet size needed for the increase in the number of tours. In addition, for a carrier operating in an urban area, the costs of congestion may be compounded by: (a) customer service employee time to handle customer complaints and rescheduling issues; (b) stiff penalties due to JIT (just-in-time) late deliveries or the cost of large time-buffers; (c) capital and operational costs of real time information systems, sophisticated vehicle routing and tracking software needed to mitigate the impact of congestion (Regan and Golob, 1999); (d) toll road usage to avoid highly congested streets – trucks that come on/off main tolled highways several times a day to

[5] The fuel and labor costs were calculated using fuel consumption of a medium-size delivery truck of approximately three kilometers per liter of diesel at a cost of $1.25 per liter of diesel. Fuel consumption was increased to account for lower fuel efficiency at low speeds and congested driving conditions. Labor cost was assumed as $20 per driver hour. Return distance to depot was assumed to be 50 kilometers and the service time per customer 30 minutes. Maintenance costs are not considered, however, in a per kilometer basis they are bound to increase when vehicles are operated in congested conditions, e.g. braking system.

access different delivery areas can accrue a significant toll cost (Figliozzi et al., 2007, Holguin-Veras et al., 2006); and (e) parking fees and/or the payment of traffic/parking fines in dense urban areas lacking loading zones (Morris et al., 1998).

## 7. Empirical Tour Data Classification and Representation

This section relates the insights of previous sections to empirical tour data obtained from a company based in Sydney, Australia. The company's customers are located in several industrial suburbs of Sydney and round trips between the depot and these industrial suburbs range between 14 to 40 kilometers. All distances are based on real road network distances as traveled by the commercial vehicles. For this particular distribution operation time windows are not an overriding concern; however, deliveries must take place within the promised day. In addition, deliveries have to be carried out within normal business hours (most customers prefer morning deliveries); therefore, the starting time of the tour and its duration are constrained to meet this condition. This is clearly revealed in the tour data: 13% of the deliveries took place before 8 am, 45% of the deliveries took place before 11 am, 76% of the deliveries took place before 2 pm, and 99% of the deliveries took place before 5 pm. A detailed description and analysis of the tour data is presented in Figliozzi et al. (2007).

In many real-world distribution routes, to reduce distribution costs customers are served and clustered according to their requirements and geographical location. At the disaggregate tour level, time driven and distance driven per customer (or tour) are highly correlated as shown in Figure 1.

<< Insert Figure 1 Here >>

More insights regarding tour characteristics and classifications can be obtained plotting percentage of time driving (in a given tour) and distance traveled per customer (in a given tour); see Figure 2. The percentage of time driving ( $PTD$ ) can be expressed as a function of average distance traveled per stop $\bar{d}$ , the average travel speed $\bar{s}$ , and service time per customer $t_c$ :

$$PTD = \frac{n_r \bar{d} / \bar{s}}{n_r \bar{d} / \bar{s} + n_r t_c} = \frac{\bar{d}}{\bar{d} + t_c \bar{s}}$$

Hence, $PTD$ is not directly related to tour duration or total distance travelled and better describes the efficiency of the tour in terms of tour length and duration per customer served. Assuming that customer service time cannot be reduced without reducing quality of service, $PTD$ can be reduced only reducing distance travelled per customer or increasing average travel speed. According to their location in Figure 2 tours can be divided into three distinct classes; a summary of these tour characteristics is shown in Table 7.

Class I tours, Figure 2 lower left, have many stops and a low percentage of the tour duration is spent driving. The average driving speed is low because the percentage of local and access roads/streets used increases with the number of customers visited. Despite the low average travel speed, tours are highly efficient from the distributor perspective because many customers are served driving a short distance and a low percentage of time is spent driving.

<< Insert Figure 2 Here >>

On the upper right section of the graph (Class III), tours have few stops and a high percentage of the tour duration is spent driving. The tour length is long because customers are located further away from each other and/or the depot is far from the distribution area.  Tour duration is high and very few customers can be served. The average driving speed is high because the percentage of local and access roads/streets used is small and main highways are used to connect the depot with the distribution area. Comparing delivery costs, class III tours have a delivery cost per customer that is approximately 3 times higher than class I tours. In addition, class III tours are more constrained; the average constraint coefficient for class I customers is 0.20 whereas for class III customers is 0.49.

Class II tours are not as efficient as class I tours as the average distance travelled per stop is significantly higher because the density of stops is lower than in class I tours. Given that the daily design of tours is based on what freight is available on a particular day, carriers cannot always utilize routes that are "tight" both in terms of customer locations and total tour duration. In class II tours, more customers could have been added to the tour if more demand had materialized. Finally, on the lower right section of the graph (Class IV or infeasible tours), below the feasibility boundary, there is an area where feasible tours cannot be found at practical travel speeds.

For a given customer time, tour efficiency and the relative weight of time and distance related costs can be classified based on percentage of time driving and the average distance per customer. As congestion worsens the relative weight of labor costs – wages and overtime – escalates and the proportion of class II and III tours will grow since reduced travel time and larger buffers preclude the design of tight or efficient routes.

<< Insert Table 7 Here >>

As indicated in sections 4 and 5, the impacts of congestion are more severe in tours that have a relatively long distance between depot and customers and there is a significant reduction in travel speed.

Given the tour classification presented in this section, class III tours are more exposed to negative congestion impacts: (a) congestion on freeways drastically reduces free-flow travel speed; (b) the longer distance between depot and customers exacerbates the increase in driving travel time; and (c) using local streets may not be feasible due to their lower travel speed.

Despite the simplifying assumptions made in the analytical modeling of congestion impacts to ensure analytical tractability, the intuition and insights obtained can be applied to the characterization and analysis of real-world tour data and networks. Future research efforts can study the impacts of congestion using routing algorithms that are designed to handle time dependent travel times (Malandraki and Daskin, 1992) , time dependent travel times with window constraints (Ichoua et al., 2003) , or more general algorithms that can handle time dependent travel times with both soft and hard time window constraints as well as general cost functions (Figliozzi, 2009) .

## 8. Conclusions

This research analyzes the impact of congestion on commercial vehicle tours. An analytical model, numerical experiments, and empirical tour data are used to understand changes in tour characteristics, carriers' costs, and VKT-VHT. An increase in average travel time increases not only driving time but also distance traveled. Therefore, the direct impact on VHT alone is insufficient to describe the effects of congestion; the impact on VKT must also be considered. This research shows that long travel time/distance between customer and depot is a crucial factor that exacerbates the negative impacts of congestion. Travel time variability is not as significant when the travel time between the depot and customers is small in relation to the maximum tour duration and when the routes are not highly constrained. For each customer, it is possible to define a dimensionless coefficient that provides an indication of the relative impact of congestion on routing constraints.

Congestion impacts on carriers' costs are also considerable since congestion not only increases carriers' operating costs but also affects carriers' cost structure. As congestion worsens labor costs, wages and overtime, may outweigh other operating costs. The productivity of the carrier can be measured in terms of tour time and distance required to serve a customer. Percentage of time driving and the average distance traveled per customer are tour characteristics suitable to indicate the efficiency of an individual tour because they are directly related to driving time and inversely related to customer time.

This paper categorizes tours into three classes based on tour efficiency and the relative weight of time and distance related costs. The proposed classification is based on percentage of time driving and the average distance per customer. In addition for a given customer time, a feasibility boundary that is a function of percentage of time driving and average distance per stop can be established. The tour classification and feasibility boundaries are valuable and intuitive parameters that represent real-world tour data and classify tours in regards to their sensitivity to congestion

## Acknowledgements

The author gratefully acknowledges the Oregon Transportation, Research and Education Consortium (OTREC) for sponsoring this project. This work was also supported by the Department of Civil and Environmental Engineering in the Maseeh College of Engineering and Computer Science at Portland State University. Any errors or omissions are the sole responsibility of the author.

## References

BEARWOOD, J., HALTON, H. & HAMMERSLEY, J. (1959) The Shortest Path Through Many Points. *Proceedings of the Cambridge Philosophical Society 55***,** 299-327.

BODIN, L., MANIEZZO, V. & MINGOZZI, A. (2003) Street Routing and Scheduling Problems. IN HALL, R. W. (Ed.) *Handbook of Transportation Science, 2nd Edition.* Norwell, Ma., Kluwer Academic Publishers.

BREMMER, D., COTTON, K. C., COTEY, D., PRESTRUD, C. E. & WESTBY, G. (2004) Measuring congestion - Learning from operational data. *TRANSPORTATION RESEARCH RECORD (1895)***,** 188-196.

CAMBRIDGE SYSTEMATICS (2003) Accounting for Commercial Vehicles in Urban Transportation Models - Task 3 - Magnitude and Distribution. prepared for Federal Highway Administration- prepared by Cambridge Systematics, Inc.Cambridge, MA.

CHEN, C., SKABARDONIS, A. & VARAIYA, P. (2003) Travel-time reliability as a measure of service. *Transportation Research Record 1855***,** 74-79.

DAGANZO, C. F. (1984) The Distance Traveled To Visit N-Points With A Maximum Of C-Stops Per Vehicle - An Analytic Model And An Application. *Transportation Science,* 18**,** 331-350.

DAGANZO, C. F. (1991) Logistics Systems-Analysis. *Lecture Notes In Economics And Mathematical Systems,* 361**,** 1-321.

ERERA, A. (2000) Design of Large-Scale Logistics Systems for Uncertain Environments. *Ph D dissertation, University of California-Berkeley*.

FIGLIOZZI, M. (2008a) An Iterative Route Construction and Improvement Algorithm for the Vehicle Routing Problem with Soft and Hard Time Windows. *Applications of Advanced Technologies in Transportation (AATT) 2008 Conference Proceedings.* Athens, Greece, May 2008.

FIGLIOZZI, M. (2009) A Route Improvement Algorithm for the Vehicle Routing Problem with Time Dependent Travel Times. *Proceeding of the 88th Transportation Research Board Annual Meeting CD rom***-** *January 2009* **-** *Washington DC. USA.* Washington, DC, January 2009.

FIGLIOZZI, M. A. (2006) Modeling the Impact of Technological Changes on Urban Commercial Trips by Commercial Activity Routing Type. *Transportation Research Record 1964***,** 118-126.

FIGLIOZZI, M. A. (2007) Analysis of the efficiency of urban commercial vehicle tours: Data collection, methodology, and policy implications. *Transportation Research Part B,* 41**,** 1014-1032.

FIGLIOZZI, M. A. (2008b) Planning Approximations to the average length of vehicle routing problems with time window constraints. *Forthcoming Transportation Research part B.*

FIGLIOZZI, M. A. (2008c) Planning Approximations to the Average Length of Vehicle Routing Problems with Varying Customer Demands and Routing Constraints. *Transportation Research Record 2089***,** 1-8.

FIGLIOZZI, M. A., KINGDON, L. & WILKITZKI, A. (2007) Analysis of Freight Tours in a Congested Urban Area Using Disaggregated Data: Characteristics and Data Collection Challenges. *Proceedings 2nd Annual National Urban Freight Conference, Long Beach, CA. December*.

GOLOB, T. F. & REGAN, A. C. (2001) Impacts of highway congestion on freight operations: perceptions of trucking industry managers. *Transportation Research Part A-Policy And Practice,* 35**,** 577-599.

GOLOB, T. F. & REGAN, A. C. (2003) Traffic congestion and trucking managers' use of automated routing and scheduling. *Transportation Research Part E-Logistics And Transportation Review,* 39**,** 61-78.

GOLOB, T. F. & REGAN, A. C. (2005) Trucking industry preferences for traveler information for drivers using wireless Internet-enabled devices. *Transportation Research Part C-Emerging Technologies,* 13**,** 235-250.

GREAVES, S. & FIGLIOZZI, M. (2008) Urban Commercial Vehicle Tour Data Collection Using Passive GPS Technology: Issues And Potential Applications. *Transportation Research Record 2049***,** 158-166.

HENSHER, D. A. & PUCKETT, S. M. (2005) Refocusing the modelling of freight distribution: Development of an economic-based framework to evaluate supply chain behaviour in response to congestion charging. *Transportation,* 32**,** 573-602.

HOLGUIN-VERAS, J. & PATIL, G. (2005) Observed Trip Chain Behavior of Commercial Vehicles. *Transportation Research Record 1906***,** 74-80.

HOLGUIN-VERAS, J., WANG, Q., XU, N., OZBAY, K., CETIN, M. & POLIMENI, J. (2006) The impacts of time of day pricing on the behavior of freight carriers in a congested urban area: Implications to road pricing. *Transportation Research Part A-Policy And Practice,* 40**,** 744-766.

HUNT, J. & STEFAN, K. (2005) Tour-based microsimulation of urban commercial movements. *presented at the 16th International Symposium on Transportation and Traffic Theory (ISTTT16), Maryland, July 2005.*

ICHOUA, S., GENDREAU, M. & POTVIN, J. Y. (2003) Vehicle dispatching with time-dependent travel times. *European Journal Of Operational Research,* 144**,** 379-396.

KENYON, A. S. & MORTON, D. P. (2003) Stochastic vehicle routing with random travel times. *Transportation Science,* 37**,** 69-82.

LAPORTE, G. & LOUVEAUX, F. V. (1993) The Integer L-Shaped Method For Stochastic Integer Programs With Complete Recourse. *Operations Research Letters,* 13**,** 133-142.

LOMAX, T., SCHRANK, D., TURNER, S. & MARGIOTTA, R. (2003) Selecting Travel Reliability Measures. *Texas Transportation Institute monograph (May 2003)*.

MALANDRAKI, C. & DASKIN, M. S. (1992) Time-Dependent Vehicle-Routing Problems - Formulations, Properties And Heuristic Algorithms. *Transportation Science,* 26**,** 185-200.

MCKINNON, A. (1999) The Effect of Traffic Congestion on the Efficiency of Logistical Operations. *International Journal of Logistics: Research & Applications,* 2**,** 111-129.

MOINZADEH, K., KLASTORIN, T. & BERK, E. (1997) The impact of small lot ordering on traffic congestion in a physical distribution system. *Iie Transactions,* 29**,** 671-679.

MORRIS, A. G., KORNHAUSER, A. L. & KAY, M. J. (1998) Urban freight mobility - Collection of data on time, costs, and barriers related to moving product into the central business district. *Freight Transportation.* Washington, Natl Acad Sci.

NOVAES, A. G. N., DE CURSI, J. E. S. & GRACIOLLI, O. D. (2000) A continuous approach to the design of physical distribution systems. *Computers & Operations Research,* 27**,** 877-893.

OUTWATER, M., ISLAM, N. & SPEAR, B. (2005) The Magnitude and Distribution of Commercial Vehicles in Urban Transportation. *84th Transportation Research Board Annual Meeting* **-** *Compendium of Papers CD-ROM*.

RAO, K., GRENOBLE, W. & YOUNG, R. (1991) Traffic Congestion and JIT. *Journal of Business Logistics,* 12**,** 105–121.

REGAN, A. C. & GOLOB, T. F. (1999) Freight operators' perceptions of congestion problems and the application of advanced technologies: Results from a 1998 survey of 1200 companies operating in California. *Transportation Journal,* 38**,** 57-67.

SANKARAN, J., GORE, K. & COLDWELL, B. (2005) The impact of road traffic congestion on supply chains: insights from Auckland, New Zealand. *International Journal of Logistics: Research & Applications,* 8**,** 159–180.

SANKARAN, J. & WOOD, L. (2007) The Relative Impact of Consignee Behaviour and Road Traffic Congestion on Distribution Costs. *Transportation Research part B,* 41**,** 1033-1049.

VLEUGEL, J. & JANIC, M. (2004) Route Choice and the Impact of 'Logistic Routes'. IN TANIGUCHI, E. & THOMPSON, R. (Eds.) *LOGISTICS SYSTEMS FOR SUSTAINABLE CITIES.* Elsevier.

WEISBROD, G., DONALD, V. & TREYZ, G. (2001) Economic Implications of Congestion. NCHRP Report #463. Washington, DC, National Cooperative Highway Research Program, Transportation Research Board.

## Tables

**Table 1 – Average Increase Factors for different customer service times ( $t_c$ )**

| | Average Speed | Service Time ( $t_c$ ) 15 min | 30 min | 45 min |
|---|---|---|---|---|
| Tours | | 1.00 | 1.00 | 1.00 |
| Driving Time | 50 km/h | 1.00 | 1.00 | 1.00 |
| Distance | | 1.00 | 1.00 | 1.00 |
| Tours | | 1.00 | 1.11 | 1.25 |
| Driving Time | 25 km/h | 2.00 | 2.16 | 2.39 |
| Distance | | 1.00 | 1.08 | 1.20 |
| Tours | | 1.50 | 1.56 | 1.58 |
| Driving Time | 12.5 km/h | 5.28 | 5.62 | 5.82 |
| Distance | | 1.32 | 1.40 | 1.46 |

**Table 2 – Constraint coefficients $\phi_i$ assuming $\upsilon = 0.0$**

| Average Speed | Service Time ( $t_c$ ) 15 min | 30 min | 45 min |
|---|---|---|---|
| 50 km/h | 0.09 | 0.13 | 0.16 |
| 25 km/h | 0.16 | 0.19 | 0.22 |
| 12.5 km/h | 0.28 | 0.31 | 0.34 |

**Table 3 – Average Increase Factors for Different Customer-depot distances ( $2\overline{r}$ )**

| | **Distance to Depot ( $2\overline{r}$ )** | **Coefficient of Variation** | **Average Tour Speed** 50 km/h | 25 km/h | 12.5 km/h |
|---|---|---|---|---|---|
| Tours | 25 km | 0.2 | 1.00 | 1.11 | 1.43 |
| Driving Time | | | 1.00 | 2.18 | 5.28 |
| Distance | | | 1.00 | 1.09 | 1.32 |
| Tours | | 0.6 | 1.05 | 1.20 | 1.68 |
| Driving Time | | | 1.04 | 2.30 | 6.04 |
| Distance | | | 1.04 | 1.15 | 1.51 |
| Tours | 50 km | 0.2 | 1.06 | 1.25 | 2.25 |
| Driving Time | | | 1.05 | 2.44 | 8.30 |
| Distance | | | 1.05 | 1.22 | 2.07 |
| Tours | | 0.6 | 1.06 | 1.60 | 6.83 |
| Driving Time | | | 1.05 | 3.04 | 23.88 |
| Distance | | | 1.05 | 1.52 | 5.97 |
| Tours | 75 km | 0.2 | 1.08 | 1.52 | 6.25 |
| Driving Time | | | 1.07 | 2.71 | 17.48 |
| Distance | | | 1.07 | 1.36 | 4.37 |
| Tours | | 0.6 | 1.18 | 2.47 | ***Infeasible for z=1.64*** |
| Driving Time | | | 1.15 | 4.23 | |
| Distance | | | 1.15 | 2.12 | |

**Table 4 – Constraint coefficients assuming $\upsilon = 0.0$**

| **Distance to Depot** | **Average Speed** 50 km/h | 25 km/h | 12.5 km/h |
|---|---|---|---|
| 25 km | 0.13 | 0.19 | 0.31 |
| 50 km | 0.14 | 0.27 | 0.52 |
| 75 km | 0.19 | 0.38 | 0.75 |

**Table 5 – Conceptual Impact of Congestion on VKT/VHT**

| | | **Distance to Depot** | | |
|---|---|---|---|---|
| | | ***Short*** | ***Medium*** | ***Long*** |
| **Constraint Coefficient** | ***Low*** | Low | High | Very High Approaching Infeasibility |
| | ***High*** | Medium | Very High Approaching Infeasibility | ***Use 3PL or New Depot*** |

**Table 6 –Impact of Congestion on Tour Costs**

| **Average Tour Speed** | **Coefficient of Variation** | **Total increase Factor** | **Service Time** | **Driving Time** | **Fuel** |
|---|---|---|---|---|---|
| 50 km/h | 0.2 | 1.01 | 60% | 13% | 27% |
| | 0.6 | 1.02 | 58% | 14% | 28% |
| 25 km/h | 0.2 | 1.33 | 43% | 24% | 32% |
| | 0.6 | 1.50 | 38% | 27% | 36% |
| 12.5 km/h | 0.2 | 2.69 | 21% | 40% | 40% |
| | 0.6 | 6.49 | 8% | 47% | 45% |

**Table 7 – Summary of Tour Characteristics by Class (Averages)**

| Tour Class | % Time Driving | Dist. per stop (km) | Stops per Tour | Tour Duration (hr) | Tour Distance (km) | Tour Speed (km/hr) | Effective Tour Speed (km/hr) |
|---|---|---|---|---|---|---|---|
| Class I | 43% | 13.3 | 7.5 | 8.2 | 88.0 | 24.9 | 11.1 |
| Class II | 58% | 21.1 | 6.4 | 7.2 | 117.4 | 26.7 | 17.2 |
| Class III | 65% | 59.6 | 3.9 | 8.3 | 206.3 | 36.4 | 28.0 |

## Figures

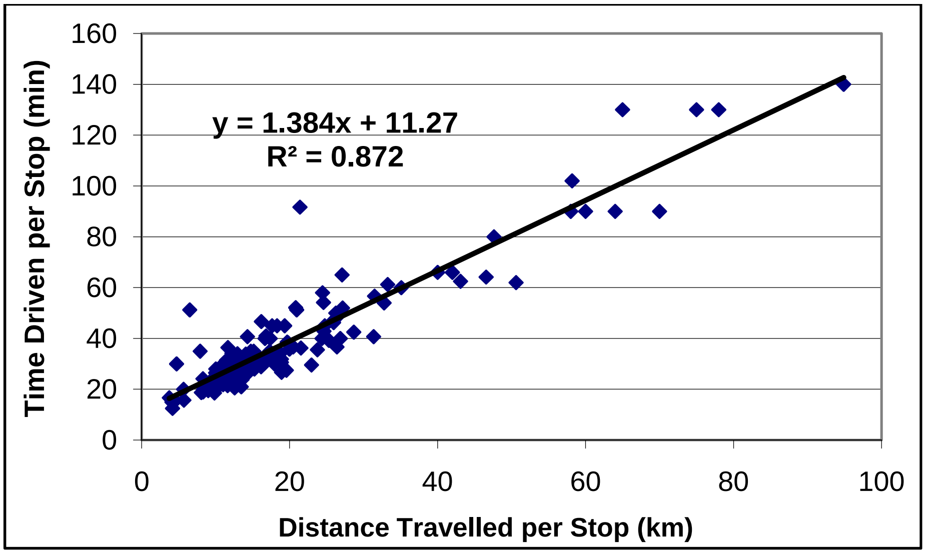


**Figure 1 – Time and Distance per Customer Served**

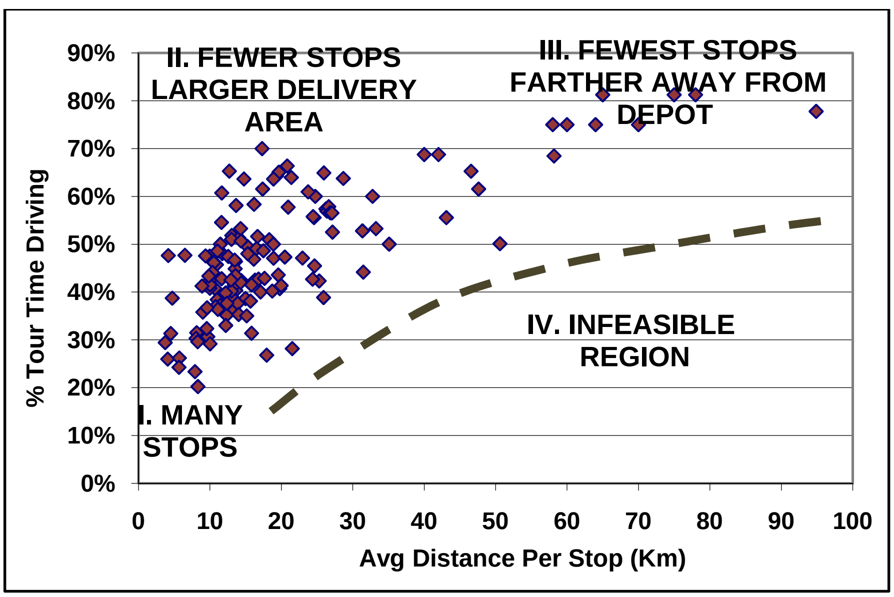


**Figure 2 - Tour Classification by Percentage Time Driving and Distance Traveled per Stop**