

**MEASURING THE VALUE OF TIME IN
HIGHWAY FREIGHT TRANSPORTATION**

A Dissertation

by

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ABSTRACT

This research investigated several aspects of the value of time (VOT) in the trucking industry. This included examining the marginal monetary benefits and costs of reduced and prolonged freight transportation time on highways.

First, a comprehensive survey estimated truckers' perceived VOT by combining stated preference, utility theory, conditional logit modeling, and maximum likelihood function. From the data collected around major cities in Texas and Wisconsin, the truckers' perceived VOT was estimated to be \$54.98/vehicle/hour. Second, scenario-based simulation examined urban truckload operations, the purpose of which was to examine the fleet effect of individual vehicle delay on the carrier's operation. Two of the most congested highway segments in Houston were used for the simulation, together with constrained delivery windows. The result showed that the scenario-based vehicle VOT varied from \$79.81/vehicle/hour to \$120.89/vehicle/hour. Third, VOT based on commodity delay only was examined in relationship to inventory management by assuming prolonged transportation time or freight delay. Delay of chemical products was ranked as the highest VOT at \$13.89/truckload/hour, followed by food products at \$7.24/truckload/hour. Finally, a continuous approximation technique was developed for fleet operations in the context of less-than-truckload deliveries. The trade-offs between travel time and roadway transportation cost were derived analytically and results were used to estimate fleet value of time. Ignoring time windows, the vehicle VOT for major distribution companies in Texas was estimated to be \$15.50/vehicle/hour for highway trips and \$22.00/vehicle/hour for local trips.

To summarize, freight VOT is not only directly due to vehicles and drivers, but depends on fleet operations and supply chain management. The several approaches adopted in this research represent possible perspectives that need to be further examined. They each reveal a component of the entire shipping process that can be appropriately utilized to calculate the overall freight VOT in future studies. For example, an urgent delivery carrying chemical products can be estimated at a total congestion cost of

\$162.86/vehicle/hour. However, trips with different characteristics need to be treated individually and carefully to avoid overestimation. It remains challenging to combine all these different elements adequately to reach valid VOT for the trucking industry.

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NOMENCLATURE

AASHTO	American Association of State Highway and Transportation Officials
BC	Benefit/Cost
BTS	Bureau of Transportation Statistics
CA	Continuous Approximation
CPI	Consumer Price Index
FAF	Freight Analysis Framework
FHWA	Federal Highway Administration
LTL	Less-Than-Truckload
NCHRP	National Cooperative Highway Research Program
MLE	Maximum Likelihood Estimation
TL	Truckload
TSP	Traveling Salesman Problem
TxDOT	Texas Department of Transportation
VOT	Value of Time
VOR	Value of Reliability

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CHAPTER I

INTRODUCTION AND BACKGROUND

1.1. An Increasing Demand for Trucking

Freight transportation is an important element of society, connecting different economic activities. Efficient and reliable freight transportation enables manufacturers to use distant sources of raw materials to produce goods for both local and distant customers. It also enables retailers to maintain supply chains at low cost, resulting in more competitive businesses.

Freight transportation is complex and has evolved with supply chain strategies. For example, American households show increasing interest in e-commerce, which demands a more fragmented, direct delivery system. The United States has extensive worldwide commerce, which relies on natural resources and manufactured products from many other countries dependent on an extended global transportation system. Including international freight, the United States transportation system moved an average of 53 million tons of freight each day in 2002 worth \$36 billion. This number reached 58.9 million tons per day in 2008 and is forecasted to reach 101.9 million tons per day in the year 2035 (Freight Analysis Framework, 2011). Although the United States has been affected by the recent global recession, long-term projected economic growth will lead to additional significant demand for freight transportation.

In addition to the increase in volume of goods moved through freight transportation, the value of these goods (freight) is increasing even faster. Assuming that the rate of increase in freight value continues based on the Freight Analysis Framework estimate (2011), the value of freight will increase in constant dollars by over 190 percent between 2002 and 2035, which is nearly twice the growth rate forecasted for total tons. The direct result of this growth in freight value is the increasing cost associated with inventory management, which encourages a structural change toward utilization of a just-in-time (JIT) system. JIT is a supply chain management system that requires highly

coordinated transportation to meet customer demand or production requirements while maintaining a lower inventory level. The many goods transported within this system are time sensitive and demand more vehicles to transport than some other types of delivery systems. A lot of freight-dependent entities no longer place large orders. Instead, they order goods or products in small amounts on a more frequent basis than they would if they could afford to order in bulk. Business owners relying on a limited number of items to arrive on time for seasonal sales or special orders can experience lost revenue when there is a freight transportation delay, as customers often cancel orders after finding what they want from another vendor or online.

Among all freight transportation modes, trucks are the most highly used. According to *Freight Story 2008* (FHWA, 2008):

“Freight moves throughout the United States on 985,000 miles of Federal-aid highways, 141,000 miles of railroads, 11,000 miles of inland waterways, and 1.6 million miles of pipelines” (USDOT/FHWA 2007a and USDOT/FHWA 2007b).

Trucks carry more total tonnage than all other modes combined. At least half of all hazardous materials shipped within the United States are moved by trucks. Trucks are the most common mode used to move imports and exports between inland locations and international gateways. Considering foreign trade, trucks carry about 58 percent of the value of goods traded with Canada and Mexico, with trains ranking second (USDOT, 2008).

1.2. Imbalance between Roadway Supply and Truck Demand

With the rapid growth of trucking demand and lagging improvement in road capacity in the United States, freight delay due to highway congestion is expected to increase (Cambridge Systematics, 2011). This phenomenon challenges every aspect of freight operation and planning, including its basic objective to provide effective transportation that operates at minimal cost and responds quickly to demand. Data from

FHWA (2008) showed that from 1980 to 2007, the number of commercial trucks climbed 56 percent.

Route distribution suggests another difficult task for truck transportation operators. Unlike commuter vehicles that usually travel locally, most freight moves on interstate highways between decentralized warehouses/distribution centers and retailers/customers. Together with passenger cars competing for space on the highway system, growing truck volume incurs congestion where there is not enough capacity for total vehicle volume. Most of the congestion takes place at major freight bottlenecks such as airport entrances and exits, border crossings, transfer points, or highway interchanges with a high density of activities. It is often caused by converging traffic, lane reductions, steep grades, channels, an emerging rail line, or large city intersections under high demand. Other possible causes include regulation in pickup and delivery time windows and shortage of facilities such as truck parking areas. Since congestion slows down traffic significantly and creates stop-and-go conditions, both passenger vehicle travel and truck operations are significantly affected.

1.3. The Impact of Freight Delay

According to the *Urban Mobility Report* from the Texas A&M Transportation Institute (Schrank et al., 2012), congestion is a problem in United States' 498 urban areas, and this problem is getting worse for all the areas.

Freight delay has a direct and significant impact on vehicle use hours, fleet efficiency, and scheduling of warehousing activities—all at a cost detriment to the national economy. In 2006, 226 million hours of truck delay took place at bottlenecks where congestion is prevalent. Delay at bottlenecks accounts for only about 40 percent of total truck delay, while the other 60 percent is due to nonrecurrent or transient congestion according to Cambridge Systematics (2005, 2008). The *Urban Mobility Report* (Schrank et al., 2012) estimated a total of 196 million hours of truck delay in the 498 urban areas for 2011. Congestion and delay add to total transportation cost, which

has been escalating over the years. For example, between 1981 and 2002, transportation costs increased from \$228 billion to \$577 billion, which corresponds to 45.1 percent and 63.4 percent of the total logistics cost, respectively (MacroSys Research and Technology, 2005). With significant growth projected in commerce due to globalization, freight traffic is expected to double in the next 30 years, which would further aggravate traffic congestion and incur additional transportation cost.

Logistics considers freight on the transportation network as in-transit inventory. In this sense, a longer travel time lengthens the stockholding period and therefore incurs greater in-transit inventory cost. McKinnon (1998) and Chiang (2010) argued that the additional in-transit inventory cost is negligible because the longer travel time just means inventory is shifted from the warehouse or factory to the highway network while total inventory does not change. This is true when travel time is perfectly predicted by downstream operators. In reality, shippers who receive an unexpected late delivery (consignees) are likely to have their operations disrupted in a variety of ways. Freight delivery and unloading are scheduled with maximum efficiency only if the workload is distributed evenly during work hours (McKinnon et al., 2008, 2009). A late delivery causes scheduled workforce and unloading bays to wait for deliveries, and to possibly become overwhelmed when several deliveries come at the same time, which reduces the productivity of warehouses/distribution centers. Staff might need to work beyond regular hours, which raises operational costs. This issue becomes even more significant to cross-docking operations, where the upstream arriving trucks have the potential to delay the entire downstream operations, such as loading and departing.

Late deliveries also cause a shortage of materials for production. Because JIT strategy reduces inventory and the associated cost of stock keeping (inventory accumulation), the risk of stock-out is magnified significantly, which results in lost sales and dissatisfied customers. The successful implementation of JIT operations relies heavily on reliable delivery as a result of reliable transportation. Without on-time delivery, JIT production can be delayed or stopped (Blanchard, 1996). To reduce the risk of stock-out, a certain amount of inventory is kept on site. This amount of inventory is

known as safety stock, and its amount is estimated based on anticipated lead time, uncertainty about the lead time, customer demand, and uncertainty about demand during the lead time (Ballou & Srivastava, 2007). A larger safety stock is necessary if delay happens more frequently, which indicates a higher inventory cost.

For freight senders, a single late delivery may not significantly affect their operation. However, their level of customer service is jeopardized if deliveries consistently do not satisfy the time windows required by customers, since late deliveries affect various operations of receivers directly as indicated above. Freight shippers that provide unreliable deliveries are risking loss of customers and corresponding sales (Ballou & Srivastava, 2007). For example, during interviews with consignees and shippers responsible for JIT deliveries, Fowkes et al. (2004) found that they are likely to discuss with customers to find a mutually acceptable solution to a delay. However, the failure to reach a solution exposes shippers to the loss of their contract, especially in a constant delay situation.

Another possible impact on shippers is the opportunity cost from loss of ability to consolidate multiple outbound shipments, facing the uncertainty of journey times (Fowkes et al., 2004). In particular, if the outbound vehicle is late on its first delivery, it is very likely to miss its unloading schedule for subsequent deliveries, which significantly affects the shipper's level of customer service. Secondly, such a consolidated delivery is usually long, where a delay may cause the violation of driving time regulation.

Not only does congestion affect business logistics, but it shrinks business market areas and reduces agglomeration economies of business operation (Weisbrod et al., 2001). Mamani and Moinzadeh (2013) found that firms will locate fewer facilities as congestion increases within market areas. The reason for this is that firms tend to locate facilities in market areas with higher market potentials and pay transportation costs to supply other markets, instead of paying increasing congestion costs within each market area.

In summary, congestion and possible late delivery result in the following potential operational impacts:

- Additional fuel, oil, and truck operation costs.
- Additional emissions.
- Extra in-transit inventory holding costs.
- Interrupted work flows at unloading bays.
- A disrupted production schedule and lower productivity.
- Dissatisfied customers and potential lost sales.
- High inventory holding costs associated with on-site safety stock.
- Inability to consolidate multiple outbound shipments.
- Reduced business areas and reduced business operation.

1.4. Congestion Relief Strategies

Many strategies have been implemented to alleviate congestion. The *Urban Mobility Report* (Schrank et al., 2012) recommended a balanced and diversified approach to reduce overall congestion, which advocates a different mix of solutions in metro regions, cities, neighborhoods, job centers, and shopping areas. These solutions include but are not limited to:

- Fully utilize low-cost improvements.
- Add capacity in critical corridors.
- Change usage patterns.
- Provide choices on different routes, travel modes, or lanes.
- Diversify land use patterns.
- Create realistic expectations.

One strategy is congestion pricing. Congestion pricing is designed to partially divert traffic overload to alternative routes by charging and managing tolls. Another strategy is to increase road capacity through capital investment. For most strategies, evaluation of travel time is a fundamental issue. Value of time (VOT) enters these

strategies because it is implicit in modeling traveler behavior and in gauging logistics impact on congestion. In this way, limited public investment can be best used on projects with the most impact. Research can identify the most urgent locations and projects for future investment, and efforts are needed to discover the value of time due to transportation delay such as delay encountered due to congestion in the framework of freight operation.

National policy makers have shown interest in applying some form of congestion-based pricing for many years. Although initial attempts failed because of local community opposition, two pieces of landmark legislation around 1990 made the congestion pricing program vigorous again (Assembly Bill 680 in 1989 and the Intermodal Surface Transportation Efficiency Act in 1991). At least nine congestion pricing programs were implemented from 1995 to 2002. A common feature of all these projects was the fact that toll charges vary according to the time of the day in an effort to encourage traffic to shift to other roadways or off-peak periods (Sullivan, 2000). Toll structures and rules vary widely among these projects. A detailed list can be seen at the website of Dr. Mark Burris (<https://ceprofs.tamu.edu/mburris/pricing.htm>) at Texas A&M University. For most projects established after 1995, evaluations were mostly positive due to fulfillment of the primary Federal Highway Administration (FHWA) objectives. Some early projects can be seen in the work of Sullivan (2002), Supemak et al. (2001), and Swenson et al. (2001). More recent projects can be seen in the work of Geiselbrecht et al. (2008) and Burris et al. (2012).

1.5. Purpose of This Research and Report Organization

The research described in this dissertation assessed the value of freight delay as the fundamental parameter driving the private sector's response to public freight projects and policies such as corridor construction and tolling. A detailed literature review can be found in Chapter II. Guided by the insights obtained from on-site interviews with logistics managers, Chapters III-VI propose four quantitative methods from different

perspectives to look into the value of time and delay in freight transportation in the trucking industry. Except for the truck driver's stated preference study, all the other methods are introduced for the first time in the VOT framework. The focused freight components and the advantage of each method are described in detail, as well as the limitations. Chapter VII summarizes the major findings of this study, followed by discussion of future research directions such as how to combine VOT from different perspectives into an integrated freight VOT.

CHAPTER II

LITERATURE REVIEW

2.1. The Definition and Effects of Freight Value of Time

To address freight transportation delay and prioritize freight projects, public-sector transportation decision makers need to know the impact of delay on stakeholders. This information is important to fully understand the benefit of transportation improvement projects and to justify infrastructure investments. While the cost of improvements can be confidently estimated, the benefits of investment are much more difficult to identify, especially for users such as shippers. Therefore, the question most typically asked is: What is the freight value of time in the trucking industry?

General guidance for establishing VOT can be found in *Revised Departmental Guidance on Valuation of Travel Time in Economic Analysis* (USDOT, 2013). The discussion views VOT as the opportunity costs of travel time on a trip. For personal travel, it is defined as the amount of money one would pay to shorten his/her trip by a certain amount of time.

In the process of developing strategies and policies to mitigate delay, the evaluation of VOT appears to be a fundamental issue. One example of this issue results from congestion pricing, which was originally designed to divert some traffic to alternative routes with different travel times and distances (usually longer) by imposing tolls (Sullivan, 2000, 2002; Supemak et al., 2001; Swenson et al., 2001). An underlying assumption in congestion pricing efforts is that a driver's diversion behavior onto alternative routes depends largely on how the driver values time savings by avoiding highway congestion. Recent studies extend this concept into managed lanes, and representative work can be found in Burris (2006), Eisele et al. (2006), Burris et al. (2012), and Devarasetty et al. (2012a, 2012b).

Another example of the fundamental nature of VOT is prioritization of roadway capacity improvement projects. The Texas Department of Transportation (TxDOT)

identifies the state's 100 most congested roads (TxDOT, 2013), and truck delay is an important parameter in the identification process. Thus, increasing accuracy and understanding of the value of time in freight transportation will enable planners and managers to make informed decisions leading to improved satisfaction from stakeholders, which is the best way of allocating transportation funds.

Generally speaking, the value of freight transportation time and delay is a special area of VOT. Since the 1950s, due to highway traffic congestion in urban areas, there have been numerous studies on VOT for commuters. These studies primarily aimed at reducing peak-hour commuter traffic congestion. VOT literature includes Hensher and Greene (2003), Small et al. (2005), and Fosgerau and Engelson (2011).

Freight VOT, however, is quite different from commuter VOT because it is inherently related to relevant logistics strategies. Eisele and Schrank (2010) developed a conceptual framework to estimate the impact of congestion on freight. Two trucking applications were conducted in Austin, Texas, and Denver, Colorado. By visually incorporating the effects of the geographic area, commodity type, and time period, this framework allowed freight congestion to be placed on equal footing with passenger travel.

Freight VOT is a complex topic. One of the difficulties comes from the absence of a homogenous effect of travel time, since the impact depends on numerous factors such as the value of goods, schedule characteristics (e.g., a hard or soft time window, robustness, etc.), downstream transportation, product perishability or seasonality, and the type of business operation such as just-in-time or overnight express delivery of perishable products (e.g., newspapers). The diversity of logistics systems requires an appropriate business classification scheme to identify the impacts of delay.

Another difficulty lies in the fact that the logistics managers themselves do not have a thorough picture of delay impact. This is partially because the freight-dependent entities interact with each other through transportation. For example, shippers (i.e., suppliers) ship according to the needs of their customers. Wholesalers take orders from suppliers according to their inventory management policies. Inventory management has

to do with traffic conditions such as travel time and travel time reliability. A longer and less reliable transportation time between the arrival of each order requires more backup (safety) stock in inventory and maybe a larger order size each time. In turn, these ordering/shipping decisions affect freight volumes on the highways and, therefore, affect traffic conditions. According to the Federal Highway Administration's (FHWA's) *FHWA Freight Benefit-Cost Analysis 2004*), the effects of improved freight transportation can be broken down into different levels:

- The first level refers to direct cost reductions to carriers and shippers, which is based on vehicle operating costs such as fuel costs, marginal costs for truck/trailer leases and maintenance, driver wages, and benefits.
- The second level refers to benefit gains from improvements in logistics such as altering the optimal balance between inventory holdings, warehousing, and fleet-routing configurations.

2.2. Freight Value of Time in Transportation Economics

Traditional trucking value of time considers direct vehicle-operating costs. In regard to fuel costs, big semitrailer trucks average about 6 miles per gallon (mpg) and usually have 120-gallon tanks on each side of the cab. Newer trucks can get 8–10 mpg, but that is rare. Although the cost of gas is a major cost to consider, other costs such as wages and repairs are important. Long-haul truckers are usually paid in cents per mile while short haul drivers are usually paid by the hour. Currently, 18-wheelers must also have a 40-gallon tank that contains diesel exhaust fuel, which is intended to eliminate emissions but adds cost. That tank can cover about 4,000 miles before it has to be filled. In regard up maintenance and repair, tires on an 18-wheeler generally cost \$500 each. Replacing a transmission can cost \$18,000. Every repair on a long-haul truck or a line-haul truck is expensive. A recent report prepared by the American Transportation Research Institute (ATRI) suggests that one additional hour of truck driving results in \$65.29 for all vehicle-related operational costs such as wear and tear (Fender & Pierce, 2013). This result is smaller than number quoted by an earlier version of the ATRI study

(\$68.21/hr) (Fender & Pierce, 2012) and the value in the *Urban Mobility Report* (Schrang et al., 2012), which is \$86.81 per vehicle per hour for commercial vehicle operating cost. Although direct assessment methods cannot entirely define value of time and do not include indirect impacts to downstream activities, they do provide two important value parameters from a total logistics perspective.

To embrace broad indirect costs, the willingness-to-pay (WTP) method estimates the value of time from the perspective of stakeholders such as truckers or logistics managers. By definition, WTP measures the maximum amount of money a person would pay in exchange for receiving benefits or avoiding losses because of shortened travel time. Details can be found in Parish (1994):

“Assuming that the research to analyze market needs is successful in identifying at least one unmet need, the core of any market analysis is in understanding the price that customers are willing to pay to have those needs met. Almost any product/service will have a certain amount of value —either to the consumer or to commercial users—the issue is whether that value is commensurate with the cost of providing the product/service.”

Using a stated preference (SP) survey technique and discrete choice models, the value of time is estimated in terms of the equivalent transportation costs for one unit of transport time in utilities theory. As an alternative method, the revealed preference (RP) method uses actual consumer choices to establish the model instead of involving hypothetical alternatives (Adamowicz et al., 1994, 1997; Adamowicz & Deshazo, 2006). Toll road facilities are major data sources for RP studies. The combined use of SP/RP techniques and discrete choice logit model appear widely in most freight studies (Frank & Els, 2005; Zamparini & Reggiani, 2007; Geiselbrecht et al., 2008).

However, SP and RP have disadvantages. According to Brownstone and Small (2005), RP tends to overestimate VOT while SP tends to underestimate it. Particularly, in the case of a pricing study by Ghosh (2001), the median value of time from SP responses was less than half that obtained from RP responses. Similar observations are found in Hensher (2001). The resulting time value also varies significantly among different participating entities. For example, Geiselbrecht et al. (2008) estimated a value

of \$44.20 per hour for truckers on State Highway 130 in Texas. A study with a relatively small sample size by HLB Decision-Economics (2002) indicated that carriers attached a value between \$144 and \$192 per hour to average travel time savings and a value of \$371 per hour to savings in non-scheduled delay (which reflects fuel, maintenance costs, and operational effects such as fleet reconfiguration). Although variable, results indicate the magnitude of savings that can be generated by improving performance of the highway system in reducing VOT. Results demonstrate the necessity to decompose the supply chain into several entities (such as shippers and carriers) to precisely estimate the indirect value of freight transportation time.

2.3. Value of Time in Operations Research

Oriented toward modeling operational research, early researchers offer a sensitivity-analysis matrix showing how shippers' inventory costs react to incremental changes in the mean and variance of transportation time. Such information is useful to compare alternative carriers, negotiate rates, and evaluate optimal carrier-shipper policies jointly. Tyworth and Zeng (1998) developed an analytical model to determine optimal transportation service within shippers' inventory control strategies. By assuming that shipping expense is a function of the order quantity, Tyworth and Zeng's model presents a way of estimating the effects of transportation performance on logistics costs for shippers. Later studies by Swenseth and Godfrey (1996, 2002) used an actual freight rate function to examine a rather simplified version of inventory control strategy known as the order quantity (EOQ) model instead of the continuous review model (Q, R). Relevant recent works include Lee and Schwarz (2007) and Nasri et al. (2008), where transportation costs are integrated into a model with one buyer and one vendor. None of the above studies adequately achieved a value of freight transportation time in an hourly manner sufficient for practical use.

From the carrier's point of view, there is a gap between analytical modeling in operational research and derivation of value of freight transportation time. The

fundamentals of freight analytical modeling can be traced back to Daganzo (1991). As far back as 1984, Daganzo (1984a) developed a simple formula to predict the distance traveled by fleets of vehicles in dispatching problems involving a depot and its area of influence. Since operating costs mainly consist of fuel, Daganzo's formula facilitated estimation of logistics costs. Later researchers extended this formula into different applications. For example, Sankaran and Wood (2007) and Sankaran et al. (2005) indicated that congestion costs for carriers increase with the average number of routes per day and are invariant with loading or unloading times at each stop; Figliozzi (2007) concluded that changes in both vehicle miles traveled (VMT) and vehicle hours traveled (VHT) differ according to routing constraints. Routes constrained by time windows are most affected by congestion. The work of Figliozzi (2010) used analytical modeling and insights, numerical experiments, and real-world data to understand the impact of congestion on urban logistics. However, it assumed that commercial vehicles experience the same levels of congestion at all points, which is not a practical assumption.

2.4. Chapter Summary

Overall, the analysis of the value of freight time and delay in the trucking industry is a difficult research topic among transportation economists. The marginal utility attached to each unit reduction in travel time is traditionally calculated through utility theory. However, researchers are increasingly considering further development from the perspective of strategic planning and operations research, which are considered quantitative tools of decision science.

This dissertation develops three new methods, used together with traditional SP study, from different perspectives to look into the value of time and delay in freight transportation. Chapter III gives estimates of truckers' perceived value of time by combining SP survey responses, utility theory, logit model, and maximum likelihood function. Chapter IV proposes a scenario-based truckload fleet simulation to examine a time-windowed urban freight network, from which vehicle value of time can be obtained.

Chapter V considers VOT for commodities being shipped in inventory management due to prolonged transportation time or freight delay. Chapter VI shows attempts to assess the effect of travel speed based on the technology of continuous approximation, from which VOT can be derived for less-than-truckload (LTL) operation without time windows. As a result, freight VOT is treated as an integrated VOT not only attached to vehicles and their drivers but in commodity shipments that are traveling from upstream to downstream entities.

CHAPTER III

TRUCKER-PERCEIVED VALUE OF TIME

3.1. Introduction

This chapter examines trucker-perceived value of time from the perspective of the drivers. As previously mentioned, there are two types of studies that can be applied to this problem. Revealed preference assumes actual consumer choices reveal the value of time. Toll stations are a major data source for a RP studies. However, RP data cannot cover all existing transportation alternatives, whereas stated preference (SP) data can fill the gaps in observed behavior (Whitehead et al., 2008). This is also true for demand forecasting. SP information provides combinations of variables to hypothetically construct new options relative to existing circumstances. A carefully designed survey intended to collect and identify trucker preferences identifies alternatives, and each alternative is associated with a travel time and a travel cost. Respondents make choices based on their experiences and perceived values including lost wages, inconvenience, etc.

A detailed illustration of SP methodology can be seen in the paper of Fowkes and Shinghal (2002), as well as in work by Hague Consulting Group (de Jong, 1996; de Jong et al., 1992, 1995) who conducted a series of early SP studies to measure the value of freight reliability and delay. In Wigan et al. (2000), commercial VOT was estimated as 1.40 Australian dollars per hour per pallet for metropolitan multi-drop freight services in Australia. Further study (Wigan et al., 2003) determined that the value of freight time for urban LTL services was significantly higher than that of other segments. The authors found that the value of full-truckload (FTL) freight time per pallet per hour on inter-capital routes was about twice that of intra-city route FTL. Similar techniques applied in Europe are presented in the work of Westin (1994), Fridstrom and Madslein (1995), Wynter (1995), and Kurri et al. (2000). Wynter (1995) noted that these values should be seen as underestimates of longer-term values due to structural changes within the industry to take advantage of transport infrastructure and operational improvements.

Kawamura (2000) applied a switch-point method in which truck drivers were asked to choose between an existing freeway versus a toll facility with combinations of travel time and toll. Together with survey data at the University of California, Irvine, from the year 1998 to 1999, Kawamura successfully identified switch points of choosing between different road facilities. The average VOT for truck drivers was found to be \$26.8 per hour. Through grouping, the study also found that hourly wage drivers indicated higher value than salaried workers (once-a-month payment).

Geiselbrecht et al. (2008) investigated the potential use of innovative truck pricing in a project along State Highway 130 in Texas. The study found that many truckers, trucking firms, and logistics managers avoided toll roads under most circumstances. Particularly, most owner-operators were found to avoid toll roads at all cost, while delivery trucks/firms were willing to carefully weigh costs and benefits of the toll route prior to making a decision. About six percent of respondents had delivery windows of one hour or less, which indicates that small time savings such as 15 minutes may have little impact on most truckers. Bari et al. (2013) investigated the impact of a toll reduction for trucks on SH 130 and the resulting changes in the number of trucks using the road. Recent SP studies can also be found in Devarasetty et al. (2012a, 2012b).

Overall, the number of survey-based truck studies conducted in the United States has been limited due to the difficulty in collecting data from truck drivers.

3.2. Methodologies

3.2.1. Stated Preference Survey Design

In the current study, the SP technique includes survey design and data processing based on a conditional logit model with the conventional utility function. The original intention of the survey was to examine both time-sensitive deliveries (i.e., JIT) and regular deliveries. However, truck drivers are not likely to want to be interviewed when they are carrying urgent loads (e.g., they may refuse to take a survey when they are approached at truck stops because they are short on time). The result is that the majority

of the data collected come from drivers running regular deliveries. Therefore, the value of time for the truck drivers is related to whether the deliveries are urgent (have tight delivery windows). To compensate for this effect, the survey was modified to ask drivers for their perceived time values by introducing two scenarios.

The first scenario deals with urgent deliveries, where drivers are assumed to be running 30 minutes late due to congested roadways, while the second scenario deals with regular deliveries that are on time no matter what happens. Both scenarios are followed by the options to gain 15, 30, or 45 minutes of time through paying different tolls. The toll rates are calculated based on a set of discrete values (\$30/hr, \$40/hr ... \$120/hr). For example, in the first scenario, the survey would ask the respondent to answer three questions; each question has three options associated with different time savings and costs (by using a noncongested toll road). A write-in option is provided if the respondent wants to indicate a different rate (typically zero) than the provided options.

Face-to-face interviews were conducted with truck drivers at highway truckstops around Houston, San Marcos, Dallas, and Fort Worth in Texas as well as Belvadere Oasis, Cottage Grove, Janesville, Mauston, and Racine in Wisconsin. These locations were chosen because they are major cities adjacent to Texas A&M University (College Station) and University of Wisconsin (Madison) facilities. Initially, truck drivers were approached as they were filling fuel tanks outside. However, the survey cannot be explained clearly because of the noisy surroundings. Therefore researchers moved into the store, where truck drivers were paying for their fuel or buying items. Survey questions were clearly explained to the respondents and their answers recorded accordingly. During the interviews, use of the word "toll" was carefully avoided because many respondents disliked it, while the "alternatives" or "options" were emphasized.

Among all the drivers interviewed, about 15 percent completed the survey, resulting in a total of 133 valid records; sample size was smaller than desired due to limited labor and time. Of those 133 records, 111 records had non-zero (positive) values while the remaining 22 respondents put zeroes in the write-in option (for cost to avoid congestion). All 133 records were included in the following analyses. Of the respondents,

49 percent were exclusive short-haul drivers while the rest of them had runs from both short-haul and long-haul businesses. Regarding ownership, 71 percent of the respondents worked for freight companies, leaving 29 percent as owner-operators. This smaller ratio of owner-operators is due to the difficulty in establishing contacts with them at the truck stops, which results in a biased sample that cannot be overcome in this study. Typical cargo included wood products, textile products, base metals, chemicals, office equipment, and machines.

An expected observation was that in the second scenario, where the respondents are assumed to be running without delay, they rarely chose to pay for additional time savings. This observation indicated that the value of time is significantly diminished if travel time is not urgent. Although this low VOT scenario is of interest, it was intuitively anticipated. Of more interest is the following analysis, built on the first scenario where the survey data showed positive perceived values for time savings. Note that this study cannot identify the drivers having zero experience on the urgent trip. Therefore, the survey is biased because inexperienced drivers may not be able to perceive the time value for the urgent trip correctly.

3.2.2. Conditional Logit Model

The conditional logit model is applied in the survey analysis. Generally speaking, it employs a utility function to examine the relationships between the response variables and the associated regressors. Consider an individual n choosing among alternatives i in a choice set. Suppose the response Y has a set of values y_i corresponding to alternatives i , where $y_1 < y_2 < \dots < y_{|I|}$. A continuous utility U is assumed to be determined by the response variables in the linear form:

$$U = -\beta x + \varepsilon \quad (3.1)$$

where β is an m -dimension vector of regression coefficient and ε a random error with a logarithmic distribution function F . The relationship between Y and U is then:

$$Y = y_i \Leftrightarrow \alpha_{i-1} < U < \alpha_i, \quad i = 1, \dots, |I| \quad (3.2)$$

$$\Pr\{Y \leq y_i | x\} = F(\alpha_i + \beta x) \quad (3.3)$$

where α_i represents a set of threshold points, and x is an individual characteristic. The conditional logit model assumes that variables have a constant impact across alternatives, while the individual characteristics are not constant variables over the alternatives. Let U_{ni} be the utility decided by both alternative i and individual n . Then the probability that the individual n chooses alternative i is:

$$P_{ni} = \exp(U_{ni}) / \sum_{l=1}^{|I|} \exp(U_{nl}) = 1 / \sum_{l=1}^{|I|} \exp(U_{nl} - U_{ni}) \quad (3.4)$$

3.2.3. Maximum Likelihood Estimation and Model Fit

For the purpose of obtaining the value of the coefficients, the author uses the maximum likelihood method. The likelihood function has the form of:

$$L(\theta) = \prod_{i=1}^{|I|} P_{ni} \quad (3.5)$$

The maximum likelihood estimation (MLE) maximizes the logarithmic likelihood:

$$\max \log L(\theta) = \max \sum_{i=1}^{|I|} \log P_{ni} \quad (3.6)$$

which is an unconstrained nonlinear optimization problem. Typical gradient search methods such as Newton's method are capable of solving it. The convergence criterion is to terminate when likelihood stops increasing. An imbedded procedure in SAS® software is applied for the analysis.

Two different utility functions were tested in this study. The first one is a generic utility function, where the trade-off between cost and travel time savings is linear:

$$U_{ni} = aC_{ni} + bT_i + \varepsilon_i \quad (3.7)$$

where

$i = \text{alternatives, } i = \{1, 2, 3, 4\};$

$n = \text{individual index};$

C_{ni} = cost specified by individual n in alternative i ;

T_i = travel time saving, measured by 0 min, 15 min, 30 min and 45 min;

a, b are coefficients of regressors;

ε_i is unobserved stochastic portion of utility.

Note that in the urgent scenario each respondent should answer three questions, and each question is treated as an individual in n . In each question, there are four alternatives (very late, little late, on time, early) associated with different time savings and costs. Only one alternative can be selected for each question. Since a mixed logit model is not applied, the following analysis cannot address the “panel effect” where the three answers from a respondent are actually correlated. For any i , ε_i are independent and identical logarithmic distributions. The trucker’s value of time is defined as the cost or payment attached to a unit of time saving, which can be derived from the resulting coefficients of regressors. The coefficient a is measured in utility/dollars, and coefficient b is measured by utility/minutes:

$$\begin{aligned} \text{Value of Time} &= -\partial C_{ni} / \partial T_i \\ &= -\frac{\partial U_{ni} / \partial T_i}{\partial U_{ni} / \partial C_{ni}} \\ &= -b / a \end{aligned} \quad (3.8)$$

The second utility function traces back to the work of Mot et al. (1989) and Cramer (1986, 1990). To model the behavior of choosing among the use of cash and checks, the authors showed a nonlinear utility function with the payment in logarithm while the other regressors are linear. The use of the logarithm is an empirical choice, and substantially improves the model fit as measured by the log likelihood. Enlightened by their work, the second utility function became:

$$U_{ni} = a \log C_{ni} + bT_i + \varepsilon_i \quad (3.9)$$

Due to the logsize of C_{ni} , the equation of value of time changes to:

$$\begin{aligned} \text{Value of Time} &= -\partial C_{ni} / \partial T_i \\ &= -C_{ni} \cdot b / a \end{aligned} \quad (3.10)$$

Both utilities were tested using actual survey data. Table 3.1 shows the comparison between Equations 3.7 and 3.9. Although little difference is found in model fit, using Equation 3.9 would lead to a VOT that is not linear and depends on travel cost (see Equation 3.10), which is not desired at the planning level because values of time must be generic to quantify the economic benefits of different transport improvement projects (for example, to calculate the overall benefit by multiplying total hours saved and the dollar value per hour).

For this reason, Equation 3.7 was chosen to conduct further analysis over Equation 3.9. This does not mean that development of Equation 3.9 was a useless task. It can be applied to nonlinearity studies of VOT, but that will not be discussed here because of the complexity.

Table 3.1: Model Fit

	b	a	ρ_c^2	% correct
Eq. 3.7	0.0230*	-0.0251***	0.31	41.60
Eq. 3.9 (logsize)	0.0077*	-0.7599**	0.29	58.35

Note: ***, **, * → Significant at 1%, 5%, 10% level. Number of observations = 399.
Adjusted $\rho_c^2 = 1 - \frac{LL(\hat{\beta}) - K}{LL(C) - K_c}$ where, $LL(\hat{\beta})$ = log-likelihood for the estimated model, K = number of parameters in the estimated model, $LL(C)$ = log-likelihood for the constant only model, K_c = number of parameters in the constant only model.

More regressors are considered when formulating the utility. However, the test on both utilities, shown below, indicates that all the additional regressors are unimportant. Therefore, only two regressors (payment and time savings) are considered in the further analysis:

$$U_{ni} = \theta Z_{ni} = aC_{ni} + bT_i + \sum_{k=1}^3 d_k R_{kn} + \sum_{k=1}^3 e_k F_{kn} + \varepsilon \quad (3.11)$$

$$U_{ni} = \theta Z_{ni} = a \text{Log} C_{ni} + bT_i + \sum_{k=1}^3 d_k R_{kn} + \sum_{k=1}^3 e_k F_{kn} + \varepsilon \quad (3.12)$$

where

$R_{1n} = 1$ if local, 0 otherwise;

$R_{2n} = 1$ if regional, 0 otherwise;

$R_{3n} = 1$ if long-haul, 0 otherwise;

$F_{1n} = 1$ if flexibility of delivery hours is less than 3 hrs, 0 otherwise;

$F_{2n} = 1$ if flexibility of delivery hours is from 3 hrs to 5 hrs, 0 otherwise;

$F_{3n} = 1$ if flexibility of delivery hours is from 5 hrs to 12 hrs, 0 otherwise;

$F_{4n} = 1$ if flexibility of delivery hours is more than 12 hrs (such as 1 day),
0 otherwise;

ε = unobserved stochastic portion of utility;

a , b , d_k and e_k are coefficients of regressors, $k = 1, 2, 3$.

Local, regional, and long-haul deliveries are options provided in the survey under trip length category. These values indicate length of a typical trip. Similarly, options about flexibility of delivery hours are provided to recognize maximum slack time in the driving schedule.

3.3. Regression Analysis and Results

Tables 3.2 and 3.3 summarize the survey results from Texas and Wisconsin, respectively. Note that in the question “trip length,” the category “11+ hours” indicates a trip consisting of multiple days. Table 3.4 shows regression results for the entire dataset using utility function Equation 3.9. The resulting VOT is first measured by minute and then translated into an hourly value by multiplying by 60. (This chapter does not discuss the issue of linearity of the VOT as previously mentioned.)

Table 3.2: Summary on Survey in Texas.

Question	Category	Drivers	Question	Category	Drivers
Type of Carrier	Owner Operator	34%	Typical route	Regional	30%
	For-hire	41%		Long-haul	61%
	Private-Carrier	25%		Local/delivery	9%
Typical Cargo	Bulk	22%	Who decides route?	Me (the driver)	44%
	Average Value	60%		Dispatcher/manager	53%
	High Value	18%		Shipper	2%
	Other	0		Other	0
Truck Size	2 axle	31%	How are you paid?	By Mile	67%
	3 axle	12%		By Load	13%
	4 axle	44%		Percentage of Revenue	16%
	Other	12%		Other	4%
Trip Length	11+ Hours	67%	Who pays the toll?	I do	49%
	5 to 11 Hours	29%		For-hire carrier	37%
	2 to 5 Hours	0		Shipper	7%
	Less than 2 Hours	2%		Other	7%
Delivery Window	1 day	38%	Route changes	Never	9%
	Less than 12 hours	20%		Occasionally	32%
	less than 5 hours	9%		Often	36%
	less than 3 hours	33%		Always	23%

Table 3.3: Summary on Survey in Wisconsin.

Question	Category	Drivers	Question	Category	Drivers
Type of Carrier	Owner Operator	26%	Typical route	Regional	33%
	For-hire	21%		Long-haul	45%
	Private-Carrier	53%		Local/delivery	22%
Typical Cargo	Bulk	21%	Who decides route?	Me (the driver)	36%
	Average Value	47%		Dispatcher/manager	55%
	High Value	32%		Shipper	3%
	Other	0		Other	6%
Truck Size	3 axle	7%	How are you paid?	By Mile	52%
	5 axle	75%		By Load	13%
	6 axle	9%		Percentage of Revenue	23%
	Other	9%		Other	12%
Trip Length	11+ Hours	49%	Who pays the toll?	I do	34%
	5 to 11 Hours	45%		For-hire carrier	53%
	2 to 5 Hours	6%		Shipper	4%
	Less than 2 Hours	0		Other	9%
Delivery Window	1 day	20%	Route changes	Never	9%
	Less than 12 hours	16%		Occasionally	58%
	less than 5 hours	20%		Often	20%
	less than 3 hours	43%		Always	14%

The overall VOT is estimated to be \$54.98 per vehicle per hour, which is greater than the value of \$26.80 in Kawamura (2000) but smaller than the recent value of \$65.29 from ATRI (Fender and Pierce, 2013) and the value of \$86.81 in the *Urban Mobility Report* (TTI, 2012). Again, the result in this study shows the perceived VOT for truck drivers under the assumption of urgent trips through stated preference survey. However, it does not eliminate the possibility that some of the respondents have no experience on

urgent trips. This reason plus the fact that the urgent truck drivers intend to refuse the survey should partially explain the difference between this study and the establishing literature. The sample size is also limited due to the limited labor and time framework.

Table 3.4: Analysis Using Conditional Logit Model

Analysis of Entire Dataset				
	b	a	VOT \$/min	VOT \$/hr
Overall	0.0230	-0.0251	0.9163	54.98
Grouping by Survey Area				
Wisconsin	0.0399	-0.0412	0.9684	58.11
Texas	0.0242	-0.0291	0.8316	49.90
Grouping by How Drivers Are Paid				
Paid by mile	0.0229	-0.0229	1.0013	60.07
Others	0.0778	-0.1201	0.6478	38.86
Grouping by Who Pays the Toll				
Driver pays toll	0.0133	-0.0204	0.6520	39.12
Others	0.0332	-0.0315	1.0540	63.24
Grouping by Type of Carrier				
Owner-operator	0.0377	-0.0464	0.8125	48.75
For-hire	0.0079	-0.0184	0.4293	25.76
Private Carrier	0.0312	-0.0321	1.2683	76.10

To disaggregate characteristics of the respondents, data were grouped according to survey area, salary method, responsibility for tolls, and type of carrier. Drivers in the Wisconsin area perceived a higher VOT (\$58.11/hr) than those in Texas (\$49.90/hr), possibly due to the different economic structures and population/industry distributions such as fuel price, salary, etc. Drivers paid by the mile perceived a significantly higher VOT (\$60.07/hr) than drivers paid by other methods, such as hourly salary or per load

revenue (\$38.86/hr). This is an intuitive response because congestion or prolonged travel time reduces total miles traveled. Particularly, drivers were more willing to pay to avoid delay if the cost did not come out of their own pockets. If the drivers had to pay the toll themselves, the VOT was \$39.12 per hour; otherwise, it was \$63.24 per hour. When comparing a private carrier with the others, truckers from private carriers perceived a much higher time value and willingness-to-pay-tolls on behalf of their companies. Actually, survey respondents indicated that private carriers usually have a tighter schedule because they transport products or materials for their own company and are usually influenced to consider indirect logistic costs such as fleet optimization and on-time delivery.

3.4. Chapter Summary

The SP survey was designed to elicit the value of time perceived by truck drivers. However, there were certain drawbacks associated with this method. First, it was almost impossible to collect data from drivers that were under urgent duties because they were always in a rush and felt no obligation to answer the survey. As a result, the survey data are biased, although hypothetical urgent situations were presented to other drivers to ask their value of time based on previous experience. Second, even if the survey provided perfect data, it would mainly reflect drivers' values and not necessarily represent the actual freight VOT to the entire fleet, especially from the perspective of a carrier's operation. The "real" VOT should not only include potential fuel loss and wages but the values of inconvenience, safety, and other psychological factors due to prior expectation. Most importantly, VOT should consider potential effect on other commercial vehicles from the same company. In particular, freight value of time should be subject to the effect on the carrier's fleet reconfiguration. This finding leads to the next step, which was a fleet simulation for freight carriers.

CHAPTER IV

FLEET SIMULATION

4.1. Introduction

This chapter examines the impact of a single vehicle delay on fleet operations. In this part of the study, a carrier simulation was conducted. It envisioned a fleet of vehicles operating within an urban area providing truckload services to customers. Demands with time windows (deadlines) were continuously generated for pickups and deliveries. The parameters were demand location, size and pattern, congestion segment, and time window. According to FHWA (FHWA, 2004) and the American Association of State Highway and Transportation Officials (AASHTO, 2003), a carrier's marginal vehicle operating cost is derived for fleet routing reconfigurations between congested and noncongested situations.

A short-haul truckload simulation with time constraints (deadlines) gained insight into the reconfiguration effect on a coordinated fleet operation. Industrial parameters were partially collected through interviews with local logistic companies and distributors. Additional information was obtained from a survey and online websites to determine possible locations for customers or depots, driver wage (\$15/hr), etc.

Generally speaking, this simulation had to consider vehicle/truck choices based on utility maximization. For example, if only time was considered, utility maximization would result in taking the shortest path. Ben-Akiva et al. (1999) provided a review of the standard model of rational behavior. To tackle the influences of various psychological elements, they presented a theoretical framework based on estimation of an integrated multi-equation model associated with a discrete choice model and the latent variable model system. The complexity of this method showed the difficulty of accurately forecasting route choices and their distributions. When the problem was reduced to the shortest-path problem, the combined constraints of distance, time window, and capacity made the problem remain difficult.

There have been numerous practical projects concerning route choices. Stephanedes and Kwon (1993) determined that commuter drivers in the Minneapolis-St. Paul metropolitan area freeway system usually considered three alternative routes at most. Enlightened by this finding, Knorrning et al. (2005) assumed that truck drivers rarely consider more than two alternative routes, and this assumption was then confirmed by using revealed preference data obtained through remote sensing of more than 249,465 trucks and 60,000,000 locations recorded over a 13-day period. Their study showed that truck drivers consider only one alternative route, compared with multiple routes for commuters, unless they are caught in extreme weather conditions. One possible explanation behind this is that, in general, truck drivers are much more flexible than commuter drivers in choosing trip start time. For example, commuter drivers must arrive at their work place during peak hours. Since their trips have strict arrival times, they have to consider more alternative routes to ensure on-time arrival. In contrast, truck drivers, especially long-haul drivers, often have a few days' time to pick up and deliver their loads, thus giving them more flexibility to avoid peak hours through an alternative route. In addition to this, the authors also observed that if the perceived speed on the through route dropped to 50 mph, about 50 percent of truck drivers shifted to bypass routes where the perceived speed was 65 mph.

Another observation is that many truck drivers do not determine their routes unless they are independent operators. Most truck drivers work for large companies and are told what route to take by a dispatcher. They have a Qualcomm that tells them where to go, which is controlled by the dispatcher. It tracks the truck so that the home office knows where each truck is at all times.

4.2. Methodologies

4.2.1. GIS Setting

This research uses the ArcGIS database from the Bureau of Transportation Statistics (BTS). Twenty locations were selected as potential shipper locations for pickup and delivery according to business locations in Houston, which reflects a many-to-many operation. Although these 20 locations may not be completely realistic, they are distributed over the entire network to include all possible routes. A similar setup can be easily modified to address one-to-many operation. Truckload demands were generated at each location randomly. Scenarios based on single-depot (central-depot) and double-depot situations were tested. Figure 4.1 illustrates this network (partially from Google map).

The shortest path between each pair of locations was calculated via ArcGIS. The cost matrix and travel time matrix between any two locations were tabulated as input to the simulation. Since the network is mainly constructed of highways, the design speed was assumed to be 65 mph uniformly except on congested roads. Several congestion scenarios were tested sequentially in the simulation to compare with free-flow scenarios to examine the effect of congestion and VOT. The data for free-flow situations were obtained by using design travel speed and distance matrix from ArcGIS. Sparse congestion resulted in a delay time to the selected segment, while pervasive congestion resulted in a two-minute delay to every segment. To decide potential congestion locations, traffic information was obtained by using the GoogleMap™ traffic function. Once congestion was introduced to the scenarios, the shortest paths between locations and depots were recalculated and new assignments of vehicles were made accordingly.

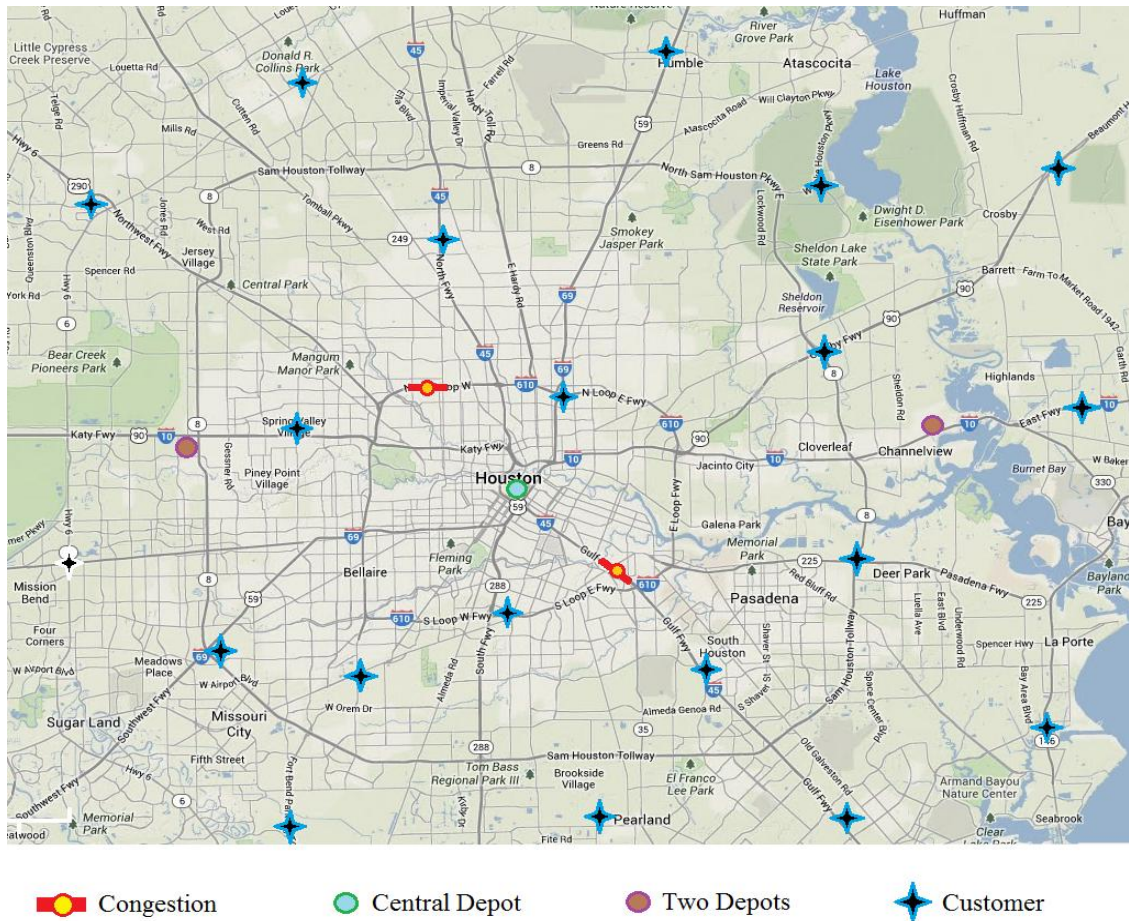


Figure 4.1: Network Setting.

4.2.2. Heuristic Algorithm

Each customer demand has an origin, destination, and associated time window for pickup and delivery. Because the travel network is subject to congestion, fleet assignment to drivers is made continuously as demand unfolds with time of day. The objective is to satisfy the demand within the time window and minimize total operating cost. In this study, the heuristic algorithm used a savings method derived from Solomon (1987) to make dispatching decisions. Although the savings method actually traces back to Clarke and Wright (1964), the algorithm used in this study is an extension of the savings heuristics proposed by Solomon (1987) for vehicle routing and scheduling problems with time window constraints (VRPTW).

The algorithm begins with n distinct routes in which each demand is served by a dedicated dummy vehicle from the depot. In the case of two or more depots, demand is served by a vehicle from the nearer depot. In each step, the tour-building heuristic joins two tours with the most savings until no positive saving is possible through joining tours. Each iteration conducts feasibility checks (mainly for time window) of mergers for every pair of existing feasible routes. However, only the two routes with the most savings are chosen to merge. The algorithm terminates when the best savings alternative is not greater than zero. The general procedure of this heuristic is summarized below:

Step 1: Prepare data for cost matrix and travel time matrix.

Step 2: Construct initial feasible tours, one for each customer with a designated dummy vehicle.

Step 3: Check feasibility (time window, etc.) of joining each pair of existing tours and record the savings from feasible mergers.

Step 4: If the best saving alternative is positive, join the two according tours, and go back to Step 2. If no feasible merger is available or no positive savings are found from the merger, terminate.

Assignment was done every two hours. All new demands requested during the previous period were considered and scheduled at the beginning of the next period. If a vehicle was already on the way to pick up or deliver a load, it had to finish that particular demand before committing to another load (dedicated vehicle). Each demand had an origin for pickup and a destination for delivery. Vehicles are allowed to wait at the pickup and delivery locations if they arrived early.

Figure 4.2 illustrates an example. Here, loading/unloading times were considered to be 30 minutes each. Congestion delay and waiting time are translated to operating costs based on the driver's salary. With no sensitivity cost, the operational costs including hiring and fuel were arbitrarily selected at \$2.00 per mile when the vehicle was not in congestion to correlate the results among different studies (e.g., Fender & Pierce, 2013).

Output of the simulation was total operating costs required to satisfy demand at a given congestion level. The difference in cost between scenarios of congestion and free-flow times is the congestion cost. Note that vehicles would not operate for consecutive 12-hour periods. Some of them started late and some of them came back to the depot early based on the dispatching algorithm. All of them should fit within a 10-hour limit.

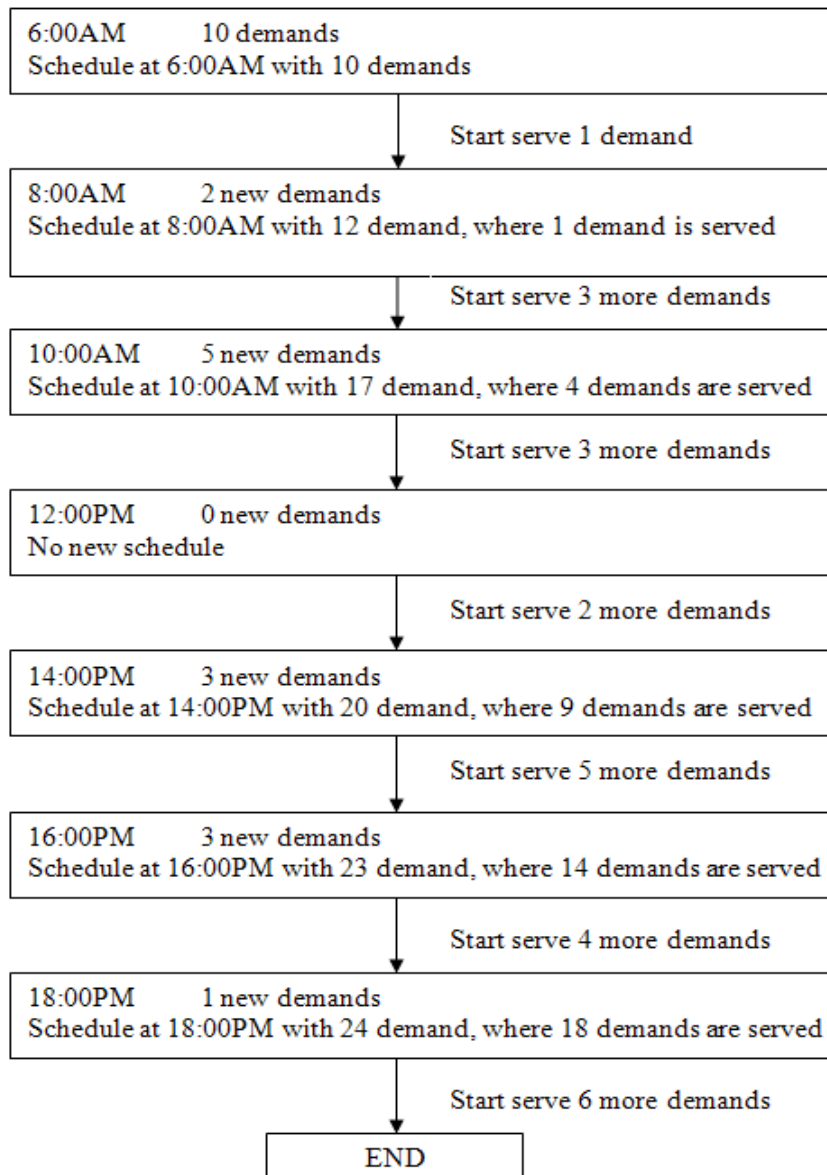


Figure 4.2: An Example of Daily Operation.

4.2.3. Simulation Results

The congestion cost to the entire fleet operation was based on increased operating costs and implementation of different fleet routings. Assume a congestion-free case where n vehicles need to drive through a particular road segment m times during a day's operation—if congestion occurs at that segment, some of these vehicles change their routes while the rest choose to sit in the congestion. If one vehicle cannot meet the next delivery window due to congestion, another vehicle is dispatched to cover the task but at a higher cost. On the other hand, the time saved by taking a detour could be put into productive use, but sometimes taking a detour costs more than waiting. The dispatching algorithm controls the above decisions. The VOT is therefore measured by:

$$\begin{aligned} \text{VOT} &= \Delta\text{Cost}/\Delta\text{Time} \\ &= \frac{\text{Additional Operating Cost Caused By Congestion}}{\text{Congestion Delay}} \\ &= \frac{\text{Cost when Congested} - \text{Cost for Free-Flow Operation}}{\text{Number of Vehicles} \times \text{Delay per Vehicle}} \end{aligned} \quad (4.1)$$

Parameters such as the number of depots, congestion location, congestion pattern (congestion at one segment or at every segment), demand size (number of truckload demands in a day), time window, and demand distribution (the time when demand occurs) varied during the simulation.

The first simulation tested single-segment congestion. In this case, two possible congestion locations were considered. One was a 1.22-mile segment on the Houston Gulf Freeway along I45. The other was located at North Loop along I610, also in Houston, with a length of 1.45 miles. The test varied the delay from 1 minute to 30 minutes. Results showed that with a 1-minute delay, drivers were better off sticking to the original route and experiencing minor congestion. In the case of congestion longer than 3 minutes, some trucks begin to move more efficiently by taking an alternative route. This is because the simulation uses the Houston network, where the alternative route takes no more than a few minutes more than the original route if both are

congestion-free. This network characteristic obviously affects the calculation of VOT. The marginal total additional operating cost diminished with increasing delay due to highway congestion.

The instances where 2-minute delays occurred on chosen highway segments are summarized in Tables 4.1–4.3. In Tables 4.1 and 4.2, each instance had 20 percent demand that was already known at the beginning of the day, leaving 80 percent demand to gradually emerge as the day unfolded and required constant scheduling updates. The instances in Table 4.3 had 80 percent demand known before daily operation began, which left a small portion (20 percent) to be called in. Table 4.1 is for one depot and is compared with Table 4.3, where demand patterns differ while the traffic conditions remain the same. Table 4.2 is for two depots, which shows a VOT from \$79.81 to \$83.81 per hour. Note that these values are high because, in the congested scenario, additional vehicles have to be dispatched to cover for the delayed vehicles, which results in a significant increase in cost from the perspective of the carrier’s fleet operation. This is an indirect cost component due to congestion and delay that usually cannot be observed by the truck drivers enroute.

Other than the test of a single-segment congestion case, this study tested a case in which a ubiquitous congestion delay of 0.5 min/mile was applied to the entire network. It was equivalent to reducing travel speed, and the simulation compared outcomes with the congestion-free scenario to calculate additional cost. Table 4.4 shows the results for this case.

The measurement in these tables is dollars per hour. The first number of each cell indicates the average VOT over 1,000 random instances. The second number shows the standard deviation over these instances. Each instance represents a full-day operation with randomly generated demands. The window size indicates the allowable time interval for both pickup and delivery. The demand size represents the number of truckload demands generated during the simulation.

Table 4.1: Value of Time for Central Depot (20% Known Demand)

Congestion at Gulf Freeway	Demand size 25	Demand size 50	Demand size 100
Window size 1 hrs	99.16/22.78	100.03/21.35	100.24/14.15
Window size 1.5 hrs	98.82/25.12	99.83/22.84	100.16/15.63
Window size 2 hrs	98.56/27.16	99.81/27.74	99.38/16.91
Window size 2.5 hrs	98.67/25.09	99.82/28.29	99.62/19.20
Window size 5 hrs	98.25/34.51	98.41/39.50	99.45/31.17
Congestion at North Loop	Demand size 25	Demand size 50	Demand size 100
Window size 1 hrs	102.61/48.92	117.26/44.57	120.89/22.63
Window size 1.5 hrs	101.36/51.92	117.30/27.20	119.79/22.15
Window size 2 hrs	101.40/52.19	117.06/28.02	118.82/23.77
Window size 2.5 hrs	101.97/52.18	117.25/34.55	120.48/27.37
Window size 5 hrs	99.71/58.84	116.55/32.08	118.24/38.68
Note*: Each cell is average/standard deviation of 1,000 cases.			

Table 4.2: Value of Time for Two Depots (20% Known Demand)

Congestion at Gulf Freeway	Demand size 25	Demand size 50	Demand size 100
Window size 1 hrs	81.98/37.13	81.55/23.62	83.81/31.44
Window size 1.5 hrs	81.38/34.40	81.61/23.35	83.34/28.57
Window size 2 hrs	81.08/32.41	81.45/25.51	82.45/29.62
Window size 2.5 hrs	80.05/26.98	80.40/23.39	82.30/30.95
Window size 5 hrs	79.81/24.86	80.13/24.55	81.18/34.13
Note*: Each cell is average/standard deviation of 1,000 cases.			

Table 4.3: Value of Time for Central Depot (80% Known Demand)

Congestion at Gulf Freeway	Demand size 25	Demand size 50	Demand size 100
Window size 1 hrs	97.73/24.96	97.92/24.48	98.39/22.79
Window size 1.5 hrs	97.10/25.02	97.82/25.49	97.94/21.47
Window size 2 hrs	96.30/25.12	97.79/26.10	98.05/23.15
Window size 2.5 hrs	95.20/25.65	97.06/28.84	97.21/25.59
Window size 5 hrs	93.99/29.20	96.69/33.13	97.33/35.86
Congestion at North Loop	Demand size 25	Demand size 50	Demand size 100
Window size 1 hrs	98.40/43.60	103.15/30.51	104.68/21.95
Window size 1.5 hrs	98.93/44.14	103.17/32.35	105.28/24.12
Window size 2 hrs	98.16/46.58	105.60/33.26	104.39/23.73
Window size 2.5 hrs	96.13/48.17	102.48/35.66	102.48/36.98
Window size 5 hrs	94.46/55.47	103.81/44.04	104.14/30.91
Note*: Each cell is average/standard deviation of 1,000 cases.			

Table 4.4: Value of Time for Ubiquitous Congestion (80% Known Demand)

Congestion on Entire network	Demand size 25	Demand size 50	Demand size 100
Window size 1 hrs	194.23/19.53	194.46/14.28	194.33/10.25
Window size 1.5 hrs	194.23/19.32	193.52/14.24	193.50/10.52
Window size 2 hrs	193.86/19.45	193.08/14.50	193.49/10.53
Window size 2.5 hrs	193.10/19.82	193.02/14.66	192.88/10.75
Window size 5 hrs	192.51/21.36	191.37/16.53	190.45/12.08
Note*: Each cell is average/standard deviation of 1,000 cases.			

4.3. Chapter Summary

In parallel with other quantitative methods, an operational simulation assessed the cost of congestion for urban truckload short-haul carriers. A single vehicle delay could incur a significant cost on fleet operations when a delivery time window was imposed. The resulting VOT ranged from \$93.99 to \$120.89 per hour for the case of one central depot. A range from \$79.81 to \$83.81 per hour was estimated for the case of two depots. Additional observations are described below:

- VOT increases with demand size.
- Congestion is a waste to productivity in general.
- VOT in the case of two depots was at least 25 percent smaller than in the one-depot case.
- Comparing Table 4.1 with Table 4.3 shows a reduced impact from congestion when more demands are known at the start of a day.
- Under ubiquitous congestion (Table 4.4), overall productivity was lower. The VOT in this case was significantly higher than the other non-extreme cases.

The simulation was conducted with relatively tight time windows. This factor plus designation as part of private fleet operating within an urban network amplified vehicle VOT due to highway congestion. It was evident that estimating the effect of highway congestion on fleet operation is not an easy task. There are many issues that need to be carefully thought through, such as whether and how to consider revenues from serving customers, how to set a realistic fleet size, how to choose a highway network on which the operation is conducted, and how to consider stochastic travel time. Additionally, the survey method tends to emphasize the trucker's value of time even when the drivers are part of the fleet operation, while the simulation tackles the operating cost from the perspective of fleet reconfiguration but ignores the driver's opinion. Nonetheless, it is reasonable to believe that the simulation study conducted here is capable of revealing the general picture of the freight vehicle's value of time.

CHAPTER V

INVENTORY VALUE OF TIME

5.1. Introduction

To survive in a competitive environment, freight stakeholders sometimes employ a third-party logistics (3PL) carrier, i.e., outsourcing logistics. It is reported that about 60 percent of the Fortune 500 companies have at least one 3PL contract (Lieb & Bentz, 2005). Such contracts provide a number of benefits such as increased reliability and shortened travel time, which in turn permits each supplier to develop inventory strategies that are compatible with their delivery schedules. Some customers are willing to pay a premium charge for fast or on-time delivery, e.g., Federal Express' next day delivery service (So, 2000). From the carriers' point of view, contracts with shippers can reduce overall transportation costs, and possibly transportation time, because the carriers can schedule in advance for both labor and equipment (Ali Ülkü & Bookbinder, 2012).

Realizing the relationship mentioned above between shippers and carriers, this chapter describes the use of inventory models to examine the effect of transportation time from the viewpoint of shippers/consignees. Values of commodity transportation time subject to optimal inventory strategy within the supply chain are calculated via case studies.

Unlike carriers, shippers/consignees experience major costs of a prolonged transportation time from increased inventory holding and lost sales (Zhang et al., 2009). There are two types of potential savings in inventory costs when transportation time is reduced. The first is due to pipeline inventory, which is also called in-transit inventory. A shorter transportation time means less inventory is caught in the transportation system and therefore less capital is tied up with the inventory. Here the pipeline takes the form of a highway system, air route, or other transportation mode. The second type of potential savings is from inventory holding costs; in other words, savings from on-shelf inventory costs. This is because inventory managers usually increase inventory levels to

counteract a longer or less reliable transportation time. Failure in maintaining an appropriate number of inventories not only results in current lost sales, but also incurs the chance of losing future customers (Smith et al., 2007). To gauge this impact, an analytical inventory model with transportation costs and lost sales has to be used to examine the value of transportation time in view of both mean and reliability from the perspective of shipment-receivers.

In inventory theory, the time from submitting a wholesale order until ordered shipment arrives is defined as lead time. It consists of transportation time from an external supplier or production time in case of an internal order, and includes order preparation time, administrative time of the supplier, and time for inspection after receiving the order (Axsater, 2000). Typically, transportation time is the most unstable component within the lead time, while nontransportation components are relatively constant and are usually treated as fixed parameters. Sometimes shortening the mean transportation time or increasing its reliability results in increased transportation costs. For example, using toll roads or special deliveries (i.e., overnight deliveries) over congested highways would be faster, but could be more costly. By estimating potential savings due to a faster supply chain or measuring extra costs due to a possible transportation delay, private-sector companies are capable of making choices between a faster resupply with more expense and cheaper but slower delivery, especially during negotiations with external carriers (Palaka et al., 1998).

This trade-off facilitates understanding of VOT in the environment of shippers' inventory management strategies, where they tend to keep operations uninterrupted by adjusting their inventories in response to prolonged transportation time and varying delay. In principle, cost-minimizing companies have three major cost components within their logistics operations. These three components are shipping cost, in-transit inventory cost, and warehousing cost.

5.2. Methodologies

5.2.1. Basic Equation for Simple Case

For shipment-receivers, trucking cost usually comes from inbound shipments. Either a company-owned fleet or contracted carriers are employed to move the ordered items. No matter which option is chosen, truck operating costs such as fuel expense and driver salary are relatively consistent as long as the location of upstream senders and downstream shipment-receivers remains unchanged. However, in the case where an external carrier is contracted, additional charges in terms of outsourcing cost or service fees cannot be ignored. Let C_T be the cost when contracted with an external carrier and F_R be the freight rate per unit weight. Given the item weight w and order quantity Q , it is straightforward to write down the total weight W within an order as shown in Equation 5.1:

$$C_T = F_R W = F_R Q w \quad (5.1)$$

Note that F_R varies among different types of commodities. The argument is that for both conceptual and business reasons, it is more realistic to treat F_R as a function of order size. For example, the payment per unit shipped is lowered for larger quantities to encourage business expansion. The earliest study (Langley, 1981) finds that the payment per unit shipped rises more proportionately as the quantity shipped is reduced, which results in a nonlinear function of F_R . Therefore, it is reasonable to assume a power function expressed as Equation 5.2:

$$F_R(Q) = aQ^b \quad (5.2)$$

where $a \geq 0$ and $b < 0$. a is zero when not hiring contracted carriers; otherwise, a is positive. b is negative (e.g., -1, -2, -3) because the larger order results in a reduced payment per unit. Note that the smaller b is, the larger discount is for the payment.

The contract payment per order when hiring an external carrier is accordingly expressed as:

$$C_T = F_R(Q)W = aQ^b Q w = aQ^{b+1} w \quad (5.3)$$

In-transit inventory cost is incurred by capital tied up with inventory during the transportation process, product shrinkage, damage, and any temporary storage cost. This cost component is usually estimated as:

$$C_{in-transit} = \frac{\mu_T Q}{365} y \quad (5.4)$$

where μ_T is the mean transportation (in-transit) time (in days), y is the in-transit cost per unit per year, and $C_{in-transit}$ is the in-transit inventory cost per order.

The third cost component of warehousing cost depends on the average inventory level and many other factors. To tackle the complexity of inventory holding decisions, the continuous review (Q, R) model was adopted. The continuous review policy indicates a continuous monitoring of inventory, which is possible with today's technology and becomes a prevalent practice, especially in a JIT system. Whenever the installation stock (remaining physical inventory) drops to a preset reorder level R , an order of size Q units is made. The total cost within the warehouse includes inventory holding cost, ordering cost, and shortage cost. The annual holding cost is defined as the product of the average inventory level and the annual storage cost per unit.

Given the same order size Q , if the reorder level R is determined at a high value, then the average inventory level $R - Q/2$ is consequentially higher, which means an unnecessary increase in annual holding cost. However, if R is too low, the firm may suffer from a significant annual shortage cost, which is defined by the product of the average inventory shortage and the shortage penalty cost per unit per year. The total ordering cost, on the other hand, is determined by the number of orders per year, which is affected by the annual demand and order size or its inverse $-T$. The annual total ordering cost is simply equal to the cost per order multiplied by the number of orders per year.

The annual warehousing cost is shown as follows:

$$\begin{aligned}
 C_{holding} &= \left(\frac{Q}{2} + s\right)h + p \frac{n(R)}{T} + \frac{K}{T} \\
 &= \left(\frac{Q}{2} + R - \mu_x\right)h + p \frac{n(R)}{T} + \frac{K}{T}
 \end{aligned} \tag{5.5}$$

where Q is the order size, s is the safety stock $s = R - \mu_x$, h is the inventory holding cost per unit per year, p is the shortage cost per unit, K is the cost per order, T is the inverse of the number of orders made per year, $n(R)$ is the expected shortage per order cycle, R is the reorder point in units, μ_D is the mean demand per day, μ_L is the mean lead time in days ($\mu_L = \mu_T + v_0$), μ_T is the mean transportation time, v_0 is nontransportation time such as order preparation time, administrative time at the supplier, production time or inspection time after receiving the order, and μ_x is the mean demand x during lead time ($\mu_x = \mu_L \mu_D$).

Given these specifications, the overall annual logistics cost for shippers (consignees) is obtained by adding the three major cost components together (shipping cost, in-transit inventory cost, and warehousing cost). During this process, the shipping cost per order when hiring an external carrier and in-transit inventory cost per order are normalized into yearly cost. Equation 5.6 describes the overall annual logistics cost:

$$\begin{aligned}
 C_{overall} &= \frac{C_T}{T} + \frac{C_{in-transit}}{T} + C_{holding} \\
 &= \frac{C_T D}{Q} + \frac{C_{in-transit} D}{Q} + C_{holding} \\
 &= aQ^b wD + \frac{\mu_T D}{365} y + \left(\frac{Q}{2} + R - \mu_x\right)h + p \frac{n(R)}{T} + \frac{K}{T} \\
 &= aQ^b wD + \frac{\mu_T D}{365} y + \left(\frac{Q}{2} + R - \mu_x\right)h + Dp \frac{n(R)}{Q} + \frac{DK}{Q}
 \end{aligned} \tag{5.6}$$

The following paragraphs discuss the process of deriving formulas to examine the value of transportation time in view of both mean and reliability from the perspective of shipment-receivers (consignees). Consider Type 1 Service (Tagarus, 1989; Xu et al.,

2003) where 95 percent of vehicles (i.e., trucks) successfully deliver shipments before the occurrence of any stock-out; hence, a certain level of reorder point R has to be chosen carefully so that the remaining inventory is sufficient to serve the demand during the lead time, which again is the time interval between making an order and receiving the ordered amount. Given a constant daily demand μ_D and a normally distributed transportation time with mean μ_T and standard deviation σ_T , the demand during the lead time is, therefore, a normal distribution with mean μ_x and standard deviation σ_x as:

$$\mu_x = \mu_L \mu_D = (\mu_T + v_0) \mu_D \quad (5.7)$$

$$\sigma_x = \mu_D \sigma_T \quad (5.8)$$

The reorder point level is then expressed as:

$$R = \sigma_x Z + \mu_x = \mu_D \sigma_T Z + (\mu_T + v_0) \mu_D \quad (5.9)$$

where Z is the number of standard deviation of lead time demand that is required by the percentage of satisfying vehicle deliveries (i.e., 95 percent indicates a Z value of 1.645; see Figure 5.1). Let $\Phi(Z)$ be the cumulative function of standard normal distribution and $\varphi(Z)$ be the probability density function of standard normal distribution. The standard loss function $L(Z)$ (i.e., $L(1.645)$ equals 0.021) and is defined as:

$$L(Z) = \int_Z^{\infty} (t - Z) \Phi(t) dt = \int_Z^{\infty} t \Phi(t) dt - Z(1 - \Phi(Z)) = \Phi(Z) - Z(1 - \Phi(Z)) \quad (5.10)$$

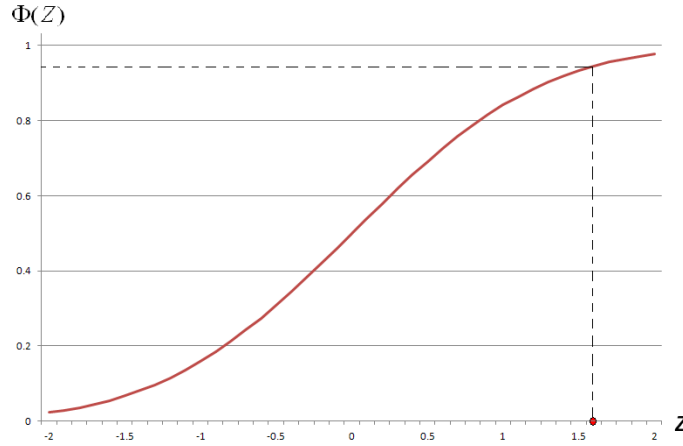


Figure 5.1: Cumulative Function of Standard Normal Distribution.

Due to normally distributed lead time demand, the expected shortage per order cycle $n(R)$ can be expressed as:

$$\begin{aligned}
 n(R) &= \int_0^R 0 f(x) dx + \int_R^\infty (x - R) f(x) dx \\
 &= E(x - R)_+ \\
 &= \sigma_x L(Z) \\
 &= \mu_D \sigma_T L(Z)
 \end{aligned} \tag{5.11}$$

where $f(x)$ represents the probability density function of lead time demand. Reforming Equation 5.6 results in:

$$C_{overall} = aQ^b wD + \frac{\mu_T D}{365} y + \left(\frac{Q}{2} + \mu_D \sigma_T Z\right) h + p \frac{D \mu_D \sigma_T L(Z)}{Q} + \frac{DK}{Q} \tag{5.12}$$

Based on this assumption, it is desirable to obtain the least-cost decision. This indicates a constrained nonlinear programming with objective function $C_{overall}(Q)$ and variable Q ($Q > 0$).

Note that if taking the derivative of $C_{overall}(Q)$, the optimal Q^* must obey the following condition (5.13):

$$\begin{aligned}\frac{\partial C_{overall}}{\partial Q} &= \frac{\partial(aQ^b wD + \frac{\mu_T D}{365} y + (\frac{Q}{2} + \mu_D \sigma_T Z)h + Dp \frac{\mu_D \sigma_T L(Z)}{Q} + \frac{DK}{Q})}{\partial Q} \\ &= abQ^{b-1} wD + \frac{h}{2} - D(\frac{p\mu_D \sigma_T L(Z) + K}{Q^2}) \\ &= 0\end{aligned}\quad (5.13)$$

Because a , Q , w , and D are all positive numbers and parameter b has to be negative to comply with the assumption that the trucking cost per unit shipped is lower for larger quantity, the optimal Q^* is the solution to Equation 5.14:

$$abwDQ^{b+1} + \frac{h}{2}Q^2 - D(p\mu_D \sigma_T L(Z) + K) = 0 \quad (5.14)$$

Obviously, Q^* is not a function of μ_T in this case. Thus:

$$\frac{\partial Q^*}{\partial \mu_T} = 0 \quad (5.15)$$

By definition, the VOT equals the derivative of $C_{overall}^*$ with respect to μ_T , and value of reliability (VOR) equals the derivative of $C_{overall}^*$ with respect to σ_T :

$$\begin{aligned}VOT &= \frac{\partial C_{overall}^*}{\partial \mu_T} \\ &= \frac{\partial C_{overall}(Q^*)}{\partial \mu_T} \\ &= \frac{\partial(aQ^{*b} wD + \frac{Q^*}{2} h + p \frac{D\mu_D \sigma_T L(Z) + DK}{Q^*})}{\partial Q^*} \frac{\partial Q^*}{\partial \mu_T} + \frac{\partial(\frac{\mu_T D}{365} y)}{\partial \mu_T} \\ &= \frac{D}{365} y\end{aligned}\quad (5.16)$$

As one can see from Equation 5.16, in this case value of time is irrelevant to current values of mean transportation time and standard deviation. The total cost here can be seen as a linear function of μ_T . The VOR, however, is quite tricky due to fact that:

$$\frac{\partial Q^*}{\partial \sigma_T} \neq 0 \quad (5.17)$$

The expression of Q^* related to σ_T can be obtained from the solution to Equation 5.14, which is discussed below:

$$abwDQ^{b+1} + \frac{h}{2}Q^2 - D(p\mu_D\sigma_T L(Z) + K) = 0, \quad b \neq -1, -2 \quad (5.18)$$

$$abwD + \frac{h}{2}Q^2 - D(p\mu_D\sigma_T L(Z) + K) = 0, \quad b = -1 \quad (5.19)$$

$$abwDQ + \frac{h}{2}Q^2 - D(p\mu_D\sigma_T L(Z) + K) = 0, \quad b = -2 \quad (5.20)$$

Equation 5.18 is only solvable when numerical values are provided for all the parameters. The typical method would involve nonlinear searching strategies such as the Newton–Raphson method or its expansions. The solution to Equation 5.19, however, can be easily obtained:

$$Q^* = \sqrt{\frac{2D(p\mu_D\sigma_T L(Z) + K) - abwD}{h}}, \quad b = -1 \quad (5.21)$$

This is followed by Equation 5.22 when inserting Equation 5.21:

$$\begin{aligned} C_{overall}^* &= \frac{awD}{Q^*} + \frac{\mu_T D}{365} y + \left(\frac{Q^*}{2} + \mu_D \sigma_T Z\right)h + p \frac{D\mu_D\sigma_T L(Z)}{Q^*} + \frac{DK}{Q^*} \\ &= \frac{\sqrt{h}(awD + pD\mu_D\sigma_T L(Z) + DK)}{\sqrt{2D(p\mu_D\sigma_T L(Z) + K) + awD}} + \mu_D \sigma_T Zh + \frac{\mu_T D}{365} y \\ &\quad + \frac{\sqrt{2Dh(p\mu_D\sigma_T L(Z) + K) + awD}}{2} \end{aligned} \quad (5.22)$$

VOR in this case ($b = -1$) is equal to:

$$\begin{aligned}
VOR &= \frac{\partial C_{overall}^*}{\partial \sigma_T} \\
&= \frac{\partial C_{overall}(Q^*)}{\partial \sigma_T} \\
&= \frac{3\sqrt{h}pD\mu_D L(Z)}{2\sqrt{2D(p\mu_D\sigma_T L(Z) + K) + awD}} + \mu_D Zh \\
&\quad - \frac{\sqrt{h}pD\mu_D L(Z)(awD + pD\mu_D\sigma_T L(Z) + DK)}{(2Dp\mu_D\sigma_T L(Z) + 2DK + awD)^{3/2}}
\end{aligned} \tag{5.23}$$

As for $b = -2$, note that:

$$\frac{-abwD - \sqrt{(abwD)^2 + 2hD(p\mu_D\sigma_T L(Z) + K)}}{h} < 0, \quad b = -2 \tag{5.24}$$

The solution to Equation 5.20 is, therefore, unique:

$$Q^* = \frac{-abwD + \sqrt{(abwD)^2 + 2hD(p\mu_D\sigma_T L(Z) + K)}}{h}, \quad b = -2 \tag{5.25}$$

Similar to Equation 5.22, inserting Equation 5.25 results in:

$$\begin{aligned}
C_{overall}^* &= \frac{awD}{Q^{*2}} + \frac{\mu_T D}{365} y + \left(\frac{Q^*}{2} + \mu_D \sigma_T Z\right)h + p \frac{D\mu_D\sigma_T L(Z)}{Q^*} + \frac{DK}{Q^*} \\
&= \frac{h^2 awD}{(2awD + \sqrt{(-2awD)^2 + 2hD(p\mu_D\sigma_T L(Z) + K)})^2} + \frac{\mu_T D}{365} y \\
&\quad + \frac{2awD + \sqrt{(-2awD)^2 + 2hD(p\mu_D\sigma_T L(Z) + K)}}{2} + \mu_D \sigma_T Zh \\
&\quad + \frac{hpD\mu_D\sigma_T L(Z) + hDK}{2awD + \sqrt{(-2awD)^2 + 2hD(p\mu_D\sigma_T L(Z) + K)}}
\end{aligned} \tag{5.26}$$

$$\begin{aligned}
VOR = & \mu_D Zh + \frac{hDp\mu_D L(Z)}{2\sqrt{(-2awD)^2 + 2hD(p\mu_D\sigma_T L(Z) + K)}} \\
& - \frac{2h^3 awD^2 p\mu_D L(Z)}{(\sqrt{(-2awD)^2 + 2hD(p\mu_D\sigma_T L(Z) + K)} + 2awD)^3} \\
& \frac{1}{\sqrt{(-2awD)^2 + 2hD(p\mu_D\sigma_T L(Z) + K)}} \\
& + \frac{hpD\mu_D L(Z)}{2awD + \sqrt{(-2awD)^2 + 2hD(p\mu_D\sigma_T L(Z) + K)}} \\
& - \frac{hpD\mu_D\sigma_T L(Z) + hDK}{(\sqrt{(-2awD)^2 + 2hD(p\mu_D\sigma_T L(Z) + K)} + 2awD)^2} \\
& \frac{hpD\mu_D L(Z)}{\sqrt{(-2awD)^2 + 2hD(p\mu_D\sigma_T L(Z) + K)}}
\end{aligned} \tag{5.27}$$

For the case where $b \neq -1, -2$, it is possible to approximate Equation 5.2 by using representative data in the industry. Tyworth and Zeng (1996) accurately fit a curve to the freight rate F_R using data from a major trucking company. Recent studies on freight rate can be found in Özkaya et al. (2010). For example, given the same freight section, and if the fuel expense and driver salary are excluded, F_R can be determined as:

$$F_R(Q) = 3.43Q^{-0.3325} \tag{5.28}$$

5.2.2. Case with Random Demand

Now consider a more complicated case where random demand replaces constant demand for real-world concerns. Starting with the assumption that both demand and transportation time are normally distributed, where daily demand is represented by mean μ_D and standard deviation σ_D , the overall cost function needs to be reconstructed.

The first obstacle is that demand during lead time becomes a product of two random normal variables, which is not a Gaussian distribution anymore. However, Blumenfeld (2001) suggests that it is reasonable to use a normal distribution to approximate the lead time demand in inventory management:

$$\begin{aligned}\sigma_x^2 &= \mu_D^2 \sigma_L^2 + \sigma_D^2 \mu_L^2 + \sigma_L^2 \sigma_D^2 \\ &= \mu_D^2 \sigma_T^2 + \sigma_D^2 (\mu_T + v_0)^2 + \sigma_T^2 \sigma_D^2\end{aligned}\quad (5.29)$$

$$\mu_x = \mu_L \mu_D = (\mu_T + v_0) \mu_D \quad (5.30)$$

Corresponding reorder level is then:

$$R = \sigma_x Z + \mu_x = Z \sqrt{\mu_D^2 \sigma_T^2 + \sigma_D^2 (\mu_T + v_0)^2 + \sigma_T^2 \sigma_D^2} + (\mu_T + v_0) \mu_D \quad (5.31)$$

The expected shortage per order cycle $n(R)$ is then:

$$\begin{aligned}n(R) &= E(x - R)_+ \\ &= \sigma_x L(Z) \\ &= L(Z) \sqrt{\mu_D^2 \sigma_T^2 + \sigma_D^2 (\mu_T + v_0)^2 + \sigma_T^2 \sigma_D^2}\end{aligned}\quad (5.32)$$

And reforming results in:

$$\begin{aligned}C_{overall} &= aQ^b wD + \frac{\mu_T D}{365} y + \left(\frac{Q}{2} + \sigma_x Z\right) h + p \frac{n(R)}{T} + \frac{K}{T} \\ &= aQ^b wD + \frac{\mu_T D}{365} y + \left(\frac{Q}{2} + \sqrt{\mu_D^2 \sigma_T^2 + \sigma_D^2 (\mu_T + v_0)^2 + \sigma_T^2 \sigma_D^2} Z\right) h + \\ &\quad \left(\sqrt{\mu_D^2 \sigma_T^2 + \sigma_D^2 (\mu_T + v_0)^2 + \sigma_T^2 \sigma_D^2} pL(Z) + K\right) D \frac{1}{Q}\end{aligned}\quad (5.33)$$

Note that taking the derivative of $C_{overall}$ with respect to Q in this case would be very difficult because the expression of $\partial C_{overall} / \partial Q$ is overwhelming, while Equation 5.12 is relatively easy. The alternative method would involve typical root search strategies such as the Newton–Raphson method or its expansions. If industry parameters are known, the commercial value of time and reliability are achievable through the comparison of two case studies. For example:

$$VOT = \frac{C_{overall}^{*s1} - C_{overall}^{*s2}}{\mu_T^{s1} - \mu_T^{s2}} = \frac{\Delta C_{overall}^*}{\Delta \mu_T} \quad (5.34)$$

where $s1$, $s2$ represent two scenarios, each having a different transportation time and optimal inventory policy. An advantage of this numerical method is the ability to provide fast answers for all levels of operations. Almost any minimization tool is capable of solving such a problem in seconds. Therefore, the trade-off cost and transportation time can be easily determined by the logistics operators and contract managers with minimal knowledge in optimization technique.

5.2.3. Numerical Method and Results

Numerical tests are conducted to estimate the monetary impact of additional transportation time on the shippers (consignees). Since inventory management practices vary with industry, tests need to be conducted for each individual sector separately. An ideal process is to consider the contribution of each industry sector (e.g., food, chemical, pharmaceutical, automotive, paper, electronics, clothing, merchandise, and other manufacturing) to the U.S. economy, from which a weighted value of transportation time subject to a shipper's inventory strategy across all sectors might be calculated.

For the test, the demand, lead time, and product values are extracted from a comprehensive study by Lalonde et al. (1988) and are representative of leading edge firms in the auto and related parts industry that are sensitive to transportation service. Unfortunately, this is the only survey available to the public due to the difficulty and cost in collecting private business data recently. Although data are from decades ago, it is possible to adjust values to present value based on the consumer price index (CPI).

From these representative firms, 332 manufacturers and 123 warehouses provided useful information related to customer service, such as demand, lead time, and product value. These data are further categorized into nine industry groups by Shirley (2000). Table 5.1 shows the representative parameters.

Note that warehouse holding cost, in-transit inventory cost, and shortage cost are based on percentage of the unit item value. A unit is usually stated in terms of box, bag, pack, or pallet. Most of the products in represent independent-demand items, which are inventoried off the shelf and are distributed directly from manufacturers or indirectly

through distributors, wholesalers, or retailers. In North America, most of these items move from 300 to 500 miles by truck. It is a very challenging task to search for the most updated representative industry parameters due to the privacy and competitive reasons. This difficulty, however, does not prevent this methodology from being useful in practice, as long as companies keep track of their own business parameters.

Two types of services (Type 1 and 2) and two types of demand patterns (random and deterministic) are tested in this study. Type 1 service is defined by the probability of not experiencing stock-out α , which is also known as the probability of having an actual lead time demand (demand between placing an order and the actual arrival of the shipment) that is smaller than the inventory in stock when ordered (Tagaras, 1989). This is an event-oriented performance criterion. The disadvantage of this type of service is that it only counts the number of late trucks when commodities are not delivered before the occurrence of stock-out. Consequentially, there is no measurement on how serious each delay or each late delivery is. Type 2 service on the other hand, overcomes the above disadvantage by its quantity-oriented nature, which is defined by the expected percentage of in-stock demand during a cycle, also known as fill rate β :

$$\beta = 1 - n(R) / \mu_x \quad (5.35)$$

where $n(R)$ is the expected shortage per order cycle and μ_x is the expected cycle demand. In Type 2 service, the influences of late shipments are different based on how late they are. A shipment having a greater delay would contribute to more units of stock out. Some technical details about Type 2 service can be found in Xu et al. (2003).

Table 5.1: Logistic Operation Data by Industry Type

		REPRESENTATIVE INDUSTRY								
		Food	Chem- ical	Pharma- ceuticals	Auto	Paper	Elec- tronics	Cloth- ing	Other Mfg.	Merchan- dise
		DEMAND								
Mean of daily demand (units)	μ_D	121	26	9	16	13	29	16	21	4
Std. dev. of daily demand (units)	α_D	72.6	15.6	5.4	9.6	7.8	17.4	9.6	12.6	2.4
Annual demand (units)	D	44165	9490	3285	5840	4745	10585	5840	7665	1460
		LEAD TIME								
Constant order processing days	v_0	2	2	1	1	4	3	3	1	1
Mean transit time (days)	μ_T	2.5	5	3	4	3	4	4	4	4
Std. dev. of transit time (days)	σ_T	0.5	1.2	1	1.6	1.2	2.2	2.2	2	2
		PRODUCT								
Unit value (dollars)	V	27.11	277.20	126.38	118.80	50.01	19.80	67.89	63.18	27.11
Unit weight (pounds)	w	4.4	37.4	0.4	6	1.5	0.4	4.3	1.6	3.4
		INVENTORY								
Holding cost (warehouse)		50%	50%	30%	30%	50%	50%	30%	30%	50%
Holding cost (\$/yr) (warehouse)	h	13.55	138.60	37.92	35.64	25.01	9.90	20.37	18.95	13.55
Inventory cost in-transit		20%	20%	20%	20%	20%	20%	20%	20%	20%
Inventory cost in-transit (\$/yr)	y	5.42	55.44	25.28	23.76	10.00	3.96	13.58	12.64	5.42
Ordering cost per order	K	19.80	19.80	19.80	19.80	19.80	19.80	19.80	19.80	19.80
Unit shortage cost		25%	25%	25%	25%	25%	25%	25%	25%	25%
Unit shortage cost (\$/yr)	P	6.78	69.30	31.60	29.70	12.50	4.95	16.97	15.80	6.78

5.2.3.1. Case 1: Type 1 service with random lead time and deterministic demand

In Case 1, assuming normal distributed lead time with a mean μ_T and standard deviation σ_T , the overall cost function for Type 1 service with service level $\alpha = 0.95$ is:

$$\begin{aligned} C_{overall} &= 3.43(Qw)^{-0.3325} wD + \frac{\mu_T D}{365} y + \left(\frac{Q}{2} + R - \mu_x\right)h + p \frac{n(R)}{T} + \frac{K}{T} \\ &= 3.43(Qw)^{-0.3325} wD + \frac{\mu_T D}{365} y + \left[\frac{Q}{2} + R - (\mu_T + v_0)\mu_D\right]h + pD \frac{n(R)}{Q} + D \frac{K}{Q} \end{aligned} \quad (5.36)$$

A Type 1 service level of $\alpha = 0.95$ requires a certain level of reorder point R to ensure that remaining inventory at the reorder point is sufficient to serve demand during lead time with a probability of 0.95 . Given the mean demand μ_x during lead time and its standard deviation σ_x , the reorder point level could be expressed as $R = \sigma_x Z + \mu_x = 1.645\mu_D \sigma_T + \mu_D(\mu_T + v_0)$, where $Z = 1.645$ is the number of standard deviations of lead time demand that are required by $\alpha = 0.95$. In other words, the probability that all custom orders arriving within the lead time will be completely delivered from stock without delay is 95 percent. From the standard loss table, the value of $L(Z)$ is found to be $L(Z) = L(1.645) = 0.021$. This gives:

$$\begin{aligned} n(R) &= \int_0^R 0f(x)dx + \int_R^\infty (x - R)f(x)dx \\ &= E(x - R)_+ \\ &= \sigma_x L(Z) \\ &= 0.021\mu_D \sigma_T \end{aligned} \quad (5.37)$$

where x represents the probability density function of the demand during lead time. By inserting Equation 5.37 into the 5.36, one obtains:

$$\begin{aligned} C_{overall} &= 3.43(Qw)^{-0.3325} wD + \frac{\mu_T D}{365} y + \left[\frac{Q}{2} + 1.645(\mu_D \sigma_T)\right]h + pD \frac{0.021\mu_D \sigma_T}{Q} + D \frac{K}{Q} \\ &= 3.43Dw^{0.6675} Q^{-0.3325} + (0.021\mu_D \sigma_T p + K)D \frac{1}{Q} + \frac{h}{2} Q + 1.645(\mu_D \sigma_T)h + \frac{\mu_T D}{365} y \end{aligned} \quad (5.38)$$

Minimizing this nonlinear function $C_{overall}(Q)$ with respect to the order size Q would result in the optimal policy associated with a positive integer value of order size Q . Obviously, a change in mean transit time contributes to a change in objective function

$C^*_{overall}(Q)$. However, the optimal order size Q is not affected by the change of mean transit time as proven in Equation 5.16. Therefore, the VOT for annual fleet is calculated as:

$$VOT_{annual_fleet} = \frac{\partial C^*_{overall}}{\partial \mu_T} = \frac{D}{365} y \quad (5.39)$$

After calculating the order size Q for the optimal policy, which is to minimize nonlinear objective function $C_{overall}(Q)$, the total weight per order can be easily calculated as the product of the order size Q and the average pounds per unit. In this study, these resulting numbers (15,000 pounds per order in the largest case) are much less than any truck loading limit imposed by FHWA (Harwood et al., 2003). Consequentially, it is reasonable to assume here that a single truck is used for each order.

The resulting single-vehicle VOT for mean transit time is shown in Table 5.2. The 10-hour driving limit is considered when converting dollars per day into dollars per hour. This is regulated by the newest hours of service rule from the Federal Motor Carrier Safety Administration. Table 5.2 shows that the VOT for mean transit time is extremely low for consignees. This can be explained by the fact that the prolonged mean transit time can be perceived in advance, therefore inventory level is adjusted accordingly to mitigate the impact. Sometimes earlier orders are made instead of increasing the inventory level.

Table 5.2: Single-Vehicle Value of Time for Mean Transit Time for Case 1

		REPRESENTATIVE INDUSTRY								
		Food	Chem- ical	Pharma- ceuticals	Auto	Paper	Elec- tronics	Cloth- ing	Other Mfg.	Merchan- dise
Annual demand (units)	D	44165	9490	3285	5840	4745	10585	5840	7665	1460
In-transit holding cost (\$/year)	y	3.70	37.83	17.25	16.21	6.83	2.70	9.27	8.62	7.37
Optimal order size (units)	Q	1758	289	78	240	159	340	308	277	89
Unit weight (pounds)	w	4.4	37.4	0.4	6	1.5	0.4	4.3	1.6	3.4
Annual fleet VOT (\$/day)	y	655.97	1441.44	227.49	380.16	130.04	114.84	217.26	265.36	43.20
Annual fleet VOT (\$/hr)		59.63	131.04	20.68	34.56	11.82	10.44	19.75	24.12	3.93
Trucks used per order		1	1	1	1	1	1	1	1	1
Annual truck #	N	25	33	42	24	30	31	19	28	16
Single-vehicle VOT (\$/hr)		2.39	3.97	0.49	1.44	0.39	0.34	1.04	0.86	0.25

In Bookbinder and Cakayildirim (1999), the expected inventory holding cost was derived at warehouse when an expedited lead time was shifted by a positive constant with a deterministic demand. The optimal Q did not change. Hence, in a general case, one can determine the optimal Q and s values as if no shift occurs, and then calculate the optimal reorder point R by adding the shift parameter. The change of mean transit time has little effect on the overall cost to consignees.

Unlike the effect of mean transit time, the change in transit time variation has a significant impact on order size decision. As a consequence, overall cost is altered accordingly. In particular, value of reliability due to the variation in transit time is calculated by first specifying the delay function:

$$\begin{aligned}
 E(\text{delay}) &= \int_0^{\mu_T} 0 f(t) dt + \int_{\mu_T}^{\infty} (t - \mu_T) f(t) dt \\
 &= \int_{\mu_T}^{\infty} (t - \mu_T) f(t) dt \\
 &= \sigma_T L(0) \\
 &= 0.399 \sigma_T
 \end{aligned} \tag{5.40}$$

$$\text{VOR}_{\text{annual_fleet}} = \frac{\partial C_{\text{overall}}^*}{\partial E(\text{delay})} = \frac{C_{\text{overall}}^{\text{post-change}} - C_{\text{overall}}^{\text{no-change}}}{E_{\text{delay}}^{\text{post-change}} - E_{\text{delay}}^{\text{no-change}}} \tag{5.41}$$

Table 5.3 summarizes VOR from the perspective of variation. It shows that the chemical industry has the highest VOR (\$46.08 per truckload per hour) among nine industry sectors, followed by the food industry and then the automotive industry. Regular merchandise has the lowest value, which is \$2.69 per truckload per hour.

Table 5.3: Value of Reliability Based on Transit Time Variation for Case 1

		REPRESENTATIVE INDUSTRY								
		Food	Chemical	Pharmaceuticals	Auto	Paper	Electronics	Clothing	Other Mfg.	Merchandise
LEAD TIME										
Constant order processing days	v_0	2	2	1	1	4	3	3	1	1
Mean transit time (days)	μ_T	2.5	5	3	4	3	4	4	4	4
Std. dev. transit time (days)	σ_T	0.5	1.2	1	1.6	1.2	2.2	2.2	2	2
Expected delay for σ_T (hr)		2.19	5.27	4.39	7.02	5.27	9.66	9.66	8.78	8.78
Std. dev. of transit time (-20%)		0.40	0.96	0.80	1.28	0.96	1.76	1.76	1.60	1.60
Expected delay for σ_T^- (hr)	σ_T^-	1.76	4.21	3.51	5.62	4.21	7.72	7.72	7.02	7.02
Std. dev. of transit time (+20%)		0.60	1.44	1.20	1.92	1.44	2.64	2.64	2.40	2.40
Expected delay for σ_T^+ (hr)	σ_T^+	2.63	6.32	5.27	8.43	6.32	11.59	11.59	10.53	10.53
OPTIMAL SOLUTION										
Order size for σ_T	Q	1758	289	78	240	159	340	308	277	89
Overall cost (\$) for σ_T	C^*	49484	91382	5143	18721	7639	6757	13594	11321	4625
Order size for σ_T^-	Q	1756	287	77	238	158	337	306	274	88
Overall cost (\$) for σ_T^-	$C_{(-)}$	49189	89779	5000	18374	7496	6525	13329	11012	4549
Order size for σ_T^+	Q	1761	291	78	242	159	343	310	280	89
Overall cost (\$) for σ_T^+	$C_{(+)}$	49780	92983	5285	19068	7782	6990	13858	11629	4700
VOR										
VOR (\$/hr) μ_T to σ_T^-		673.81	1521.24	162.70	247.06	135.85	120.49	136.96	175.71	43.03
VOR (\$/hr) μ_T to σ_T^+		673.72	1520.14	162.30	246.81	135.78	120.38	136.86	175.40	43.02
Avg. annual fleet VOR		673.77	1520.69	162.50	246.93	135.81	120.44	136.91	175.55	43.03
Annual truck #	N	25	33	42	24	30	31	19	28	16
Single-vehicle VOR (\$/hr)		26.95	46.08	3.87	10.29	4.53	3.89	7.21	6.27	2.69

5.2.3.2. Case 2: Type 1 service with random lead time and random demand

In Case 2, demand was also normally distributed with a mean μ_D and standard deviation σ_D . The derivation of this is seen in Equation 5.32 and 5.33 for when $\alpha = 0.95$, one should have:

$$R = \sigma_x Z + \mu_x = 1.645 \sqrt{\mu_D^2 \sigma_T^2 + \sigma_D^2 (\mu_T + v_0)^2 + \sigma_T^2 \sigma_D^2} + \mu_D (\mu_T + v_0) \quad (5.42)$$

$$\begin{aligned} n(R) &= \int_0^R 0 f(x) dx + \int_R^\infty (x - R) f(x) dx \\ &= 0.021 \sqrt{\mu_D^2 \sigma_T^2 + \sigma_D^2 (\mu_T + v_0)^2 + \sigma_T^2 \sigma_D^2} \end{aligned} \quad (5.43)$$

Therefore:

$$\begin{aligned} C_{overall} &= 3.43 D w^{0.6675} Q^{-0.3325} + (0.021 \sqrt{\mu_D^2 \sigma_T^2 + \sigma_D^2 (\mu_T + v_0)^2 + \sigma_T^2 \sigma_D^2} p + K) D \frac{1}{Q} + \\ &\frac{h}{2} Q + 1.645 h \sqrt{\mu_D^2 \sigma_T^2 + \sigma_D^2 (\mu_T + v_0)^2 + \sigma_T^2 \sigma_D^2} + \frac{\mu_T D}{365} y \end{aligned} \quad (5.44)$$

Unlike the first case, Equation 5.44 shows that the mean transit time has an influence on both warehouse inventory holding costs and in-transit inventory costs when lead time and demand are both independent random variables (normal). In addition to this, minimizing this nonlinear function $C_{overall}(Q)$ would result in different optimal Q if the mean transit time varies. Recall Equation 5.34 to approximate $\partial C_{overall}^* / \partial \mu_T$:

$$VOT_{annual_fleet} = \frac{\partial C_{overall}^*}{\partial \mu_T} \approx \frac{\Delta C_{overall}^*}{\Delta \mu_T} = \frac{C_{overall}^{*post-change} - C_{overall}^{*no-change}}{\mu_T^{post-change} - \mu_T^{no-change}} \quad (5.45)$$

Table 5.4 shows the calculated VOT for Case 2, where Type 1 service with random lead time and random demand is considered. Again, α is set to be 0.95—a prevailing value among the industries. Table 5.6 shows the VOR. Note that calculation of VOR is similar as in Equation 5.41, except the optimal overall cost is expressed and calculated differently as shown in Equation 5.44. These results show that under conditions where lead time and demand are both random, VOT for mean transit time

becomes a significant number compared to Case 1. Therefore, the consignees need to adjust their optimal policy to compensate for the change in mean transit time. The VOR, however, has values that are less than half of those in Case 1.

Table 5.4: Value of Time for Mean Transit Time for Case 2

		REPRESENTATIVE INDUSTRY								
		Food	Chem- ical	Pharma- ceuticals	Auto	Paper	Elec- tronics	Cloth- ing	Other Mfg.	Merchan- dise
Annual demand (units)	D	44165	9490	3285	5840	4745	10585	5840	7665	1460
Mean transit time (days)	μ_T	2.5	5	3	4	3	4	4	4	4
Optimal order size for μ_T (units)	Q	1868	332	92	263	177	379	333	309	91
Annual fleet VOT (\$/day)	$\frac{\partial C_{overall}^*}{\partial \mu_T}$	2476.87	5431.47	645.49	970.99	486.54	399.77	542.97	657.37	135.96
Annual fleet VOT (\$/hr)		225.17	493.77	58.68	88.27	44.23	36.34	49.36	59.76	12.36
Annual truck #	N	24	29	36	22	27	28	18	25	16
Single-vehicle VOT (\$/hr)		9.38	17.03	1.63	4.01	1.64	1.30	2.74	2.39	0.77

Table 5.5: Value of Reliability Based on Transit Time Variation for Case 2

REPRESENTATIVE INDUSTRY										
		Food	Chemical	Pharmaceuticals	Auto	Paper	Electronics	Clothing	Other Mfg.	Merchandise
LEAD TIME										
Constant order processing days	v_0	2.	2	2	2	2	2	1	1	1
Mean transit time (days)	μ_T	2.5	5	3	4	3	4	4	4	4
Std. dev. of transit time (days)	σ_T	0.5	1.2	1	1.6	1.2	2.2	2.2	2	2
Expected delay for σ_T (hr)		2.19	5.27	4.39	7.02	5.27	9.66	9.66	8.78	8.78
Std. dev. of transit time (-20%)	σ_T^-	0.40	0.96	0.80	1.28	0.96	1.76	1.76	1.60	1.60
Expected delay for σ_T^- (hr)		1.76	4.21	3.51	5.62	4.21	7.72	7.72	7.02	7.02
Std. dev. of transit time (+20%)	σ_T^+	0.60	1.44	1.20	1.92	1.44	2.64	2.64	2.40	2.40
Expected delay for σ_T^+ (hr)		2.63	6.32	5.27	8.43	6.32	11.59	11.59	10.53	10.53
OPTIMAL SOLUTION										
Order size for σ_T	Q	1868	332	92	263	177	379	333	309	91
Overall cost (\$) for σ_T	C^*	56620	114799	6559	21131	9723	8362	15427	12973	4992
Order size for σ_T^-	Q	1867	331	91	261	176	377	332	306	91
Overall cost (\$) for σ_T^-	$C_{(-)}^*$	56551	114236	6487	20919	9672	8225	15270	12752	4940
Order size for σ_T^+	Q	1869	333	92	264	177	382	335	312	91
Overall cost (\$) for σ_T^+	$C_{(+)}^*$	56704	115474	6644	21375	9783	8521	15608	13224	5052
VOR										
VOR (\$/hr) μ_T to σ_T^-		157.37	534.92	82.58	150.46	47.80	71.19	81.36	126.04	29.80
VOR (\$/hr) μ_T to σ_T^+		190.62	640.61	96.98	173.77	57.25	82.34	94.13	142.63	33.78
Avg. annual fleet VOR		174.00	587.76	89.78	162.11	52.53	76.77	87.74	134.33	31.79
Annual truck #	N	24	29	36	22	27	28	18	25	16
Single-vehicle VOR (\$/hr)		7.25	20.27	2.49	7.37	1.95	2.74	4.87	5.37	1.99

5.2.3.3. Case 3: Type 2 service with random lead time and deterministic demand

Service level 0.95 ($\beta = 0.95$) for Type 2 means that five percent of the demand during lead time is not met. This can be expressed by:

$$\frac{n(R)}{\mu_x} = \frac{\int_0^R 0f(x)dx + \int_R^\infty (x-R)f(x)dx}{\mu_x} = \frac{\int_R^\infty (x-R)f(x)dx}{\mu_x} = \frac{\sigma_x L(Z)}{\mu_x} = 0.05 \quad (5.46)$$

Thus, it is easy to obtain Z value by solving $L(Z)$ first, where:

$$L(Z) = 0.05 \frac{\mu_x}{\sigma_x} = 0.05 \frac{\mu_D(\mu_T + v_0)}{\mu_D \sigma_T} = 0.05 \frac{(\mu_T + v_0)}{\sigma_T} \quad (5.47)$$

The reorder point is then determined by $R = \sigma_x Z + \mu_x$. Given all the precalculated parameters, the overall cost function can be rewritten as:

$$\begin{aligned} C_{overall} &= 3.43(Qw)^{-0.3325} wD + \frac{\mu_T D}{365} y + \left(\frac{Q}{2} + R - \mu_x\right)h + p \frac{n(R)}{T} + \frac{K}{T} \\ &= 3.43(Qw)^{-0.3325} wD + \frac{\mu_T D}{365} y + \left(\frac{Q}{2} + \mu_D \sigma_T Z\right)h + p \frac{0.05 D \mu_D (\mu_T + v_0)}{Q} + \frac{DK}{Q} \end{aligned} \quad (5.48)$$

Note that Z is affected by μ_x , and μ_x is affected by μ_T , which makes it difficult to obtain the expression of $\partial Z / \partial \mu_T$. Accordingly, it is not viable to calculate VOT based on $\partial C_{overall}^* / \partial \mu_T$. Although there is a similarity between Case 1 and Case 3 due to the same lead time demand pattern, the difference in service requirement still causes a significant difference in numerical values. Recall Equation 5.41 and 5.45 for approximation. Table 5.6 summarizes results for Case 3.

Table 5.6: Value of Time and Value of Reliability for Case 3

		REPRESENTATIVE INDUSTRY								
		Food	Chemical	Pharmaceuticals	Auto	Paper	Electronics	Clothing	Other Mfg.	Merchandise
		LEAD TIME								
Mean transit time -20%	μ_T^-	2	4	2.4	3.2	2.4	3.2	3.2	3.2	3.2
Mean transit time +20%	μ_T^+	3	6	3.6	4.8	3.6	4.8	4.8	4.8	4.8
Std. dev. of transit time (days)	σ_T	0.5	1.2	1	1.6	1.2	2.2	2.2	2	2
		OPTIMAL SOLUTION FOR MEAN TRANSIT DELAY								
Order size for μ_T	Q	2168	436	126	322	224	481	401	388	98
Z for μ_T		-0.100	0.240	0.490	0.650	0.235	0.635	0.635	0.780	0.780
Overall cost (\$) for μ_T	C^*	52080	101015	6461	20076	8436	7309	14309	12347	4628
Order size for μ_T^-	Q	2127	419	120	310	219	466	391	371	96
Z for μ_T^-		0.000	0.345	0.595	0.750	0.300	0.710	0.710	0.875	0.875
Overall cost (\$) for μ_T^-	$C_{(-)}$	51413	98027	6133	19512	8279	7137	14028	11942	4582
Order size for μ_T^+	Q	2208	453	133	334	229	495	410	404	99
Z for μ_T^+		-0.190	0.145	0.400	0.555	0.180	0.570	0.570	0.690	0.690
Overall cost (\$) for μ_T^+	$C_{(+)}$	52748	103968	6784	20632	8595	7485	14592	12744	4675
		VALUE OF TIME FOR MEAN TRANSIT TIME								
VOT (\$/hr) μ_T to σ_T^-		121.38	271.57	49.69	64.10	23.81	19.64	31.86	45.97	5.29
VOT (\$/hr) μ_T to σ_T^+		121.45	268.47	48.81	63.17	24.07	19.92	32.24	45.17	5.36
Avg. annual fleet VOT		121.41	270.02	49.25	63.64	23.94	19.78	32.05	45.57	5.32
Annual truck #	N	20	22	26	18	21	22	15	20	15
Single-vehicle VOT (\$/hr)		6.07	12.27	1.89	3.54	1.14	0.90	2.14	2.28	0.35
		VALUE OF RELIABILITY BASED ON TRANSIT TIME VARIATION								
Single-vehicle VOR (\$/hr)		13.82	35.08	3.36	8.99	3.32	3.66	6.09	6.08	2.2

5.2.3.4. Case 4: Type 2 service with random lead time and random demand

In Case 4, $L(Z)$ is expressed as:

$$L(Z) = 0.05 \frac{\mu_x}{\sigma_x} = 0.05 \frac{\mu_D(\mu_T + v_0)}{\sqrt{\mu_D^2 \sigma_T^2 + \sigma_D^2 (\mu_T + v_0)^2 + \sigma_T^2 \sigma_D^2}} \quad (5.49)$$

By obtaining the corresponding Z value from the standard loss table, $C_{overall}$ in Case 4 is:

$$\begin{aligned} C_{overall} &= 3.43(Qw)^{-0.3325} wD + \frac{\mu_T D}{365} y + \left(\frac{Q}{2} + R - \mu_x\right)h + p \frac{n(R)}{T} + \frac{K}{T} \\ &= 3.43(Qw)^{-0.3325} wD + \frac{\mu_T D}{365} y + \left(\frac{Q}{2} + \sqrt{\mu_D^2 \sigma_T^2 + \sigma_D^2 (\mu_T + v_0)^2 + \sigma_T^2 \sigma_D^2} Z\right)h \\ &\quad + p \frac{0.05D\mu_D(\mu_T + v_0)}{Q} + \frac{DK}{Q} \end{aligned} \quad (5.50)$$

Table 5.7 shows the calculated VOT and VOR.

Table 5.7: Value of Time and Value of Reliability for Case 4

REPRESENTATIVE INDUSTRY									
	Food	Chem- ical	Pharma- ceuticals	Auto	Paper	Elec- tronics	Cloth- ing	Other Mfg.	Merchan- dise
VALUE OF TIME FOR MEAN TRANSIT TIME									
Single-vehicle VOT (\$/hr)	11.10	22.27	2.67	5.44	2.05	1.68	3.43	3.40	0.76
VALUE OF RELIABILITY BASED ON TRANSIT TIME VARIATION									
Single-vehicle VOR (\$/hr)	5.94	22.73	2.40	6.99	2.15	2.87	4.77	5.35	1.94

5.3. Chapter Summary

The (Q, R) inventory model with a continuous review policy was adopted in this study for analysis of shipment value of time and reliability. That model shares similar findings with the periodic review policy of inventory management. To summarize the results, Table 5.8 provides average commodity VOT and VOR for all four cases described in this chapter, categorized according to industry group in terms of mean transit time and its variations. The results reveal significant variations among different industries.

Companies in chemical (\$13.89/truckload/hour) and food (\$7.24/truckload/hour) transportation are most influenced by constant delay, possibly due to higher unit value or large quantity per truckload in these industries. In addition, the significantly larger VOR (\$31.04/truckload/hour for chemical and \$13.49/truckload/hour for food) indicates that companies are more sensitive to the uncertainty of travel time than when a delay is unexpected. This agrees with the fact that consignees usually have preventive measures to alleviate impacts of consistently occurring late deliveries, such as increasing inventory level or ordering early. This method measures the commodity value of time for different industry groups, which can be seen as part of the overall freight VOT.

Table 5.8: Average Truckload Value of Time and Reliability w/o Vehicle Operating Cost

		REPRESENTATIVE INDUSTRY								
	Case	Food	Chem- ical	Pharma- ceuticals	Auto	Paper	Elec- tronics	Clothing	Other Mfg.	Mer- chandise
VOT (\$/hr)	1	2.39	3.97	0.49	1.44	0.39	0.34	1.04	0.86	0.25
	2	9.38	17.03	1.63	4.01	1.64	1.30	2.74	2.39	0.77
	3	6.07	12.27	1.89	3.54	1.14	0.90	2.14	2.28	0.35
	4	11.10	22.27	2.67	5.44	2.05	1.68	3.43	3.40	0.76
	Avg.	7.24	13.89	1.67	3.61	1.31	1.06	2.34	2.23	0.53
VOR (\$/hr)	1	26.95	46.08	3.87	10.29	4.53	3.89	7.21	6.27	2.69
	2	7.25	20.27	2.49	7.37	1.95	2.74	4.87	5.37	1.99
	3	13.82	35.08	3.36	8.99	3.32	3.66	6.09	6.08	2.2
	4	5.94	22.73	2.4	6.99	2.15	2.87	4.77	5.35	1.94
	Avg.	13.49	31.04	3.03	8.41	2.99	3.29	5.74	5.77	2.21

CHAPTER VI

VALUE OF TIME USING CONTINUOUS APPROXIMATION

6.1. Introduction

The objective of this part of the study was to develop simple formulas to predict time and distance costs traveled by fleets of vehicles in physical distribution problems involving a depot and its area of influence. From there, insights on the trade-off between freight time value and cost can be obtained for less-than-truckload (LTL) deliveries, also known as the traveling salesman problem (TSP).

Since the 1970s, many researchers (Elion et al., 1971; Geoffrion, 1976; Hall, 1986; Daskin, 1985) have advocated use of the continuous approximation model. A main goal of the continuous approximation model is to devise strategic models and obtain reasonable solutions with as little data as possible. Typical examples include the LTL operation of postal mail and grocery items. In fact, if discrete data such as the location of origins and destinations or travel distance and travel time can be closely approximated by continuous functions, one should expect closed-form solutions to the logistics and distribution through simple model development. In this way, it is viable to realize trade-offs between parameters.

Continuous approximation modeling of freight distribution can be traced back to research fields such as transportation economics, location theory, and geometrical probability. It has been applied to many problems as a decision support tool for strategic planning. Before the 1970s, continuous models of freight distribution were rarely developed, and the modeling method was mainly used to analyze public transportation. Szplett (1984) provided an introduction and review of continuous models used to analyze the public transit system. Recent studies can be found in Quadrifoglio et al. (2006), Quadrifoglio and Li (2009), and Shen and Quadrifoglio (2012). There is some overlap between passenger transportation models and freight distribution models since passenger transport shares some characteristics with freight transport (Daganzo, 1984c;

Daganzo & Newell, 1985). Freight distribution models flourished after the work of Daganzo (1984a), where geometrical probability and asymptotical optimization were combined to produce equations. Geometrical probability provided approximations of travel distances for continuously distributed points in a zone (Campbell, 1990, 1993). Asymptotical optimization is probabilistic analysis of an algorithm for a distribution problem, which provides asymptotically optimal cost when the size of the problem tends to infinity.

This chapter focuses on a special case within the continuous approximation framework by introducing a varying cost component that depends on travel time. Generally speaking, the previous work in this research area focuses on a transportation rate that was decided purely by travel distance (Daganzo, 1984b; Newell & Daganzo, 1986a). The authors believed that the shipping cost associated with operating a break-bulk terminal or a warehouse was intimately related to the distance traveled. Newell and Daganzo (1986c) compared different strategies to deliver valuable goods in a network where travel time was equal to travel distance. Recently, due to the fact that freight delay has become an increasingly important issue for the shipping industry, recurrent and nonrecurrent congestion have added to total transportation costs and have been escalating for years.

Figliozzi (2007) explored the efficiency of urban commercial vehicle tours (buses) by disaggregating routing characteristics. Suggestions on data collection and policy implications were made based on the analytical results. In his later work, Figliozzi (2010) conducted numerical experiments to examine the impact of congestion in terms of tour changes. Unfortunately, this work assumes that commercial vehicles experience the same levels of congestion at all points, which is not common in practice. Because of the overwhelming complexity of the problem, no simple equation for overall cost has been developed. Wang's (2009) study followed Newell and Daganzo (1986b) and determined that given the same demand density the shape of delivery zones could vary significantly to better balance local and line-haul truck delivery costs that include

environmental externalities. This chapter continues that line of that work. Unfortunately, again the urgency is not captured.

6.2. Methodologies

6.2.1. Square Service Region

First of all, one should begin with revisiting an empirical formula as shown in Equation 6.1 (Elion et al., 1971), which gives the Euclidean distance, L , needed to visit N points uniformly scattered in a square region with a central depot (source), where routes were built with the best computer algorithm available:

$$(L / N) = 1.8 \bar{\rho} [(1 / C) + (1 / \sqrt{N})] \quad (6.1)$$

The first term, $1.8 \bar{\rho} / C$ is interpreted as the line-haul portion of the distance needed to reach the general location of each point. The difference between line-haul and long-haul is that line-haul trucks do not have sleeper cabs because those drivers are home every night. Long-haul drivers drive 18-wheelers with sleeper cabs because they are gone for several days at a time driving 10-hour days, hoping to get home before their 36-hour mandatory layover goes into effect. The second term, $1.8 \bar{\rho} \sqrt{N}$ is the amount of detour distance needed to actually deliver each item. It assumes that each vehicle can make a maximum of number C ($C \leq N$) stops before returning to the depot. The average distance from the depot to a random point in the square is expressed in Equation 6.2:

$$\bar{\rho} = (A^{1/2} / 6)(\sqrt{2} + \log \tan(3\pi / 8)) = 0.382A^{1/2} \quad (6.2)$$

where A is the area of the service region.

To illustrate this idea, Figure 6.1 shows a conceptualized arrangement for a fully developed urban transportation area of 100 square miles with one depot and 63 customers. The service area was divided into multiple routes with at most seven customers each. A length formula similar to Equation 6.1 can be applied to zones of

irregular shapes with point densities that need not be uniform when a simple, near-optimal route construction is used. Optimal shape is needed when dividing the zone into sectors for routing, especially in a large-scale distribution area (Ouyang, 2007). Equation 6.1 defines the line-haul travel to a zone containing C points as the distance from the depot to the center (gravity) of that zone. The detour distance is better interpreted as the distance per point in a local TSP tour for actual deliveries.

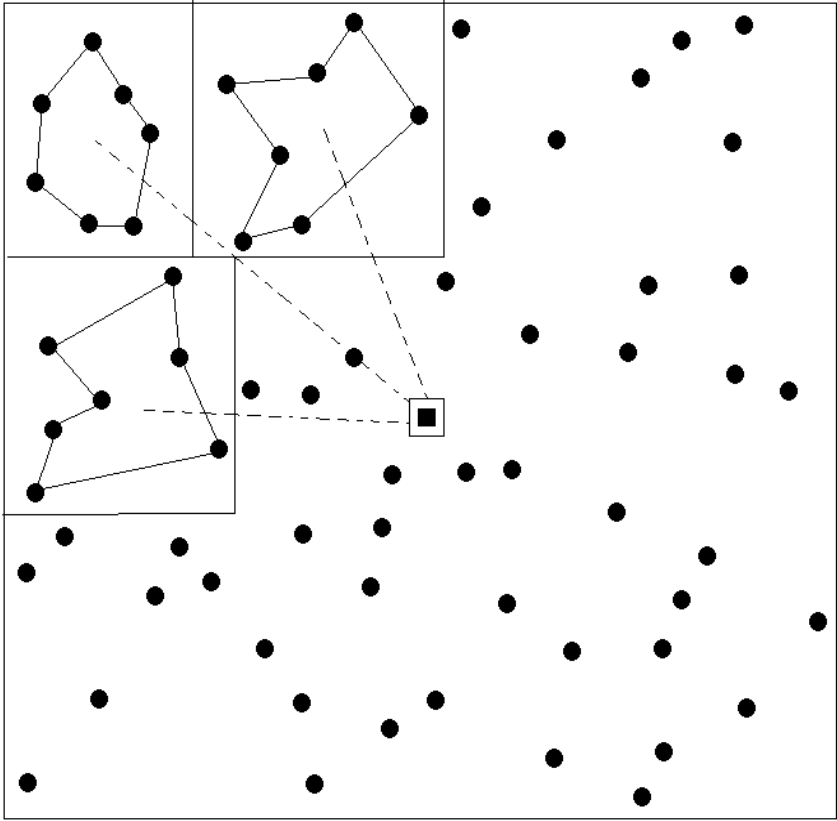


Figure 6.1: An Example Square Zone ($C = 7, N > 63$).

To derive the total cost function in this study of freight time value, vehicle-related costs not only include mileage-based costs such as fuel/oil, tolling, taxes, and equipment, but also labor-time based costs such as salary/wages and driver benefits.

Travel time plays an important role here. Assume unit mileage cost (for example, fuel) is F_m (\$/mile) and unit time cost (for example, wage) is F_t (\$/hr), the average cost I spent in visiting each customer point is then:

$$I = 1.8 \bar{\rho} [(1/C) + (1/\sqrt{N})] (F_m + F_t/S) \quad (6.3)$$

where S is the average speed within the service area.

Now it is time to consider some realistic geometry of roads. In practice, there may be a hierarchy of roadways such as arterials, freeways, local streets, etc. Line-haul travel can be put on faster major corridors to access each delivery zone more quickly, which is normally the case. Local travel tours, however, usually leave the driver with no choice but to drive on local streets/roads for actual delivery purposes. Therefore, it is rational to assume a different speed for line-haul travel (interstate highways) and local travel (streets). Equation 6.4 is rewritten in terms S_1 and S_2 , representing line-haul speed and local speed, respectively. In most situations, $S_1 \geq S_2$ because line-haul travel is usually made through faster and better roadways. The distance cost is then $1.8 \bar{\rho} [(1/C) + (1/\sqrt{N})] F_m$. The travel time cost is $1.8 \bar{\rho} / C (F_t / S_1)$ for line-haul and $1.8 \bar{\rho} / \sqrt{N} (F_t / S_2)$ for local. The total logistics cost spent for visiting each customer is:

$$\begin{aligned} I &= 1.8 \bar{\rho} [(1/C) + (1/\sqrt{N})] F_m + 1.8 \bar{\rho} / C (F_t / S_1) + 1.8 \bar{\rho} / \sqrt{N} (F_t / S_2) \\ &= 1.8 \bar{\rho} (F_m + F_t / S_1) / C + 1.8 \bar{\rho} (F_m + F_t / S_2) / \sqrt{N} \end{aligned} \quad (6.4)$$

This equation is derived for square networks having Euclidean distances. The observation is that overall cost scales differently between line-haul travel and local travel. For fixed-unit mileage cost and hourly salary expenses, average total cost spent in visiting each customer point decreases with a rate of $1.8 \bar{\rho} F_t C^{-1} S_1^{-2}$ for line-haul speed and a rate of $1.8 \bar{\rho} F_t N^{-1/2} S_2^{-2}$ for local speed, as presented below:

$$\begin{aligned} \partial I / \partial S_1 &= -1.8 \bar{\rho} F_t C^{-1} S_1^{-2} \\ \partial I / \partial S_2 &= -1.8 \bar{\rho} F_t N^{-1/2} S_2^{-2} \end{aligned} \quad (6.5)$$

Consider a situation where the delivery region or the total number of customers are not extremely large, especially when compared with the number of customers that each vehicle can serve (assume $C \leq N \leq C^2$). In such a case, a unit increase in local travel speed results in more savings than that in line-haul because when comparing the two, one should have:

$$\frac{\partial I / \partial S_1}{\partial I / \partial S_2} = \frac{C^{-1} S_1^{-2}}{N^{-1/2} S_2^{-2}} = \frac{\sqrt{N}}{C} \cdot \frac{S_2^2}{S_1^2} < 1 \quad (6.6)$$

In this circumstance, one would seek any method that can improve local road travel rather than line-haul. The options are usually related to local transportation improvement projects, using commercial vehicles of convenient size for local travel and easy access to unloading facilities.

For the delivery region that is extremely large ($N > C^2$), influences of speed on the overall cost may vary depending on the situation. However, it is still possible to see that there is always a threshold ratio ($N^{0.25} / C^{0.5}$) between line-haul speed and local speed. Figure 6.2 shows when a unit increase in line-haul travel speed results in more savings. In other words, for the situation where the local speed is getting very close to (or equal to in an extreme case) line-haul speed, the priority of speed improvement should always to be given to the line-haul travel. Once speed difference or total number N is large enough to be on the right side of the dashed line, improving local speed would take priority.

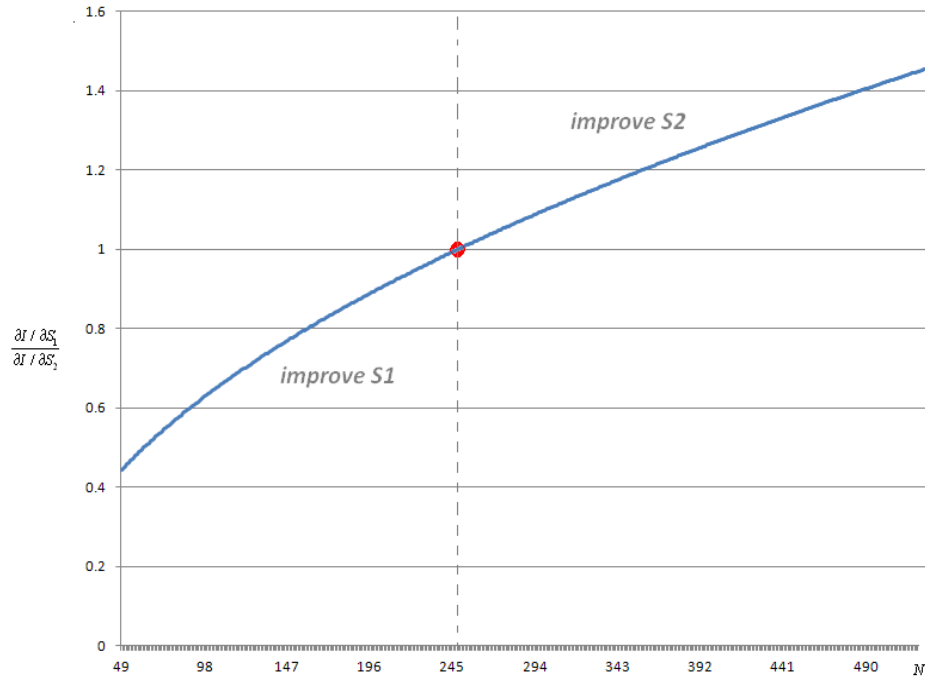


Figure 6.2: An Example of Speed Benefit ($C=7, S_1=60\text{mph}, S_2=40\text{mph}$).

6.2.2. Irregular Service Region

To generalize the above speed and travel time analysis, consideration moves to a delivery region that is beyond a square shape; for example, rectangular or circular. Some basic studies on the travel distance already exist. Daganzo (1984b) developed a simple formula to predict the distance traveled to visit N points within a rectangular area (see Equation 6.7). Based on this work, Newell and Daganzo (1986b) showed how equi-travel time contours can affect zone designs. However, the trade-off relationship between travel distance cost and travel time value remains unclear, particularly for the case where travel speed is not identical within a service region. This dissertation relies on the following assumptions that are typically made in the continuous approximation studies.

First, a review of Newell and Daganzo's work (1986b) shows how they assumed that the entire service region can be divided into several rectangular delivery zones. Each

zone is served by a single vehicle of capacity C . The width of this zone is assumed to be $2w$ and the length is assumed to be L . Given the density of \mathcal{S} , it must hold that $2wL\mathcal{S} = C$. Second, a delivery tour is assumed to follow the pattern shown in Figure 6.3. This pattern has proven to be very effective when the only consideration is minimizing total distance. Each tour basically serves half the zone on the way in and the other half on the way out.

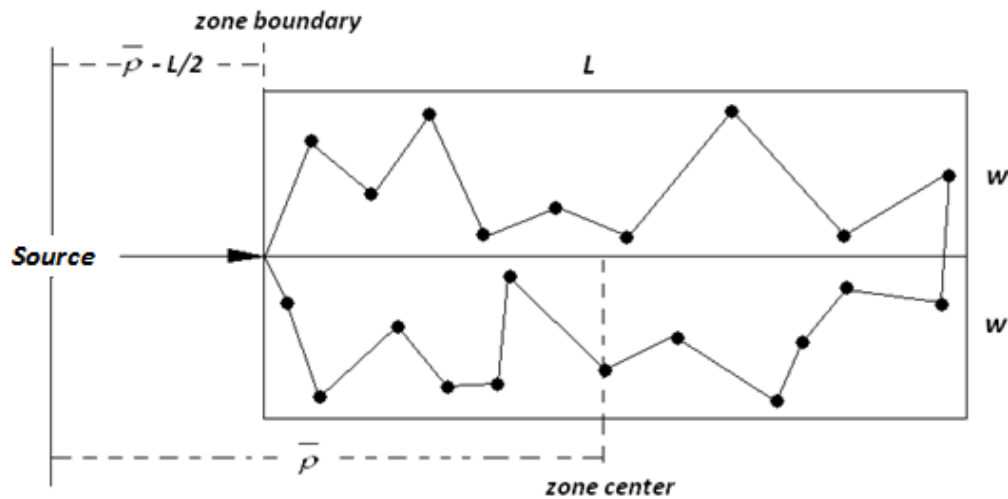


Figure 6.3: A Delivery Tour Pattern.

It is more convenient to treat line-haul travel to a zone containing C points as the distance from the depot to the center (gravity) of the zone rather than to the nearest point from the depot. Assume the average distance from the depot (source) to a random point within the region is $\bar{\rho}$. The average distance from the depot to reach the nearest boundary of any rectangular area of service for a certain vehicle is then $\bar{\rho} - L/2$. Line-haul distance is twice this value because the vehicle has to return to the depot after its delivery.

The local delivery distance is a little complicated because it has to be broken down into longitudinal and latitudinal travels. Without losing generality, one can find that the latitudinal travel distance between two consecutive points is $w/3$ if the points

are uniformly, independently, and randomly scattered along the longitudinal direction. To satisfy the assumption that the points are random in a two-dimensional region, the distance between two consecutive points along the longitudinal direction is assumed to be a Poisson process with the mean $2L/C = w\delta$. The Euclidean local distance between two consecutive points can be approximated by Equation 6.7. This dissertation shows the result, but Daganzo (1984a) includes all derivations:

$$d \approx \frac{w}{3} + \frac{2}{\delta^3 w^5} ((1 + \delta w^2) \ln(1 + \delta w^2) - \delta w^2) \quad (6.7)$$

Now that the review of the problem has been established, the next step is to introduce previously mentioned mileage-based costs F_m , time based costs F_t , line-haul speed S_1 , and local speed S_2 ; hence, the overall logistics costs I can be written as:

$$I = (2\bar{\rho} - L)(F_m + F_t / S_1) / C + (F_m + F_t / S_2) \left(\frac{w}{3} + \frac{2}{\delta^3 w^5} ((1 + \delta w^2) \ln(1 + \delta w^2) - \delta w^2) \right) \quad (6.8)$$

After replacing L with $L = C/2w\delta$, Equation 6.8 can be seen as a function of W . Let $J(w)$ be the W related portion within the overall logistics costs:

$$\begin{aligned} J(w) &= I - 2\bar{\rho}a / C \\ &= -a / 2w\delta + b \left(\frac{w}{3} + \frac{2}{\delta^3 w^5} ((1 + \delta w^2) \ln(1 + \delta w^2) - \delta w^2) \right) \end{aligned} \quad (6.9)$$

where a and b are positive numbers ($a = F_m + F_t / S_1$, $b = F_m + F_t / S_2$).

If taking the first-order derivative, the result is:

$$\begin{aligned} \frac{\partial I}{\partial w} &= \frac{\partial (J(w) + 2\bar{\rho}a / C)}{\partial w} \\ &= \frac{\partial J(w)}{\partial w} + 0 \\ &= \frac{a}{2\delta w^2} + \frac{b}{3} + \frac{b(10 - 6 \ln(1 + \delta w^2))}{\delta^2 w^4} - \frac{10b \ln(1 + \delta w^2)}{\delta^3 w^6} \end{aligned} \quad (6.10)$$

Since the necessary condition is to have $\partial J(w) / \partial w = 0$ at the optimum, replacing δw^2 with Z ($Z = \delta w^2$) would help solve the problem, as in Equation 6.11:

$$\frac{\partial J(w)}{\partial w} = J^{(1)}(Z) = \frac{a}{2Z} + \frac{b}{3} + \frac{b(10 - 6 \ln(1+Z))}{Z^2} - \frac{10b \ln(1+Z)}{Z^3} = 0 \quad (6.11)$$

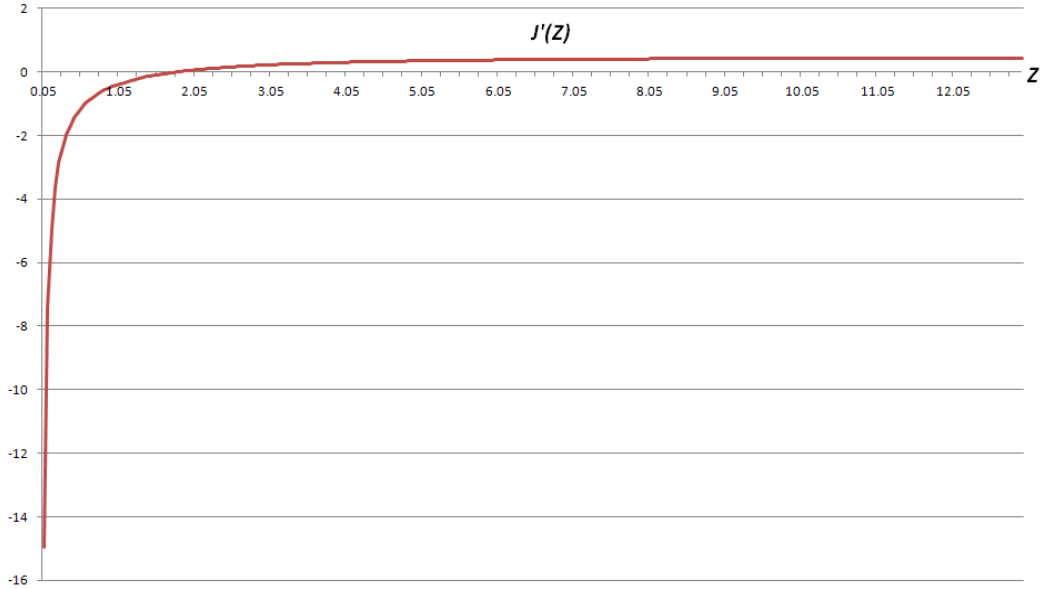


Figure 6.4: Behavior of $J^{(1)}(Z)$ ($F_m=\$1/\text{mile}$, $F_t=\$15/\text{hr}$, $S_1=60\text{mph}$, $S_2=40\text{mph}$).

Based on a set of practical parameters (\$1/mile cost, \$15/h salary) from Fender and Pierce (2013), it is easy to tabulate the value of a ($a = 1.250$) and b ($b = 1.375$). Figure 6.4 shows that the optimal point is found to be $Z^* = 1.8$ when solving $J^{(1)}(Z)$ graphically. For any $Z < 1.8$, $J^{(1)}(Z)$ is shown to be negative. On the other hand, for $Z > 1.8$, it has $J^{(1)}(Z)$ that is positive. The second-order derivative is $J^{(2)}(Z) = \partial J^{(1)}(Z) / \partial Z < 0$ for all positive Z . This optimal value Z^* may change when different parameters are configured. Nonetheless, the deviation would not be large and the value of 1.8 is somewhat representative because of real-world parameters. Figure 6.5 shows the optimal Z for different speed combinations. It is interesting to see that $Z^* = 1.8$ holds very well for a variety of cases (Figure 6.5).

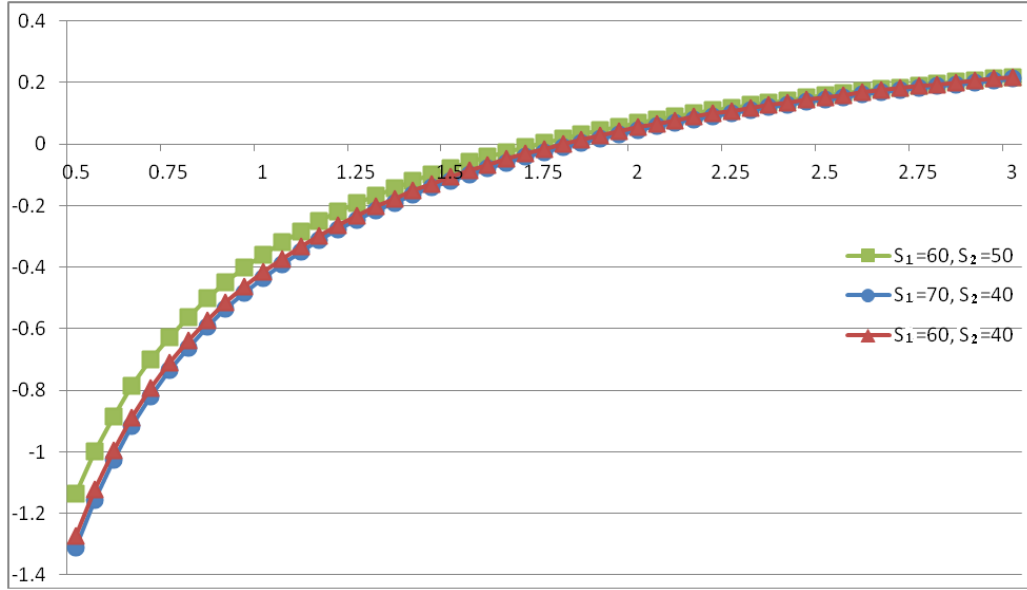


Figure 6.5: Performance of Z^* .

The optimal zone width w^* and the expression for the least overall logistics costs I in this case is therefore:

$$\begin{aligned}
 w^* &= \sqrt{1.8/\delta} = 1.34/\delta^{1/2} \\
 I^* &= 1.25\left(\frac{2\bar{\rho}}{C} - \frac{1}{2w^*\delta}\right) + 1.375\left(\frac{w^*}{3} + \frac{2}{\delta^3 w^{*5}} ((1 + \delta w^{*2}) \ln(1 + \delta w^{*2}) - \delta w^{*2})\right) \\
 &= \frac{2.5\bar{\rho}}{C} + \frac{0.83}{\delta^{0.5}}
 \end{aligned} \tag{6.12}$$

The zone length for the least cost strategy is:

$$L^* = \frac{C}{2w^*\delta} = \frac{0.37C}{\delta^{0.5}} \tag{6.13}$$

The zone width w^* alone, shown in Equation 6.12 and 6.13, provides the optimal logistics strategy if the entire service region can be divided into rectangular zones with each having a dedicated vehicle to deliver, as shown in Figure 6.6. The ratio between optimal zone length and width is $r^* = 0.5L^* / w^* = 0.14C$. It indicates that the divided zones are elongated toward the depot if each vehicle has a fixed capacity larger than $1/0.14 = 7.14$. In the extreme case when C (again, the number of customers each

vehicle can serve) goes to infinity, the zones become wedge-shaped and have a tendency to cover the whole region without need for any line-haul travel. This is consistent with Equation 6.8, where the first term (line-haul cost) has a denominator C . In other words, the cost for line-haul decreases with C . The improvement or change in the line-haul speed has less impact on overall logistics cost when C is larger, while improvement in local speeds would significantly reduce overall cost because the larger portion of the total travel distance is put on local routes. Figure 6.6 shows this relationship.

On the other hand, it is possible to have a case where a vehicle can visit no more than seven customers in a single route of $C \leq 7$ ($C < 7.14$, technically speaking). For $C = 1$, each vehicle is assigned to a single customer. There is no local distance in this case. All one has to do is to improve the line-haul speed or to pick the fastest line-haul route to minimize total cost. For the case where $2 \leq C \leq 7$, local travel cost is relatively small but still cannot be ignored. The delivery pattern does not change—each tour serves half the zone, which has one customer at least—with one or more customers served on the way in and the other half on the way out (see Figure 6.7). The average latitudinal travel between two consecutive points, however, is no longer $w/3$ because of “end effect,” as noted in Newell and Daganzo (1986a). In this case, there are two latitudinal trips of average distance $w/2$, and a number of $C - 2$ latitudinal trips of average distance $w/3$, plus the average cross-over latitudinal trip at the far end of the zone W . Figure 6.7 explains this phenomenon.

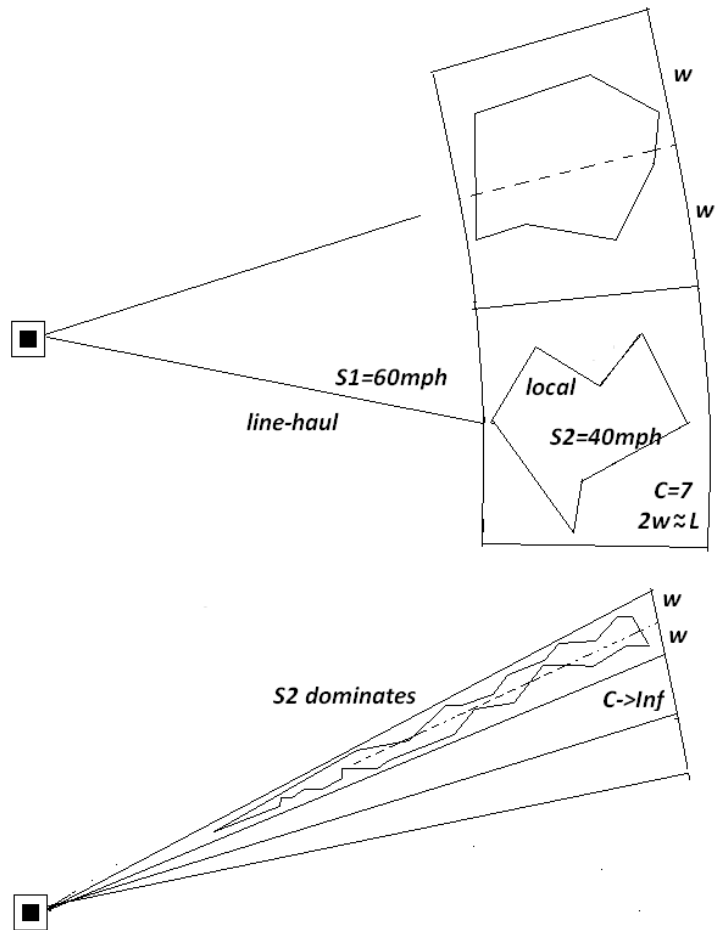


Figure 6.6: Zone Shape Related to Capacity.

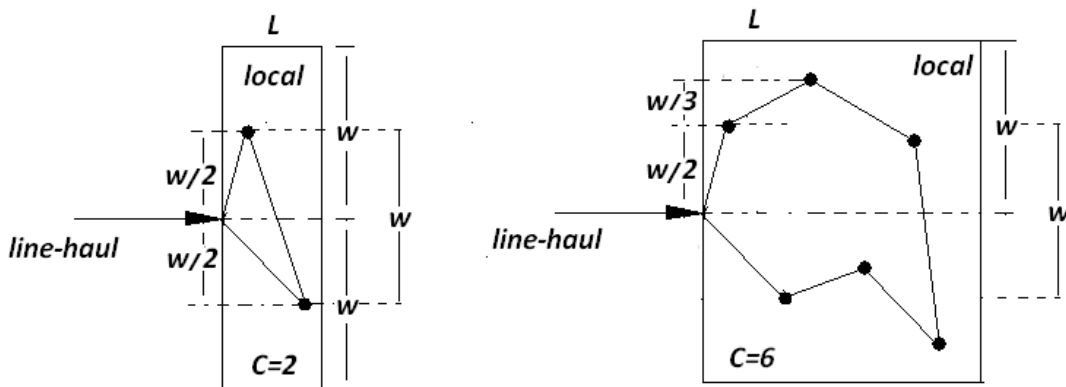


Figure 6.7: "End Effect" for Small C.

The local latitudinal travel distance is thus $2\frac{w}{2} + w + \frac{(C-2)w}{3} = \frac{(C+4)w}{3}$, which is larger than $\frac{Cw}{3}$ by a constant $\frac{4w}{3}$. The smaller C is, the more significant impact that the end effect has on the local travel distance. For example, the local latitude travel from Equation 6.7 is $\frac{Cw}{3} = \frac{2w}{3}$ when $C=2$. The end effect, however, would suggest a value of $\frac{(C+4)w}{3} = 2w$, which is 200 percent larger than estimated in Equation 6.7. Consequently, local travel cost is larger than the estimation. In a case such as $2 \leq C \leq 7$, although the line-haul speed still plays the most important role in determining total cost, local speed cannot be ignored due to the extra cost brought about by the end effect.

In conclusion, improving local speed is generally reliable in reducing overall cost when the vehicle capacity is large enough (for example, able to serve more than seven customers in one trip). A smaller capacity, on the other hand, would suggest improving line-haul speed while the cost from local travel remains competitive.

6.2.3. More Complicated Network

The characteristics of line-haul highways and local roads differ, and travel speed is not the only consideration. Sometimes it is simply impossible to divide the entire service region into multiple delivery zones having the same latitude or longitude direction. This becomes a noticeable problem when local travel occurs on a fully developed grid network instead of using Euclidian distance for two consecutive customers. In Figure 6.8, the service region on the right side (b) shows a circular network with local grid. The left side (a) is a simplified network proposed by Newell and Daganzo (1986a). Obviously, the different speeds of line-haul and local travels are still important factors in such a case. Again, the optimal assignment strategy and zone shapes depend on these speeds because total logistics costs not only relate to mileage-based costs but also time-based costs, particularly fuel costs and driver wages.

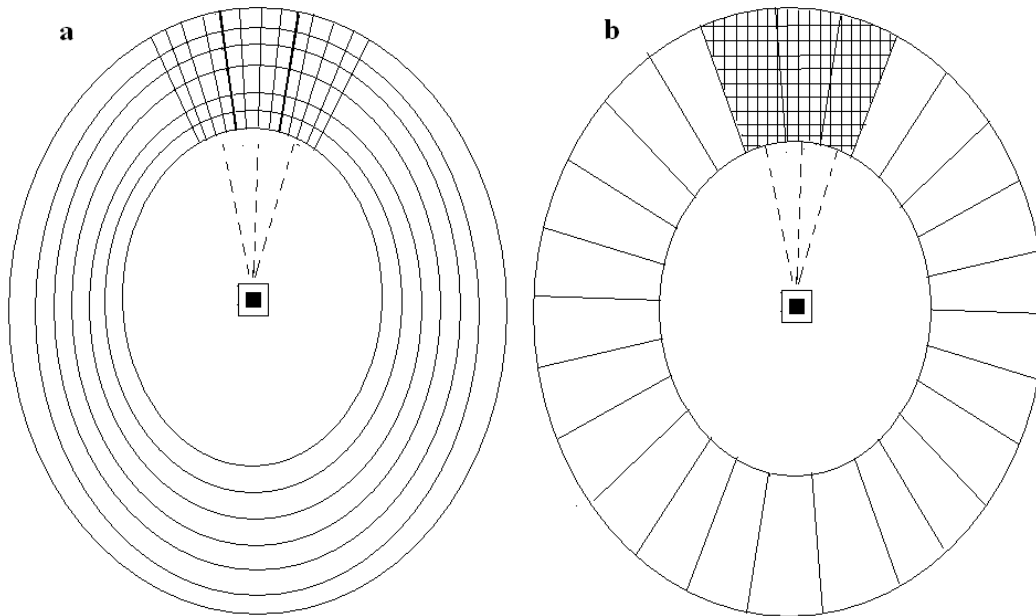


Figure 6.8: Different Characteristics in Local Travel.

Without losing generality, one can pick a random zone that is served by a dedicated vehicle, containing C points/customers as shown in Figure 6.9. Now that local travel is no longer made in Euclidian space, some angle is expected between the grid and the latitude/longitude direction of the zone. Newell and Daganzo (1986b) investigated the general impact of this angle but gave little consideration to the combinational logistics costs. To provide the analysis on the overall costs and the discussion on freight time value for both line-haul (interstate travel) and local delivery (on single-lane, street and more congested roads), it is better keep the above assumptions on the distribution pattern, costs (F_m, F_t) and speeds (S_1, S_2) .

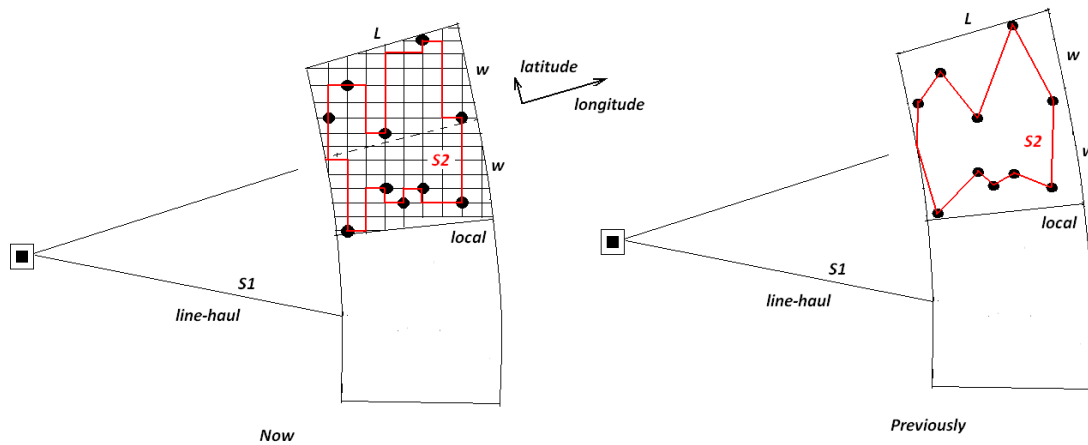


Figure 6.9: The Features of Local Grid Network.

Previously, a two-dimensional random distribution has been defined for customer locations. In each delivery zone that is divided, travel distance between two consecutive points follows a uniform distribution in a latitudinal direction and an exponential distribution (i.e., Poisson arrivals) in a longitudinal direction. These two distributions are independent. One may observe that it is very hard to describe the overall distribution for the entire service region because it includes multiple distribution patterns that are differentiated by the angle between the grid and the latitude/longitude direction of the zone.

One way to address this issue is to define a polar coordinate system in which each point is determined by a distance from the center and an angle from a fixed direction. The longitudinal distance is, therefore, represented by radius and the latitude is expressed as the product of radius and degree. An alternative is to use Cartesian coordinates over the entire service region and then calculate the distribution pattern for each divided zone based on shape and location. This alternative method, although technically feasible, significantly raises the difficulty of analyzing logistics cost for each delivery zone. The reason is that distributions along the latitude and longitude directions in each zone are no longer independent. As a result, the goal of obtaining a simple formula to define total logistics cost is not likely to be achieved, especially when one also needs to gain insight on the trade-off between freight time value and cost. This

should explain the advantage of having a two-dimensional random distribution for customer locations on a polar coordinate system.

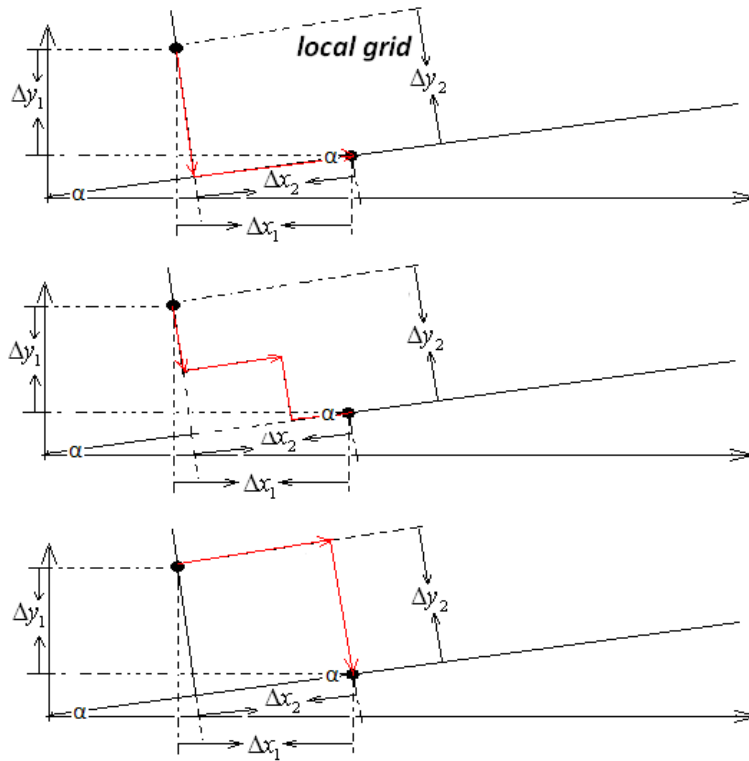


Figure 6.10: Angled Travel in Local Grid.

To verify the divided delivery zones, if one allows an angle α between the grid and the latitude/longitude direction of the zone, travel from point to point no longer follows Euclidean distance or grid distance. Figure 6.10 shows a general picture on how to make trips between each pair of consecutive points. All these travel patterns have the same travel length in both grid directions.

Given the assumed distributions of customer locations:

$$\Delta x_1 = \frac{1}{\delta w} \text{ and } \Delta y_1 = \frac{w}{3} \tag{6.14}$$

Given the angle α , one can derive the expressions for Δx_2 and Δy_2 :

$$\begin{aligned}\Delta x_2 &= \Delta x_1 \cos \alpha - \Delta y_1 \sin \alpha \\ \Delta y_2 &= \Delta x_1 \sin \alpha + \Delta y_1 (\sec \alpha - \tan \alpha \sin \alpha)\end{aligned}\quad (6.15)$$

Therefore, the local distance between two consecutive points is:

$$\begin{aligned}d_2 &= \Delta x_2 + \Delta y_2 \\ &= \Delta x_1 (\sin \alpha + \cos \alpha) + \Delta y_1 (\sec \alpha - \tan \alpha \sin \alpha - \sin \alpha) \\ &= \frac{1}{\delta w} (\sin \alpha + \cos \alpha) + \frac{w}{3} (\sec \alpha - \tan \alpha \sin \alpha - \sin \alpha) \\ &= \frac{1}{\delta w} (\sin \alpha + \cos \alpha) + \frac{w}{3} (\cos \alpha - \sin \alpha)\end{aligned}\quad (6.16)$$

The overall cost per customer considering travel distance and travel time is then:

$$\begin{aligned}I &= \frac{2\bar{\rho} - L}{C} (F_m + \frac{F_t}{S_1}) + (F_m + \frac{F_t}{S_2}) (\frac{\sin \alpha + \cos \alpha}{\delta w} + \frac{w}{3} (\cos \alpha - \sin \alpha)) \\ &= (\frac{2\bar{\rho}}{C} - \frac{1}{2w\delta}) (F_m + \frac{F_t}{S_1}) + (F_m + \frac{F_t}{S_2}) (\frac{\sin \alpha + \cos \alpha}{\delta w} + \frac{w}{3} (\cos \alpha - \sin \alpha))\end{aligned}\quad (6.17)$$

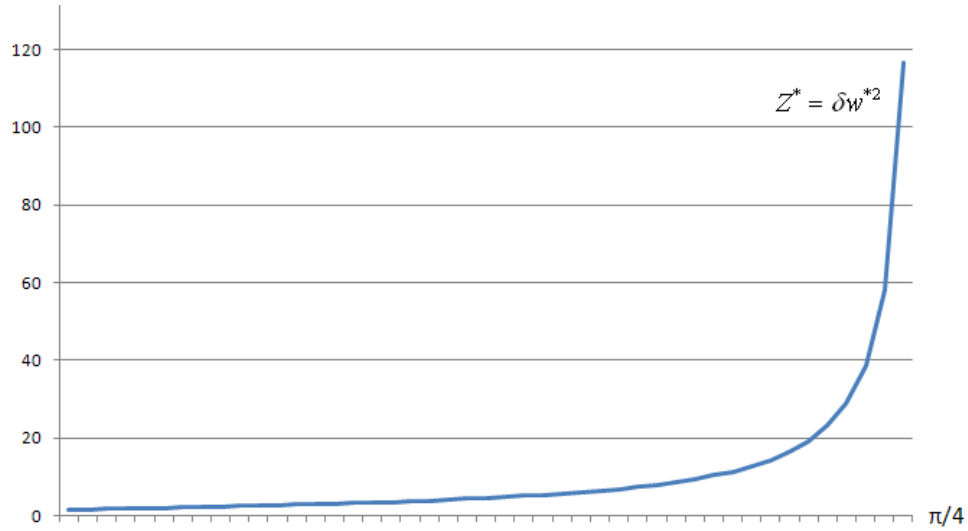
To decide the minimal cost strategy, it is necessary to check:

$$\frac{\partial I}{\partial w} = (F_m + \frac{F_t}{S_2}) \frac{\cos \alpha - \sin \alpha}{3} - \frac{(F_m + \frac{F_t}{S_2})(\sin \alpha + \cos \alpha) - 0.5(F_m + \frac{F_t}{S_1})}{\delta w^2} = 0 \quad (6.18)$$

The optimal w^* is then decided to be:

$$w^* = \sqrt{\frac{3(F_m + \frac{F_t}{S_2})(\sin \alpha + \cos \alpha) - 1.5(F_m + \frac{F_t}{S_1})}{\delta(F_m + \frac{F_t}{S_2})(\cos \alpha - \sin \alpha)}} \quad (6.19)$$

Obviously, optimal width is significantly affected by the angle α between the grid and latitude/longitude directions of the zone. Due to the symmetric feature of α , it is sufficient to consider $[0, \pi/4]$ as 1/8 of the entire circular area $[0, 2\pi]$. Again, one would like to check the behavior of this optimal width subject to the changes in α . Figure 6.11 shows the optimal width in terms of $Z^* = \delta w^{*2}$, which is dimensionless with point density δ being a constant.



**Figure 6.11: Behavior of $Z^* = \delta w^{*2}$
($F_m = \$1/\text{mile}$, $F_t = \$15/\text{hr}$, $S_1 = 60\text{mph}$, $S_2 = 40\text{mph}$)**

6.2.3.1. Radius network $\alpha = 0$

At $\alpha = 0$, the optimal width for each delivery zone is:

$$w^* = \sqrt{\frac{3(F_m + \frac{F_t}{S_2}) - 1.5(F_m + \frac{F_t}{S_1})}{\delta(F_m + \frac{F_t}{S_2})}} \quad (6.20)$$

For the case of ring-radial network, as shown in Figure 6.8 (left side), every delivery zone on the same concentric ring follows this optimal width shown in Equation 6.20 because the angle α is always zero. One would expect the entire region to be divided into several rings and a total of N/C zones with each being approximately rectangular in shape and elongated toward the central depot.

The total optimal logistics cost I_{zone}^* for each delivery zone is then:

$$\begin{aligned}
 I_{zone}^* &= I(w^*)C \\
 &= C(F_m + \frac{F_t}{S_1}) \left(\frac{2\bar{\rho}}{C} - \sqrt{\frac{(F_m + \frac{F_t}{S_2})}{12\delta(F_m + \frac{F_t}{S_2}) - 6\delta(F_m + \frac{F_t}{S_1})}} \right) + \\
 &C(F_m + \frac{F_t}{S_2}) \left(\sqrt{\frac{(F_m + \frac{F_t}{S_2})}{3\delta(F_m + \frac{F_t}{S_2}) - 1.5\delta(F_m + \frac{F_t}{S_1})}} + \sqrt{\frac{(F_m + \frac{F_t}{S_2}) - 0.5(F_m + \frac{F_t}{S_1})}{3\delta(F_m + \frac{F_t}{S_2})}} \right)
 \end{aligned} \tag{6.21}$$

where $I(w^*)$ is the cost per customer in Equation 6.17 subject to optimal zone width w^* in Equation 6.20.

Equation 6.21 not only shows total optimal logistics cost for each zone having C stops or customers, but also shows the possibility of investigating the influence of travel speed and travel time. As previously stated, S_1 and S_2 represent line-haul speed and local speed respectively ($S_1 > S_2$). Ideally, one should take derivatives of I_{zone}^* with S_1 and S_2 to see the benefit of improving line-haul and local speeds in general. However, realistic travel speeds usually come within a certain range. For example, one may find in Texas that line-haul speed is about 60 mph and local is about 40 mph for off-peak hours. Operating in peak hours would suggest speeds that are much lower than off-peak. Therefore, it is much easier and convenient to check the speed influences around these representative values instead of a theoretical expression on an arbitrary value.

Table 6.1 shows an example where the total optimal logistics cost varies with the line-haul and local speeds (as usual $F_m = \$1/\text{mile}$, $F_t = \$15/\text{hr}$); in each scenario, the delivery strategy is configured as optimal.

Table 6.1: An Example of Cost Subjected to Speed Changes

	$w^* =$	$I_{zone}^* =$
<i>Base Scenario:</i> $S_1=60$ mph, $S_2=40$ mph	$\frac{1.279}{\sqrt{\delta}}$	$2.5\bar{\rho} + \frac{1.173C}{\sqrt{\delta}}$
<i>Improve Line Haul:</i> $S_1=70$ mph, $S_2=40$ mph	$\frac{1.294}{\sqrt{\delta}}$	$2.429\bar{\rho} + \frac{1.186C}{\sqrt{\delta}}$
<i>Improve Local:</i> $S_1=60$ mph, $S_2=50$ mph	$\frac{1.248}{\sqrt{\delta}}$	$2.5\bar{\rho} + \frac{1.082C}{\sqrt{\delta}}$

Table 6.1 shows that optimal width does not change much when different speeds are considered in practical cases. This is expected and intuitive because one can use this property to build concentric rings for the entire region. Similar results are shown in Figure 6.4, where local grid is not considered. As previously explained, a polar coordinate system is preferred in this case. Although the density gradually increases when the delivery zone gets closer to the depot ($\delta(r) \propto \frac{1}{r}$), for each ring having optimal length $L^* = \frac{C}{2w^*\delta}$, density can be approximately seen as a constant (e.g., the average over a small radius interval or the density at the midpoint of the radius interval). Because customers are plotted as having identical random distributions along every polar axis (isotropy, meaning for all directional rays), it is easy to find that the expected distance from the depot to a random point in the concentric ring is equal to the maximum radius R of the ring minus half the length of the delivery zone L :

$$\bar{\rho} = R - \frac{L^*}{2} = R - \frac{C}{4w^*\delta} \quad (6.22)$$

Substituting $\bar{\rho}$ with Equation 6.20, Table 6.2 compares the benefit that can be obtained from speed improvements.

Table 6.2: Comparison of Benefits

<i>Improve Speed by 10mph:</i>	<i>Line-Haul</i>	<i>Local</i>
<i>Benefit:</i>	$0.071R - \frac{0.033C}{\sqrt{\delta}}$	$\frac{0.103C}{\sqrt{\delta}}$

Table 6.2 shows the difference between the two costs before and after the speed changes subject to optimal delivery strategies. If the strategies are not adaptive to the speed improvements or not tuned to the optimal, benefits would be diminished. To decide which speed is more important when it comes to the cost, one has to check the difference Δ between these two benefits:

$$\Delta = 0.071R - \frac{0.033C}{\sqrt{\delta}} - \frac{0.103C}{\sqrt{\delta}} = 0.071R - \frac{0.136C}{\sqrt{\delta}} \quad (6.23)$$

The capacity threshold is, therefore, $C_0 = 0.522R\sqrt{\delta}$. If the vehicles, in this case trucks, have capacities greater than this value, importance of local speed would dominate that of line-haul speed. Such an instance would suggest improving local speed because these vehicles spend the majority of their travel time on the local grid network. On the other hand, if the capacities of the vehicles are smaller than the threshold, it is more beneficial to improve highway speeds because these vehicles spend most of their time traveling back and forth in line-haul travel.

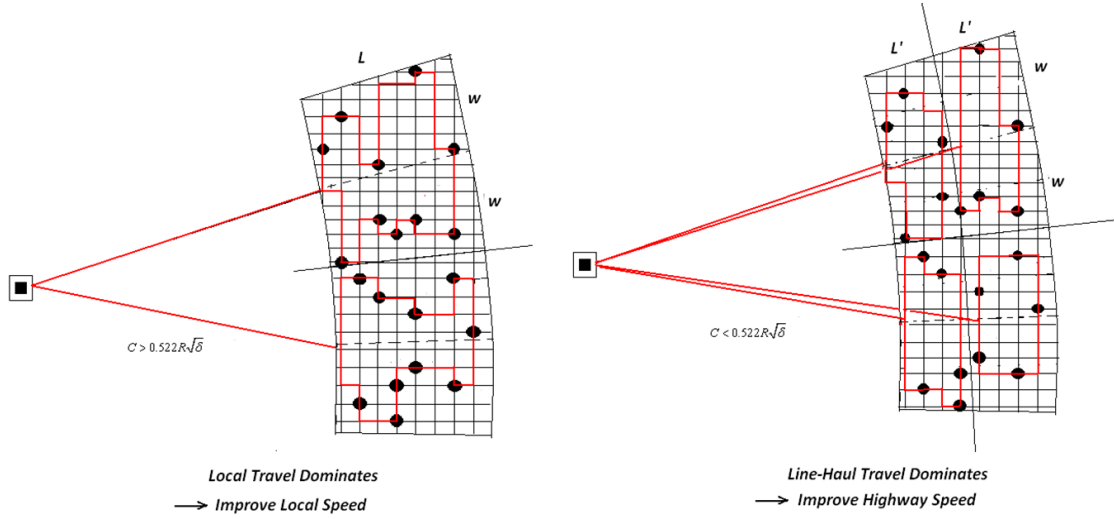


Figure 6.12: The Impact of Capacities when Serving the Same Area.

Figure 6.12 illustrates this trade-off. The left side shows an example when $C_0 > 0.522R\sqrt{\delta}$, while the right side shows an example when $C_0 < 0.522R\sqrt{\delta}$. From Figure 6.12 demonstrates that to serve the same area, capacity makes a significant difference in line-haul travel (in terms of distance, fuel, and travel time). For different rings, the densities are slightly different because $\delta(r) \propto \frac{1}{r}$ in the polar coordinate system is assumed. Therefore, the capacity threshold increases when the ring is placed farther from the center (having a larger R):

$$\begin{aligned}
 C_0 &= 0.522R\sqrt{\delta} \\
 &\propto 0.522R \frac{1}{\sqrt{R}} \\
 &\propto \sqrt{R}
 \end{aligned} \tag{6.24}$$

For any vehicle having a fixed capacity, the threshold C_0 would eventually exceed the maximum capacity of each vehicle when the delivery zone is far enough from the center. The relative importance of line-haul and local speeds is altered accordingly. Therefore, to investigate speed influences for the entire circular region, one has to consider every concentric ring starting from the center to the farthest edge of the region. This concept was previously introduced in the discussion of calculating expected

distance from the depot to a random point in the concentric ring (Equation 6.20). By adding up the costs of serving all these concentric rings, one should be able to conduct a similar analysis on speed influences, as shown in Tables 6.1 and 6.2. Figure 6.13 shows the general idea of this process. The following sections discuss how to divide these rings and how to refine delivery zones in each ring.

If starting from the farthest ring, N_4^{zone} is the number of the delivery zones in ring 4:

$$N_4^{zone} = \frac{2\pi R_4}{2w_4^*} = \frac{\pi R_4 \sqrt{\delta_4(F_m + \frac{F_t}{S_2})}}{\sqrt{3(F_m + \frac{F_t}{S_2}) - 1.5(F_m + \frac{F_t}{S_1})}} \quad (6.25)$$

Due to the integer property of N_4^{zone} , Equation 6.21 needs to be rounded up in case of a fractional number. The number of the delivery zones in ring 4 is therefore:

$$N_4^{zone} = \left\lceil \frac{\pi R_4 \sqrt{\delta_4(F_m + \frac{F_t}{S_2})}}{\sqrt{3(F_m + \frac{F_t}{S_2}) - 1.5(F_m + \frac{F_t}{S_1})}} \right\rceil \quad (6.26)$$

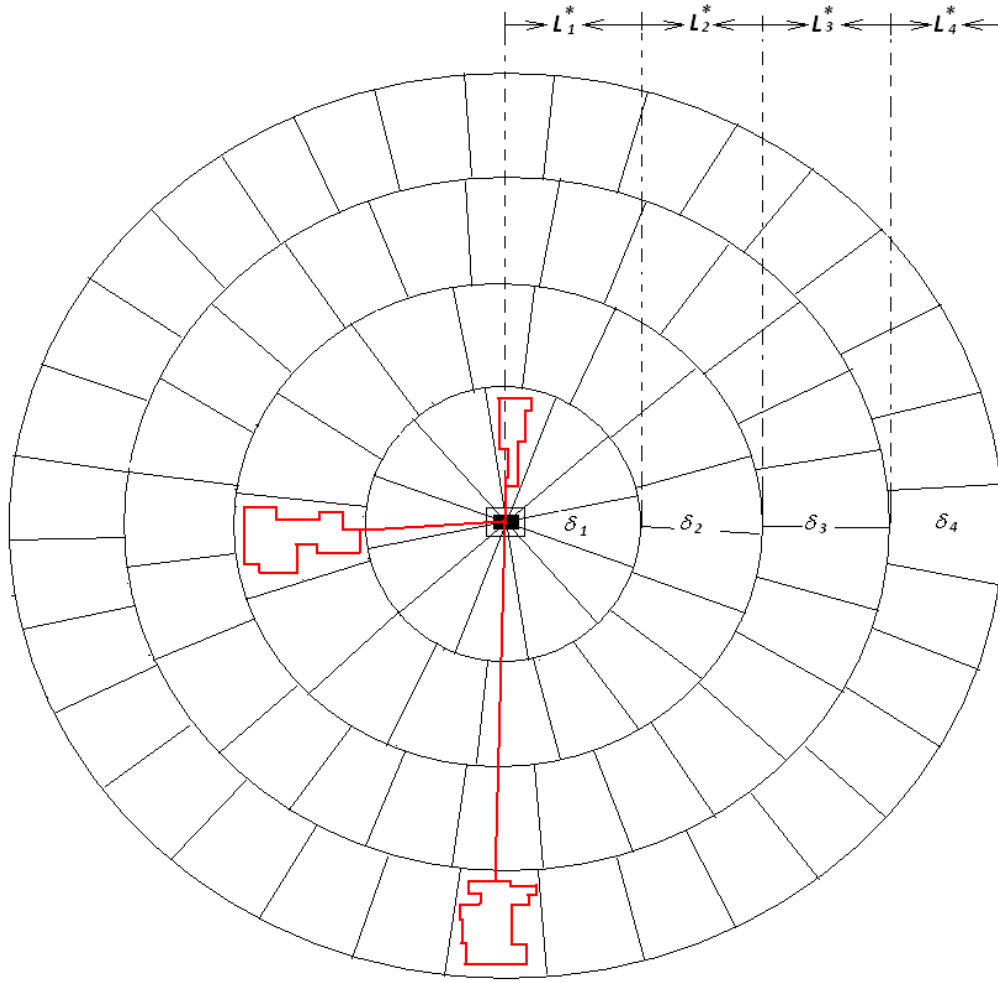


Figure 6.13: Different Rings with Different Delivery Strategies.

The actual half zone width w_4 needs to be adjusted to satisfy the integer constraint on the number of delivery zones:

$$w_4 = \frac{\pi R_4}{N_4^{zone}} = \pi R_4 / \left| \frac{\pi R_4 \sqrt{\delta_4 \left(F_m + \frac{F_t}{S_2}\right)}}{\sqrt{3\left(F_m + \frac{F_t}{S_2}\right) - 1.5\left(F_m + \frac{F_t}{S_1}\right)}} \right| \quad (6.27)$$

The actual length L_4 is:

$$L_4 = \frac{C}{2w_4\delta_4} = C \left| \frac{\pi R_4 \sqrt{\delta_4 (F_m + \frac{F_t}{S_2})}}{\sqrt{3(F_m + \frac{F_t}{S_2}) - 1.5(F_m + \frac{F_t}{S_1})}} \right| / (2\pi R_4 \delta_4) \quad (6.28)$$

For a typical case where $F_m = \$1/\text{mile}$, $F_t = \$15/\text{hr}$, $S_1 = 60 \text{ mph}$ and $S_2 = 40 \text{ mph}$, these values are:

$$\begin{cases} N_4^{zone} = \lceil 2.456 R_4 \sqrt{\delta_4} \rceil \\ w_4 = \pi R_4 / \lceil 2.456 R_4 \sqrt{\delta_4} \rceil \\ L_4 = C \lceil 2.456 R_4 \sqrt{\delta_4} \rceil / (2\pi R_4 \delta_4) \end{cases} \quad (6.29)$$

Repeating this process with Equations 6.25 and 6.26 should complete dividing the entire region into optimal concentric rings subject to different line-haul and local speeds. The central area adjacent to the depot may need further adjustment but it should not significantly affect the result due to its small size.

$$R_3 = R_4 - L_4 \quad (6.30)$$

6.2.3.2. Grid network $0 < \alpha < \pi/4$

When the angle α between the grid and the latitude/longitude direction of the zone is positive, Equation 6.20 and 6.21 are no longer valid. Optimal logistics costs needed to visit a customer are now:

$$\begin{aligned}
I^* = & \left(\frac{2\rho}{C} - \sqrt{\frac{(F_m + \frac{F_t}{S_2})(\cos \alpha - \sin \alpha)}{12\delta(F_m + \frac{F_t}{S_2})(\sin \alpha + \cos \alpha) - 6\delta(F_m + \frac{F_t}{S_1})}} \right) (F_m + \frac{F_t}{S_1}) \\
& + (F_m + \frac{F_t}{S_2})(\sin \alpha + \cos \alpha) \sqrt{\frac{(F_m + \frac{F_t}{S_2})(\cos \alpha - \sin \alpha)}{3\delta(F_m + \frac{F_t}{S_2})(\sin \alpha + \cos \alpha) - 1.5\delta(F_m + \frac{F_t}{S_1})}} \\
& + \sqrt{\frac{(F_m + \frac{F_t}{S_2})(\sin \alpha + \cos \alpha)(\cos \alpha - \sin \alpha) - 1.5(F_m + \frac{F_t}{S_1})(\cos \alpha - \sin \alpha)}{3\delta(F_m + \frac{F_t}{S_2})}}
\end{aligned} \tag{6.31}$$

Notice that now the logistics costs for the zone depend on angle α . This is because the local distance required to visit each customer varies with α , which creates changes in the LTL vehicle tour construction and associated cost. Recall in Equation 6.19 and Figure 6.11 that the optimal zone width increased significantly when the zone was placed closer to the direction having an angle of $\pi/4$ (between zone direction and the local grid). This would not only affect the relative importance of line-haul and local speeds, but also make it almost impossible to form rings because of the varying zone shapes on the same radius. Figure 6.14 shows this concern.

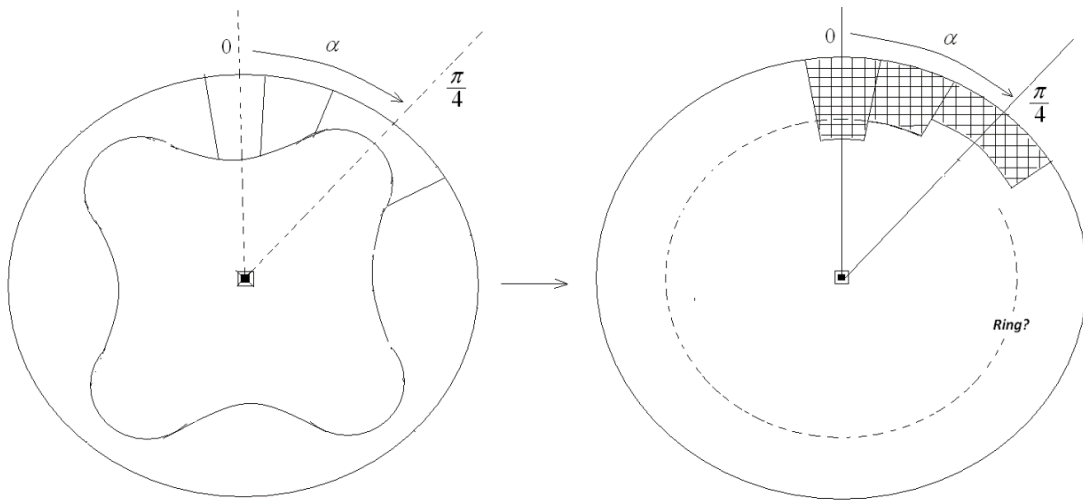


Figure 6.14: Zone Distribution with the Angle Effect.

To prevent this problem from getting over complicated, it would be better to find a compromise width (or length) that is not necessarily the least cost but is independent of the angle (zone direction). To accomplish this purpose, the summation on all delivery zones in $(0, \pi/4)$ must be considered. Define the total logistics costs over a ring in direction $(0, 2\pi)$ as I_{ring} . Due to the symmetric property, this is simply eight times the sum covering direction $(0, \pi/4)$. Since one should look for the best compromise width (or length) over all directions, $\bar{\rho}$ (the expected distance from the depot to a random point in the concentric ring) needs not be changed with the direction of the zone.

Similarly, the density is assumed to be fixed at the midpoint of the zone (ring) length:

$$\begin{aligned}
I_{ring} &= 8 \int_0^{\pi/4} CI(\alpha) d\alpha \\
&= 8C \left\{ \int_0^{\pi/4} \frac{2\bar{\rho} - L}{C} (F_m + \frac{F_t}{S_1}) d\alpha + (F_m + \frac{F_t}{S_2}) \left(\frac{\sin \alpha + \cos \alpha}{\delta w} + \frac{w}{3} (\cos \alpha - \sin \alpha) \right) d\alpha \right\} \\
&= 8C \left\{ \int_0^{\pi/4} \left(\frac{2R}{C} - \frac{1}{w\delta} \right) (F_m + \frac{F_t}{S_1}) d\alpha + (F_m + \frac{F_t}{S_2}) \left(\frac{\sin \alpha + \cos \alpha}{\delta w} + \frac{w}{3} (\cos \alpha - \sin \alpha) \right) d\alpha \right\} \\
&= 2\pi C \left(\frac{2R}{C} - \frac{1}{w\delta} \right) (F_m + \frac{F_t}{S_1}) + 8C (F_m + \frac{F_t}{S_2}) \left(\frac{\sin \alpha - \cos \alpha}{w\delta} \Big|_0^{\pi/4} + \frac{w}{3} (\sin \alpha + \cos \alpha) \Big|_0^{\pi/4} \right) \\
&= 2\pi C \left(\frac{2R}{C} - \frac{1}{w\delta} \right) (F_m + \frac{F_t}{S_1}) + 8C (F_m + \frac{F_t}{S_2}) \left(\frac{1}{w\delta} + \frac{w(\sqrt{2}-1)}{3} \right) \\
&= 4\pi R (F_m + \frac{F_t}{S_1}) + \left\{ (8-2\pi)F_m + \left(\frac{8}{S_2} - \frac{2\pi}{S_1} \right) F_t \right\} \frac{C}{w\delta} + 8(F_m + \frac{F_t}{S_2}) \frac{(\sqrt{2}-1)}{3} wC
\end{aligned} \tag{6.32}$$

Equation 6.32 is minimized with first-order condition such that:

$$\begin{cases} 8(F_m + \frac{F_t}{S_2}) \frac{(\sqrt{2}-1)}{3} - \left\{ (8-2\pi)F_m + \left(\frac{8}{S_2} - \frac{2\pi}{S_1} \right) F_t \right\} \frac{1}{w^2\delta} = 0 \\ S_1 S_2 (4-\pi) F_m + (4S_1 - \pi S_2) F_t > 0 \end{cases} \tag{6.33}$$

or

$$\begin{cases} w \rightarrow 0 \\ S_1 S_2 (4-\pi) F_m + (4S_1 - \pi S_2) F_t \leq 0 \end{cases} \tag{6.34}$$

Under the assumption that line-haul speed is greater than local speed (which means $S_1 > S_2$), Equation 6.33 should always hold. In fact, it is sufficient to have $S_1/S_2 > \pi/4$ because highway speed can sometimes be less than local speed due to congestion. To carefully examine the case where $S_1 \leq S_2$, it is possible to enumerate all the speed combinations as in Table 6.3. By using the representative cost rate ($F_m = \$1/\text{mile}$, $F_t = \$15/\text{hr}$), one can observe that $S_1 S_2 (4 - \pi) F_m + (4 S_1 - \pi S_2) F_t > 0$ is always true regardless of the speed combinations, with only two exceptions—when the line-haul speed is much less than local speed, shown as a negative speed in two instances as per Table 6.3. Therefore, it is reasonable to believe the first-order condition should always be considered in a general case. The corresponding optimal width for the compromise ring is derived as:

$$w^* = \sqrt{\frac{(4 - \pi) F_m + \left(\frac{4}{S_2} - \frac{\pi}{S_1}\right) F_t}{4 \delta \left(F_m + \frac{F_t}{S_2}\right) \frac{(\sqrt{2} - 1)}{3}}} \quad (6.35)$$

Table 6.3: Validation on First-Order Condition

$S_1 S_2 (4 - \pi) F_m + (4 S_1 - \pi S_2) F_t$		<i>Line-Haul Speed</i>						
		20 mph	30 mph	40 mph	50 mph	60 mph	70 mph	80 mph
<i>Local Speed</i>	10 mph	900	1586	2272	2958	3644	4330	5015
	20 mph	601	1373	2144	2916	3688	4459	5231
	30 mph	301	1159	2016	2874	3731	4589	5446
	40 mph	2	945	1888	2832	3775	4719	5662
	50 mph	<u>-298</u>	731	1761	2790	3819	4848	5877
	60 mph	<u>-597</u>	518	1633	2748	3863	4978	6093

In the case where speed and hourly cost are not considered, one can simply set $F_t = 0$ and neglect S_1 and S_2 . Equation 6.35 reduces to $w^* = \sqrt{\frac{3(4-\pi)}{4\delta(\sqrt{2}-1)}} \approx 1.25 / \delta^{0.5}$, which is relatively smaller when compared with optimal width without angle effect (Equation 6.12, $w^* \approx 1.34 / \delta^{1/2}$). Due to the fact that $\delta(r)$ increases toward the center, the optimal zone w^* for the ring near the center would be smaller as well.

Inserting Equation 6.35 into Equation 6.32 would give the compromise total logistics costs over the ring in direction $(0, 2\pi)$, which is also the least costly solution one can obtain from the previously defined delivery strategy:

$$I_{ring}^* = 4\pi R(F_m + \frac{F_t}{S_1}) + C \sqrt{\frac{32(\sqrt{2}-1)}{3\delta} (F_m + \frac{F_t}{S_2}) [(8-2\pi)F_m + (\frac{8}{S_2} - \frac{2\pi}{S_1})F_t]} \quad (6.36)$$

Taking the partial derivatives of S_1 and S_2 verifies speed influence on the ring:

$$\frac{\partial I_{ring}^*}{\partial S_1} = -\frac{\pi F_t}{S_1^2} (4R - C \sqrt{\frac{32(\sqrt{2}-1)}{3\delta} (F_m + \frac{F_t}{S_2}) [(8-2\pi)F_m + (\frac{8}{S_2} - \frac{2\pi}{S_1})F_t]}) \quad (6.37)$$

$$\frac{\partial I_{ring}^*}{\partial S_2} = -C \left[\frac{(8-\pi)F_t F_m}{S_2^2} + (\frac{8}{S_2} - \frac{\pi}{S_1}) \frac{F_t^2}{S_2^2} \right] \sqrt{\frac{32(\sqrt{2}-1)}{3\delta (F_m + \frac{F_t}{S_2}) [(8-2\pi)F_m + (\frac{8}{S_2} - \frac{2\pi}{S_1})F_t]}} \quad (6.38)$$

6.3. Case Study

While theoretical derivation is capable of showing the relative influence of line-haul and local speeds on total logistics cost, one may wish to eventually see the time value in a real-world case. To serve this purpose, this section presents a case study based on Brenham Wholesale Grocery Co. (BWG). Before starting the BWG case study, about 30 managers in different companies are contacted around College Station, Texas. None of these companies agreed to take the interview except the logistic manager at BWG,

who was particularly interested in supporting the study because he is an alumnus of Texas A&M University.

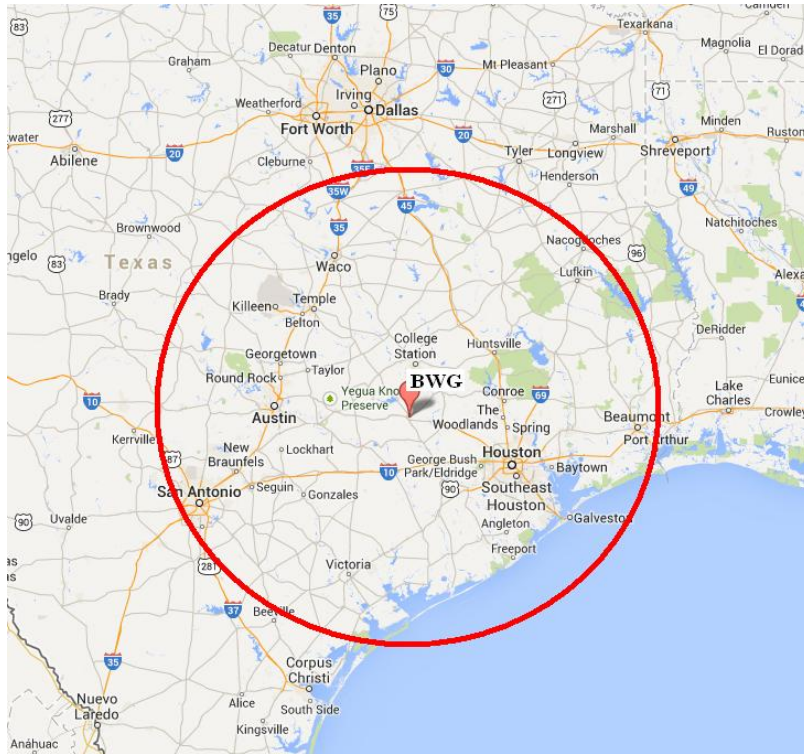


Figure 6.15: BWG Service Region.

BWG is a distribution company that delivers over 17,000 grocery items such as candy, drinks, and beauty products to nearby customers. The company has its own fleet consisting of about 32 drivers with 28 trucks with a delivery radius of 250 miles (see Figure 6.15).

At the time of surveying, the company had about 1,000 customers including convenience stores, supermarkets, meat markets, restaurants, schools, and hospitals. According to an interview with BWG’s logistics manager, the company’s cost of hiring drivers and operating vehicles was typical: \$15 per hour for the driver and about \$1 per mile for fuel. The major corridors and crossing highways within the service region have a speed limit of 50–70 mph (averaged at 60 mph). The speed for local roads and streets ranges from 20–40 mph (averaged at 30 mph). For customers such as convenience stores,

restaurants, or hospitals, each truck was capable of delivering items for 5–15 customers per tour (a capacity averaged at $C = 10$). Although there were some truckload deliveries for supermarkets and other bigger customers, bigger-store tours were rare.

To check the speed influence for the entire delivery region and the associated value of time, one needed to determine the optimal strategy for making deliveries first.

Since $\delta(r) \propto \frac{1}{r}$ and $N = \int_0^R \delta(r) 2\pi r dr$, the density function was determined to be:

$$\delta(r) = \frac{N}{2\pi r R} \quad \text{where } N = 1000, R = 250 \quad (6.39)$$

Based on Equation 2.35:

$$w^* = \sqrt{\frac{(4 - \pi)F_m + (\frac{4}{S_2} - \frac{\pi}{S_1})F_t}{\frac{2N}{\pi r R} (F_m + \frac{F_t}{S_2}) \frac{(\sqrt{2} - 1)}{3}}} \quad (6.40)$$

For the first ring $r = R$, the optimal width w^* is calculated to be:

$$w^* = \sqrt{\frac{(4 - \pi)F_m + (\frac{4}{S_2} - \frac{\pi}{S_1})F_t}{\frac{2N}{\pi R^2} (F_m + \frac{F_t}{S_2}) \frac{(\sqrt{2} - 1)}{3}}} = \sqrt{\frac{(4 - \pi) + 15(\frac{4}{30} - \frac{\pi}{60})}{\frac{2000}{\pi 250^2} (1.5) \frac{(\sqrt{2} - 1)}{3}}} = 31.35 \quad (6.41)$$

From Equation 2.25, one had integer number of zones on this ring:

$$N_1^{zone} = \left\lceil \frac{2\pi r}{2w^*} \right\rceil = \lceil 25.054 \rceil \approx 26 \quad (6.42)$$

Consequently, it is calculated that:

$$w_1 = \frac{\pi r}{N_1^{zone}} = 30.21 \quad (6.43)$$

$$L_1 = \frac{C\pi r}{4w_1} = 65.00$$

Similarly, one should be able to repeat the process for adjacent rings, starting from the second ring $r = R - L_1$. Table 6.4 summarizes the completed optimal delivery strategy. Ring 5 was modified because there were 100 zones in total ($N = 1,000$ and

$C = 10$) and the zone length needed to be smaller or equal to the available radius. This usually happened on the very last ring which contained the central depot. In such a ring, all the travels are made locally. Symbols $\partial I_{ring}^* / \partial S_1$ and $\partial I_{ring}^* / \partial S_2$ show the speed influence on each ring (Equations 6.37 and 6.38). This can be seen as a cost saving for marginal speed improvements at the current travel speed. Based on Equation 6.32, the last two rows provide the distances traveled on highways (interstate) and locally for each ring. Column Σ shows the summation of costs and mileages over the entire region.

Table 6.4: Optimal Delivery Strategy

	1 st Ring	2 nd Ring	3 rd Ring	4 th Ring	5 th Ring	5 th Ring modified	Σ
r (mile)	250.0	185.0	130.0	82.5	45.0	45.0	/
N^{zone}	26	22	19	15	20	18	/
W (mile)	30.2	26.4	21.5	17.3	9.3	37.5	/
L (mile)	65.0	55	47.5	37.5	50.0	45.0	/
$\partial I_{ring}^* / \partial S_1$ (\$)	9.8	6.9	4.4	2.4	/	0	23.6
$\partial I_{ring}^* / \partial S_2$ (\$)	31.2	26.8	22.5	17.9	/	23.6	122.1
$D_{line-haul}$ (mile)	2324.8	1633.6	1036.7	565.5	/	0	5560.6
D_{local} (mile)	1373.6	1171.8	997.4	790.9	/	834.4	5168.1

Table 6.5 calculates the value of time in terms of hourly cost. Let $T_{line-haul}$ denote the total travel time spent on line-haul and T_{local} denote the total travel time spent on local:

$$\begin{aligned}
 T_{line-haul} &= \sum D_{line-haul} / S_1 \\
 T_{local} &= \sum D_{local} / S_2
 \end{aligned}
 \tag{6.44}$$

Let $\Delta I_{line-haul}^{region}$ and $\Delta I_{local}^{region}$ denote the extra logistics cost when the average line-haul or local speed is reduced by 1 mile per hour, respectively:

$$\begin{aligned}\Delta I_{line-haul}^{region} &= \sum \partial I_{ring}^* / \partial S_1 \\ \Delta I_{local}^{region} &= \sum \partial I_{ring}^* / \partial S_2\end{aligned}\tag{6.45}$$

The value of time by definition is therefore:

$$\begin{aligned}VOT_{line-haul} &= \Delta I_{line-haul}^{region} / \Delta T \\ VOT_{local} &= \Delta I_{local}^{region} / \Delta T\end{aligned}\tag{6.46}$$

where ΔT is the difference in travel time when the speed is reduced.

Table 6.5: Value of Time of Case Study

	S (mph)	T (hour)	S' (mph)	T' (hour)	ΔT (hour)	ΔI (\$)	$\Delta I / \Delta T$ (\$/hr)
Line-haul	60	92.7	61	91.2	1.5	23.6	15.5
Local	30	172.3	31	166.7	5.6	122.1	22.0

Table 6.5 shows calculated VOT to be \$15.5/hr for line-haul travel (e.g., highways), and \$22.0/hr for local deliveries (e.g., on local roads or streets). These VOT calculations are low because the model does not consider time windows, which means there is no penalty for the late deliveries.

This case study is based on the “then-current” business coverage of BWG and the underlying transportation network within the delivery region. If either changes due to business expansion or traffic-related issues, the number must be recalculated. For now, it appears that local travel has a greater VOT. Although this study has its limitations and cannot represent all the logistic entities, its operation of a 250-mile radius can be used for companies having similar operations.

6.4. Chapter Summary

This chapter discussed a method to efficiently construct LTL delivery routes in a freight network with radial highways and grid local facilities. This type of network combination represents a realistic transportation system common in developed countries, especially around major cities. The advantage of the method discussed, rather than a simulation or a software package, is that it requires no detailed schedule. Without consideration of urgent or time-windowed deliveries, this method is capable of formulating and predicting the time and distance traveled by fleets of vehicles making less-than-truckload deliveries without time windows. The overall logistics cost can be modeled easily to gain insights on the freight value of time. The analytical solution should not differ much from exact delivery strategies in the real world, as the large number of randomly distributed points nullifies individual differences between zones and customers. Therefore, it has great application potential for large distribution companies.

This study found that different line-haul and local speeds have a significant impact on the optimal delivery plan. First of all, it is rare to have a network with the same travel speed everywhere. Typically, local speed would be much lower than line-haul speed unless there is severe highway congestion on major corridors. Second, different service regions would have local and line-haul speeds averaged at different miles per hour depending on the location and delivery time. If the fleet is planning to travel during peak hours, the tour construction should be significantly different than if traveling at night because the combination of line-haul and local speeds determines the optimal zone shape and the least-cost strategy.

Intuitively and analytically, the cost for the line-haul portion of deliveries decreases with vehicle customer capacity, which is the maximum number of customers each vehicle can serve in a single tour. The improvement or change in line-haul speed has less impact on overall logistics cost when vehicle capacity is relatively larger (compared to customer need), while the improvement in local speed would significantly reduce overall cost.

The BWG case study analyzes freight distribution for Brenham Wholesale Grocery Co. based on the operational data collected from a face-to-face interview with its dispatching manager. To serve about 1,000 customers over a 250-mile delivery radius, the model estimates a total of 5,561 miles (90 hours) to be put on line-haul travel and 5,168 miles (170 hours) to be local on a weekly basis, which is very close to the current operation. By considering fuel and driver salaries as fleet operating costs, the result from the case study shows that the value of time is calculated to be \$15.5/hr for line-haul travel and \$22.0/hr for local deliveries, which are low values because time windows and urgent deliveries are not considered in the model. Another limitation of this work is that it only deals with overall speed changes instead of congestion on a single segment.

Future work should include consideration of urgent deliveries, inventory and production costs for manufacturers, warehouses, and other supply chain components. In addition, the problem of having multiple sources instead of a single depot needs to be addressed. This study only shows one-to-many (one depot to multiple customers) distribution while there are many-to-one and many-to-many distributions to be studied for a complete perspective. Nevertheless, the contribution of including travel time and speed parameters in a complex distribution network should remain essential when examining freight value of time.

CHAPTER VII

CONCLUSION AND FUTURE RESEARCH

This dissertation examined several aspects of the value of time in the trucking industry. Most VOT studies have focused on commuters, with applications primarily dealing with peak-hour traffic. In contrast, there is sparse literature about commercial VOT. In both types of studies, VOT is usually based on perceived values from drivers. Regarding commercial vehicle operations, little research on VOT has been conducted for shippers and carriers, which is partially attributed to the complexity of the supply chain and the diverse impact of freight delay on the shipping business. There are numerous factors affecting freight VOT, such as the labor and fuel cost, value of goods, schedule characteristics, traffic conditions, product perishability, and warehousing operations.

To approach freight VOT from a commercial framework, this study developed methodologies that provide insight into how carriers perceive vehicle VOT in fleet operations. In addition to a traditional approach to studying transportation economics, which is usually through stated preference surveys, three new methods were used in this study—all of which were presented from different perspectives (fleet vehicle, driver, and commodity) to look into the value of time and delay. Table 7.1 summarizes this work.

Table 7.1: Summary of the Study

Chapter Number	Value of Time Element	Method	Assumption	VOT Estimate (in 2013 dollars)
III	Truck Driver	Stated Preference	Urgent Trip	\$54.98/hr
IV	Fleet	Fleet Simulation	Time Window	\$93.99/hr
V	Commodity	Inventory Management	No Time Window	\$7.24/hr
VI	Fleet	Continuous Approximation	No Time Window	\$15.50/hr

Chapter III investigated the truck driver's VOT through face-to-face trucker surveys. From the data collected at truck stops around major cities in Texas and Wisconsin, overall trucker-perceived VOT on an urgent trip is estimated to be \$54.98 per vehicle per hour. Chapter IV developed a scenario-based fleet simulation framework to gauge the trade-off between highway delay and cost. Scenarios were generated to represent situations where two of the most congested highway segments in Houston were simulated with time constraints. The result shows vehicle VOT varies from \$79.81 to \$120.89 per vehicle per hour. Chapter V examined the value of time based on delay to the commodity in inventory management by assuming prolonged transportation time or freight delay. Chemical products had the highest VOT of \$13.89 per truckload per hour while VOR was estimated at \$31.04 per truckload per hour, followed by food products at \$7.24 for VOT and \$13.49 for VOR. Chapter VI applied the continuous approximation technique to fleet operations in the context of less-than-truckload trucking, in which one truck delivers to a large number of customer locations by following a specific routing strategy. Without considering time windows, the fleet vehicle's VOT was estimated between \$15.50 and \$22.00 per vehicle per hour for a major distribution company in Texas.

This study considered costs from vehicles and drivers as well as fleet operations and warehousing operations. The several approaches adopted in this research each revealed a component (vehicle/fleet, driver, and shipment/commodity) in the trucking industry that can be utilized to calculate overall freight VOT. For example, for an urgent delivery carrying chemical products, an hour highway delay should have an average cost of \$54.98 on its driver, \$93.99 on its fleet carrier, and \$13.89 on its downstream (of supply chain) receiver. This results in an overall congestion cost estimated at \$162.86 per vehicle per hour, which should closely reflect the overall freight VOT for a particular trip.

Trips with different characteristics need to be treated differently. For example, for an owner-operator of just one commercial vehicle, there would be no fleet effect from the delay on highways. The private carrier may have partially considered fleet

effect in the driver-perceived VOT already, in which case adding the three components (driver VOT, vehicle/fleet VOT, commodity VOT) together would produce an overestimate.

Overall, it remains a challenge how to combine all these different values and adequately eliminate their overlapping effect, or double counting. Nonetheless, it is reasonable to believe that this research has set the stage for future research where all the considerations and costs defined herein can be used to gain a better understanding of the overall freight VOT in the trucking industry.

REFERENCES

- Adamowicz, W. L. & Deshazo, J. R. (2006) Frontiers in stated preferences methods: An introduction. *Environmental and Resource Economics*. 34 (1). pp. 1–6.
- Adamowicz W. L., Swait, J., Boxall, P., Louviere, J. & Williams, M. (1997) Perceptions versus objective measures of environmental quality in combined revealed and stated preference models of environmental valuation. *Journal of Environmental Economics and Management*. 32 (1). pp. 65–84.
- Adamowicz, W. L., Louviere, J. & Williams, M. (1994) combining stated and revealed preference methods for valuing environmental amenities. *Journal of Environmental Economics and Management*. 26. pp. 271–292.
- Ali Ülkü, M. & Bookbinder, J. H. (2012) Modelling shipment consolidation and pricing decisions for a manufacturer–distributor. *International Journal of Revenue Management*. 6 (1/2). pp. 62–76.
- American Association of State Highway and Transportation Officials. (2003.) *Manual: User Benefit Analysis for Highway*, National Cooperative Highway Research Program (NCHRP) Project 02-23, Washington, DC: NCHRP.
- Axsater, S. (2000) *Inventory Control*. Boston, MA: Kluwer Academic Publishers.
- Ballou, R. H. & Srivastava, S. K. (2007) *Business Logistics/Supply Chain Management*, 5th edition. India: Dorling Kindersley.
- Bari, M. E., Burris, M. & Huang, C. (2013) The Impact of a Toll Reduction for Truck Traffic Using SH 130, working paper, Texas A&M University System.
- Ben-Akiva, M., McFadden, D., Garling, T., Gopinath, D., Walker, J., Boldue, D., Borsch-Supan, A., Delquie, P., Larichev, O., Morikawa, T., Polydoropoulou, A. & Rao, V. (1999) Extended framework for modeling choice behavior. *Marketing Letters*. 10, (3). pp. 187–203.
- Blanchard, G. (1996) *Highways and Logistics and Production Performance*. Ottawa: Transport Canada.
- Blumenfeld, D. (2001) *Operations Research Calculation Handbook*. New York: CRC Press.

- Bookbinder, J. H. & Cakayildirim, M. (1999) Random lead times and expedited orders in (Q,R) in inventory systems. *European Journal of Operation Research*. 115. pp. 300–313.
- Brownstone, D. & Small, K. A. (2005) Valuing time and reliability: Assessing the evidence from road pricing demonstrations. *Transportation Research Part A*. 39. pp. 279–293.
- Burris, M. (2006) Incorporating variable toll rates in transportation planning models. *International Journal of Transport Economics*. 33 (3). pp. 351–368.
- Burris, M., Nelson, S., Kelly, P., Gupta, P. & Cho, Y. (2012) Willingness to pay for HOT lanes—empirical analysis from I–15 and I–394. *Transportation Research Record*. 2297. pp 47–55.
- Cambridge Systematics, Inc. (2005) *An Initial Assessment of Freight Bottlenecks on Highways*. Washington, DC: Federal Highway Administration.
- Cambridge Systematics, Inc. (2008) *Estimated Cost of Freight Involved in Highway Bottlenecks*. National Cooperative Freight Research Program Report. Washington, DC: NCHRP.
- Cambridge Systematics, Inc. (2011) *Georgia Statewide Freight and Logistics Plan, 2010–2050*, Task 5 Report. Freight Improvement Project Recommendations, Final Report. Atlanta, GA.
- Campbell, J. F. (1990) Freight consolidation and routing with transportation economies of scale. *Transportation Research Part B*. 24 (5). pp. 173–193.
- Campbell, J. F. (1993) One-to-many distribution with transshipment: An analytic model. *Transportation Science*. 27. pp. 330–340.
- Chiang, C. (2010) An order expediting policy for continuous review systems with manufacturing lead-time. *European Journal of Operational Research*. 203 (2). pp. 526–531.
- Clarke, G. & Wright, W. (1964) Scheduling of vehicles from a central depot to a number of delivery points, *Operations Research*. 12 (4). pp. 568–581.
- Cramer, J. S. (1986) *Econometric Applications of Maximum Likelihood Methods*. Cambridge, UK: Cambridge University Press.

- Cramer, J. S. (1990) Further Developments of the Model. In *The Logit Model: An Introduction for Economists*. London, UK: Hodder Arnold.
- Daganzo C. F. (1984a) The length of tours in zones of different shapes. *Transportation Research Part B*. 18B (2). pp. 135–145.
- Daganzo C. F. (1984b) the distance travelled to visit n points with a maximum of c stops per vehicle: An analytic model and an application. *Transportation Science*. 18 (4). pp. 331–350.
- Daganzo C. F. (1984c) Checkpoint dial-a-ride systems. *Transportation Research Part B*. 18 (4/5). pp. 315–327.
- Daganzo C. F. (1991) *Logistics Systems Analysis*. Lecture Notes in Economics and Mathematical Systems #361. Heidelberg, Germany: Springer-Verlag.
- Daganzo C. F. & Newwell, G. F. (1985) Physical distribution from a warehouse: Vehicle coverage and inventory levels. *Transportation Research Part B*. 19 (5). pp. 397-408.
- Daskin M. S. (1985) Logistics: An overview of the state of the art and perspectives on future research. *Transportation Research Part A*. 19A (5/6). pp. 383–398.
- de Jong, G. C. (1996) Freight and Coach Value of Time Studies. In *Easthampstead Park Seminar on the Value of Time*. Easthampstead, London: PTRC.
- de Jong, G. C., Gommers, M., Inwood, H. & Klooster, J. (1992) Time valuation in freight transport: Method and results. In *PTRC European Transport Highways and Planning 20th Annual Summer Meeting*. London: PTRC.
- de Jong, G. C., van de Vyvre, Y. & Inwood, H. (1995) The value of time for freight transport. In *World Conference on Transport Research*, Sydney: NSW.
- Devarasetty, P., Burris, M. & Shaw, W. (2012a) The value of travel time and reliability—evidence from a stated preference survey and actual usage. *Transportation Research Part A*. 46 (1). pp. 1227–1240.
- Devarasetty, P., Burris, M. & Shaw, W. (2012b) Do travelers pay for managed lane travel as they claimed they would? : A before-after study of Houston Katy Freeway travelers. *Transportation Research Record*. 2297. pp 56–65.

- Eisele, W. L., Burris, M., Wilner, H. T. & Bolin, M. J. (2006) Developing and applying an analytical tool for evaluating adaptation of a high-occupancy vehicle lane to a high-occupancy toll lane. *Transportation Research Record*. 1960. pp. 68–79.
- Eisele, W. L. & Schrank, D. L. (2010) Conceptual framework and trucking application to estimate the impact of congestion on freight. *Transportation Research Record*. 2168. pp. 94–103.
- Elion, S., Waston–Gandy C. D. T. & Christofides, N. (1971) *Distribution Management: Mathematical Modelling and Practical Analysis*. New York: Hafner.
- Federal Highway Administration. (2004) *FHWA Freight BCA Study: Summary of Phase II Results*. Maryland: ICF Consulting, Virginia and HLB Decision-Economics.
- Federal Highway Administration. (2008) *Freight Story 2008*. Accessed Oct 18, 2013. http://ops.fhwa.dot.gov/freight/freight_analysis/freight_story/fs2008.pdf
- Fender, K. J. & Pierce, D. A. (2012) *An Analysis of the Operational Costs of Trucking: A 2012 Update*. American Transportation Research Institute (ATRI).
- Fender, K. J. & Pierce, D. A. (2013) *An Analysis of the Operational Costs of Trucking: A 2013 Update*. American Transportation Research Institute (ATRI).
- Figliozzi, M. A. (2007) Analysis of the efficiency of urban commercial vehicle tours: Data collection, methodology, and policy implications. *Transportation Research Part B*. 41 (9). pp. 1014–1032.
- Figliozzi, M. A. (2010) The impacts of congestion on commercial vehicle tour characteristics and cost. *Transportation Research Part E*. 46 (4). pp. 496–506.
- Fosgerau, M. & Engelson, L. (2011) The value of travel time variance. *Transportation Research Part B*. 45 (1). pp. 1–8.
- Fowkes, A. S. & Shinghal, N. (2002) *The Leeds Adaptive Stated Preference Methodology*. Working paper, Institute of Transportation Studies, University of Leeds, UK, 2002.
- Fowkes, A. S., Firmin, P. E., Tweddle, G. & Whiteing, A. E. (2004) How highly does the freight transport industry value journey time reliability—and for what reasons? *International Journal of Logistics: Research and Applications*. 7 (1). pp. 33–43.

- Frank, W. & Els, V. (2005) Determining the monetary value of quality attributes in freight transportation using a stated preference approach. *Transportation Planning and Technology*. 28 (2). pp. 77–92.
- Freight Analysis Framework. (2011) *Commodity Origin-Destination Database: 2002-2035*. Federal Highway Administration: Freight Management and Operations. Accessed Aug. 18, 2013. http://ops.fhwa.dot.gov/freight/freight_analysis/faf/
- Fridstrom, L. & Madslie, A. (1995) *A Stated Preference Analysis of Wholesalers: Freight Choice*. TOII Report 1995/09. Oslo, Norway: Transport Economics Institute.
- Geiselbrecht, T., Burriss, M., Baker, R., Zhou, L., Waltman, M. & Montes, J. (2008) *State Highway 130 Value Pricing Project for the Austin District*. College Station, TX: Texas Transportation Institute, Texas A&M University System.
- Geoffrion A. M. (1976) The purpose of mathematical programming is insight, not numbers. *Interface*. 7. pp. 81–92.
- Ghosh, A. (2001) *Valuing Time and Reliability: Commuters Mode Choice from a Real Time Congestion Pricing Experiment*. Ph.D. Dissertation, Department of Economics. Irvine, CA: University of California at Irvine.
- Hall R. W. (1986) Discrete models / continuous models. *Omega, International Journal of Management Science*. 14. pp. 213–220.
- Harwood, D. W., Torbic, D. J., Richard, K. R., Glauz, W. D. & Elefteriadou, L. (2003) *Review of Truck Characteristics as Factors in Highway Design*. National Cooperative Highway Research Program Report 505, Transportation Research Board. Washington, DC: NCHRP.
- Hensher, D. A. (2001) Measurement of the valuation of travel time savings. *Transportation Research Part E*. 37 (2/3). pp. 71–98.
- Hensher, D. A. & Greene, W. H. (2003) The mixed logit model: The state of practice. *Transportation*. 30 (2). pp. 133–176.
- HLB Decision-Economics. (2002) *Economic Effects of Transportation: The Freight Story*. Maryland: ICF Consulting.

- Kawamura, K. (2000) Perceived value of time for truck operators. *Transportation Research Record*. 1725 (5). pp. 31–36.
- Knorrning, J. H., He, R. & Kornhauser, A. L. (2005) An analysis of route choice decisions by long-haul trucks drivers. *Transportation Research Record*. 1923 (6). pp. 46–60.
- Kurri, J., Sirkia, A. & Mikola, J. (2000) Value of time in freight transport in Finland. *Transportation Research Record*. 1725 (4). pp 26–30.
- LaLonde, B. J., Cooper, M. & Noordewier, T. G. (1988) *Customer Service: A Management Perspective, Council of Logistics Management*. Oak Brooks, IL: Council of Logistics Management.
- Langley, C. J. Jr., 1981. The inclusion of transportation costs in inventory models: Some considerations. *Journal of Business Logistics*. 2 (1). pp. 106–211.
- Lee, J. & Schwarz, L. (2007) Leadtime reduction in a (Q,R) inventory system: An agency perspective. *Production Economics*. 105. pp. 204–212.
- Lieb, R. C. & Bentz, B. A. (2005) The use of third-party logistics services by large American manufacturers: The 2004 survey. *Transportation Journal*. 2. pp. 24–33.
- MacroSys Research and Technology. (2005) *Logistics Costs and U.S. Gross Domestic Product*. Prepared for the Federal Highway Administration, Department of Transportation. Washington, DC: FHWA.
- Mamani, H. & Moinzadeh, K. (2013) Lead time management through expediting in a continuous review inventory system. *Production and Operations Management*. 1 (1). pp. 1–15.
- McKinnon, A. (1998) *The Impact of Traffic Congestion on Logistical Efficiency*. Heriot-Watt University. Edinburgh, UK: Institute of Logistics Research Series No. 2.
- McKinnon, A. (1999) The effect of traffic congestion on the efficiency of logistical operations. *International Journal of Logistics: Research and Applications*. 2 (2). pp. 111–128.
- McKinnon, A., Palmer, A., Edwards, J. & Piecyk, M. (2008) Reliability of road transport from the perspective of logistics managers and freight operators. *Joint Transport*

Research Centre of the OECD and the International Transport Forum.
Edinburgh, UK.

- McKinnon, A., Edwards, J., Piecyk, M. & Palmer, A. (2009) Traffic congestion, reliability and logistical performance: A multi-sectoral assessment. *International Journal of Logistics: Research and Applications*. 12 (5). pp. 331–345.
- Mot, E. S., Cramer, J. S. & van der Gulik, E. M. (1989) *Choice of mode of payment*, Report 228. Stichting voor Economisch Onderzoek. In Dutch.
- Nasri, F., Paknejad, J. & Affisco, J. (2008) Investing in lead-time variability reduction in a quality-adjusted inventory model with finite-range stochastic lead-time. *Journal of Applied Mathematics and Decision Sciences*. 2008. pp. 1-13.
- Newell G. F. & Daganzo C. F. (1986a) Design of multiple-vehicle delivery tours–I: A ring-radial network. *Transportation Research Part B*. 20 (4). pp. 345–363.
- Newell G. F. & Daganzo C. F. (1986b) Design of multiple-vehicle delivery tours–II: other metrics. *Transportation Research Part B*. 20 (5). pp. 365–376.
- Newell G. F. & Daganzo C. F. (1986c) Design of multiple-vehicle delivery tours–III: valuable goods. *Transportation Research Part B*. 20 (6). pp. 377–390.
- Ouyang, Y. (2007) Design of vehicle routing zones for large-scale distribution systems. *Transportation Research Part B*. 41 (10). pp. 1079–1093.
- Özkaya, E., Keskinocak, P., Joseph, V. R. & Weight, R. (2010) Estimating and benchmarking less-than-truckload market Rates. *Transportation Research Part E*. 46 (5). pp.667–682.
- Palaka, K., Erlebacher, S. & Kropp, D. H. (1998) Lead-time setting, capacity utilization, and pricing decisions under lead-time dependent demand. *IIE Transactions*. 30. pp. 151–163.
- Parish, T. R. (1994) *Case Studies of Market Research for Three Transportation Communication Products*. Arthur D. Little, Inc. for Economic Analysis Division of the John A. Volpe National Transportation Systems Center in Cambridge, MA and the FHWA Office of Policy Development at Washington, DC. Cambridge, MA: Arthur D. Little. Accessed Oct 18, 2013.
<http://ntl.bts.gov/lib/16000/16600/16687/PB2000104497.pdf>

- Quadrifoglio, L. & Li, X. (2009) A Methodology to derive the critical demand density for designing and operating feeder transit services. *Transportation Research Part B*. 43 (10). pp. 922-935.
- Quadrifoglio, L., Hall, R. W. & Dessouky, M. (2006) Performance and design of MAST services: Bounds on the maximum longitudinal velocity. *Transportation Science*. 40 (3). pp. 351-363.
- Sankaran, J. K., Gore, A. & Coldwell, B. (2005) The impact of road traffic congestion on supply chains: Insights from Auckland, New Zealand. *International Journal of Logistics: Research and Applications*. 8 (2). pp. 159–180.
- Sankaran, J. K. & Wood, L. (2007) The relative impact of consignee behaviour and road traffic congestion on distribution costs. *Transportation Research Part B*. 41 (9). pp. 1033–1049.
- Schrank, D., Eisele, B., & Lomax, T. (2012) *Urban Mobility Report*. College Station, TX: Texas Transportation Institute, Texas A&M University System.
- Shen C. & Quadrifoglio L. (2012) Evaluating the zoning design with transfers for paratransit services. *Transportation Research Record*. 2277. pp. 82–89.
- Shirley, C. M. (2000) *Firm Inventory Behavior and the Returns from Infrastructure Investment*. Ph.D. dissertation submitted at the University of California, Berkeley. Berkeley, CA: University of California.
- Small, J. A., Winston, C. & Yan, J. (2005) Uncovering the distribution of motorists: Preferences for travel time and reliability. *Econometrica*. 73 (4). pp. 1367-1382.
- Smith, D. L., Campbell, J. F. & Mundy, R. (2007) Modeling net rates for expediting freight services. *Transportation Research Part E*. 43 (2). pp. 192–207.
- So, K. C. (2000) Price and time competition for service delivery. *Manufacturing and Service Operations Management*. 2. pp. 392–409.
- Solomon, M. M. (1987) Algorithms for the vehicle routing and scheduling problems with time constraints. *Operations Research*. 35 (2). pp. 254–265.
- Stephanedes, T. & Kwon, E. (1993) Adaptive demand diversion prediction for integrated control of freeway corridors. *Transportation Research Part C*. 1 (1). pp. 23–42.

- Sullivan, E. C. (2000) *Continuation Study to Evaluate the Impacts of the SR 91 Value-Priced Express Lanes – Final Report*. Project report to the State of California Department of Transportation, Traffic Operation Program, HOV Systems Branch, pp. 123-135. San Diego, CA: DOT.
- Sullivan, E. C. (2002) State Route 91 value-priced express lanes: Updated observations. *Transportation Research Record*. 1812 (5). pp. 37–42.
- Supemak, J., Golob, J., Golob, T., Kaschade, C., Kazimi, C., Schreffler, E. & Steffey, D. (2001) *I-15 Congestion Pricing Project Monitoring and Evaluation Services*. Phase II Year Three Overall Report. San Diego, CA: San Diego Council of Governments.
- Swenseth, S. R. & Godfrey, M. R. (1996) Estimating freight rates for logistics decisions. *Journal of Business Logistics*. 17 (1). pp. 213–231.
- Swenseth, S. R. & Godfrey, M. R. (2002) Incorporating transportation costs into inventory replenishment decisions. *International Journal of Production Economics*. 77 (1). pp. 113–130.
- Swenson, C. R., Alasdair, C. & Burris, M. W. (2001) Toll Price Traffic Demand Elasticity Analysis on Variable Priced Toll Bridges. *ITE Annual Meeting*. Chicago, IL: ITE.
- Szplett, D. B. (1984) Approximate procedures for planning public transit systems: A review and some examples. *Journal of Advanced Transportation*. 18. pp. 245-257.
- Tagaras, G. (1989) Effects of pooling on the optimization and service levels of two-location inventory systems. *IIE Transactions*. 21. pp. 250–257.
- Texas Department of Transportation (TxDOT). (2013) *100 Congested Roadways*. Available at http://www.txdot.gov/inside-txdot/projects/100-congested-roadways.html?CFC_target=http%3A%2F%2Fwww.dot.state.tx.us%2Fapps-cg%2Ftop_100%2Flist.htm%3Fitem%3D10. Accessed Nov18, 2013.
- Tyworth, J. E., Guo, Y. & Ganeshan, R. (1996) Inventory control under gamma demand and random lead time. *Journal of Business Logistics*. 17 (1). pp. 291-304.

- Tyworth, J. E. & Zeng, A. (1998) Estimating the effects of carrier transit-time performance on logistics cost and service. *Transportation Research Part A*. 32 (2). pp. 89–97.
- U.S. Department of Transportation (USDOT). (2007a) *Highway Statistics 2006*. Table HM-18. Washington, DC: Federal Highway Administration (FHWA), Office of Highway Policy Information. Accessed Nov18, 2013. Available at www.fhwa.dot.gov/policy/ohim/hs06/roadway_extent.htm
- U.S. Department of Transportation (USDOT). (2007b) *Freight Facts and Figures 2007*. Table 3-1. Washington, DC: Federal Highway Administration (FHWA), Office of Freight Management and Operations. Accessed Nov18, 2013. Available at www.ops.fhwa.dot.gov/freight/freight_analysis/nat_freight_stats/docs/07factsfigures
- U.S. Department of Transportation (USDOT). (2008) *Large and Growing Demand for Freight Transportation*. Figure 2-1. Washington, DC: Federal Highway Administration (FHWA), Office of Freight Management and Operations. Available at http://ops.fhwa.dot.gov/freight/freight_analysis/freight_story/large.htm#1b Accessed Nov18, 2013.
- U.S. Department of Transportation (USDOT). (2013) *Revised Departmental Guidance on Valuation of Travel Time in Economic Analysis*. Washington, DC: USDOT. Accessed Nov18, 2013. Available at <http://www.dot.gov/office-policy/transportation-policy/guidance-value-time>
- Wang B. X. (2009) Determining the shape of delivery zones to balance local and line haul costs. *The Open Transportation Journal*. 3. pp. 49-51.
- Weisbrod, G., Vary, D. & Treyz, G. (2001) *Economic Implications of Congestion*. National Cooperative Highway Research Program Report 463. Washington, DC: Transportation Research Board.
- Westin, K. (1994) *Valuation of Goods Transportation Characteristics: A Study of a Sparsely Populated Area*. Umea, Sweden: Umea University.
- Whitehead, J. C., Pattanayak, S. K., van Hantven, G. L. & Gelso, B. R. (2008) Combining Revealed and Stated preference data to estimate the nonmarket value of ecological services: An assessment of the state of the science. *Journal of Economic Surveys*. 22 (5). pp. 872–908.

- Wigan, M., Rockliffe, N., Thoresen, T. & Tsolakis, D. (2000) Valuing long-haul and metropolitan freight travel time and reliability. *Journal of Transportation and Statistics*. 3 (3). pp. 83–89.
- Wigan, M., Fuller, T. N., Rockliffe, N. R., Tsolakis, D. & Thoresen, T. (2003) *Economic Evaluation of Road Investment Proposals: Valuing Travel Time Savings for Freight*. Project Report, AustRoads, AP-R230-03, pp. 1–64, Sydney, Australia: AustRoads.
- Wynter, L. M. (1995) The value of time of freight transport in France: Estimation of continuously distributed values from a stated preference survey. *International Journal of Transport Economics*. 22 (2). pp. 151–65.
- Xu, K., Evers, P. T. & Fu, M. C. (2003) Estimating customer service in a two-location continuous review inventory model with emergency transshipments. *European Journal of Operational Research*. 145. pp. 569–584.
- Zamparini, L. & Reggiani, A. (2007) Freight transport and the value of travel time savings: A meta-analysis of empirical studies. *Transport Reviews*. 27 (6). pp. 621-636.
- Zhang, J. L., Lee, C. Y. & Chen, J. (2009) Inventory control problem with freight cost and stochastic demand. *Operations Research Letters*. 37. pp. 443–446.

APPENDIX

Truck Driver Value of Time Survey

<i>Measurement</i>	Options (Choose at least one option from each row)			
<i>Type of carrier</i>	Owner-operator	For-hire	Private Carrier	
<i>Typical route</i>	Regional	Long Haul	Local/Delivery	
<i>Typical cargo</i> ¹	Bulk	Average value	High value	Other:
<i>Truck Size</i>	2 axle	3 axle	4 axle	Other:
<i>Trip Length</i>	11+ hours	5 to 11 hours	2 to 5 hours	Less than 2 hours
<i>Who decides Route</i>	Me (the driver)	Dispatcher or the fleet manager	Shipper	Other:
<i>How are you paid</i>	By mile	By load	Percentage of revenue	Other:
<i>Who pays the toll</i>	I do	For-hire carrier	Shippers	Other:
<i>How often do you change route to avoid congestion</i>	Never	Occasionally	Often	Always
<i>Flexibility of delivery hours on an average trip</i>	1 day	Less than 12-hours	Less than 5 hours	Less than 3 hours

You are running **30 minutes late**. Please select the maximum you are willing to pay for each scenario:

Arrival Time:											
45 / 30 / 15 minutes early											
\$30	\$20	\$13	Other	\$50	\$35	\$20	Other	\$68	\$45	\$23	Other

You are running **on time**. Please select the maximum you are willing to pay for each scenario:

Arrival Time:											
45 / 30 / 15 minutes early											
\$30	\$20	\$13	Other	\$50	\$35	\$20	Other	\$68	\$45	\$23	Other

Background (optional) Affiliation _____ Phone #: _____
 ethnicity _____ age _____ family size _____ annual income _____

¹ **Bulk commodity:** agricultural product, fertilizer, coal and other mineral, oil product, sand, gravel, log and rough wood, waste and scrap; **Average value:** wood product, paper print, paper board, textile product, base metal, chemical product, machinery, vehicles, office equipment, and mixed freight; **high value:** electronic equipment, precision instrument, perishable product such as seafood, fashion item.