Assessing Public Benefits and Costs of Freight Transportation Projects: Measuring Shippers' Value of Delay on the Freight System

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16. Abstract

Freight delay is detrimental to the national economy. In an effort to gauge the economic impact of freight delay due to highway congestion, this project focuses on estimating shippers' value of delay (VOD). We have accomplished this through three strategies to monetize the impacts of congestion on shippers' operations:

- Three half-structured on-site interviews with shipping managers in different type of industries were conducted to obtain insights into their daily logistic operations and their subjective assessment of the delay impacts. In light of the interviews, a comprehensive survey of major manufacturers and wholesalers within Texas and Wisconsin was conducted.
- The analytical hierarchy process (AHP) and willingness-to-pay (WTP) method were then applied to quantify the impact of congestion on shippers. The AHP reveals that among four possible delay components, en route transportation delay is the most important, which justifies WTP evaluating the value of highway congestion delay. We have found a value of $56 per hour for congestion. Furthermore, a value of $0.4 per percentage delay was also calculated for transportation time reliability using individual defined travel time.
- An analytical inventory model was used to examine the value of delay in view of mean and reliability of transit time for shipment receivers. Nine industrial groups were analyzed. For example, shippers in the chemical industry are calculated to have an additional $13.89 cost on a truckload delivery if the transit time is expected to increase by one hour. The random delay has an average of $31.04 per hour per truckload delivery.

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This is a collaborative research project between CFIRE at the University of Wisconsin–Madison and UTCM at Texas A&M University. The support from the two university transportation centers promoted collaborations between regions and university programs, and improved geographic coverage of stakeholders in this study.

The research team acknowledges the assistance of the staff at both CFIRE and the Texas Transportation Institute in conducting this project. We are particularly grateful for Martha Raney Taylor at UTCM, who took care of the paperwork and managed the operational budget, Michelle Benoit at TTI Communications, who edited and greatly improved the presentation of the report, Tim Lomax at TTI, who provided advice and help during the project, Greg Waidley at CFIRE, who coordinated our quarterly report patiently, just to name a few. This report would not have been possible without the vision and gracious support from Teresa Adams, Director of CFIRE, and Melissa Tooley, Director of UTCM.

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EXECUTIVE SUMMARY

With a significant growth projected in commerce partially due to globalization, freight traffic is expected to double in the next 30 years. Highway congestion is being exacerbated. Late freight delivery is increasingly impacting private-sector production and logistics operations. In addition, freight delay is accompanied by escalating freight cost. According to MacroSys Research and Technology (2005), transportation cost increased from $228 billion in 1981 to $577 billion in 2002. Freight delay is detrimental to the national economy.

Researchers and planners need to understand the impact of delay on stakeholders in order to effectively address the issue of freight delay and highway congestion. The impact of delay is usually measured using a monetary value such as U.S. dollars. Although the general concept of value of delay or value of time has been studied for decades, most studies are about commuters or commercial vehicle drivers' perceived value of time. Little research has been conducted regarding the value of delay (VOD) from the perspective of shippers. Freight delay impacts shippers in many ways. In normal cases, freight delay and travel time reliability affect shippers' decisions on the safety stock in inventory. In an extreme case, if a shipper operates a just-in-time production system, freight delay directly leads to loss of productivity and even loss of sales.

This research project is jointly funded by two university transportation centers, the National Center for Freight and Infrastructure Research and Education (CFIRE) at the University of Wisconsin–Madison and the University Transportation Center for Mobility™ (UTCM) at Texas A&M University. Researchers joined forces to tackle this significant problem of the economic impact of freight delay on highways. The principal investigators, Dr. Teresa M. Adams at the University of Wisconsin–Madison and Dr. Bruce Wang at Texas A&M University, both have many years of research experience in freight transportation.

The research team realized the complexity involved in studying shippers' value of delay. Delay has very diverse impacts on businesses. The impact depends on numerous factors such as the value of goods, schedule characteristics (hard or soft pick-up and delivery windows, robustness, etc.), downstream transportation, product perishability or seasonality, and the type of business operations such as just-in-time or overnight express delivery of perishable products (e.g., newspapers). The diversity of logistics operations requires appropriate business classification for the impact study. Another difficulty in getting shippers' value of delay is that the production managers themselves do not have a thorough picture of this impact either. The exact impact is not clear to shippers in the first place.

This research has the following objectives:

- Study how freight delay incurs cost to shippers and how the cost varies with the shipper's operational characteristics.
- Propose study methodologies to quantify the shippers' VOD.
- Conduct a pilot survey among a limited number of shippers for model testing.
- Identify issues related to shippers' participation in this study.

This research project considers three ways to look into the impact of congestion on shippers: individual interviews, survey and analysis, and analytical study of inventory management. First, three half-structured on-site interviews were conducted with shipping managers in different types of industries to obtain insights into their daily logistic operations and subjective assessment of delay impact. These interviews provided insights about the impacts on logistics operation. In fact, the interviews helped us develop an idea of investigating delay effects from different perspectives, such as from the shipment-sending end or shipment-receiving end. The interviews also supported our decision to employ the willingness-to-pay (WTP) method to measure VOD for shippers.

Our second way concerned a more comprehensive survey of major manufacturers and wholesalers within Texas and Wisconsin. The analytic hierarchy process (AHP) and WTP methods were applied to the survey data to prioritize and quantify the impacts of congestion for shippers. AHP is a structured technique that prioritizes alternatives. The participants were asked to assess the delay components (i.e., en route delay, delay at collection point, at the transfer point, and at the delivery point) on a scale from 0 to 10, with 0 being least relevant and 10 being most important. Through pair-wise comparisons for each combination of two components, AHP indicated that the en route transportation delay is the most influential factor that affects the stakeholders' operation. This finding supported our subsequent adoption of WTP in evaluating the value of highway congestion delay from the perspective of the shipment-sending end. The application of WTP suggested a value of $56 per hour for travel time on shippers' operations. It should be noted that this value does not include the cost to carriers/truckers. In addition, travel time reliability has its economic value. A value of $0.4 per percentage delay was estimated for travel time reliability. The percentage represents the hypothetical delay time divided by normal travel time specified by the individual.

In our third way, an analytical inventory model was used to examine the value of delay in view of the mean and reliability of transit time from the perspective of shipment receivers. This exploration was intended to overcome the supply chain managers' lack of understanding of delay impact. Congestion and delay have significant impacts on shippers' operation regarding inventory level and order size. The inventory management practices vary with industry. The analysis was conducted individually for each industry. For example, shippers in the chemical industry have an additional $13.89 cost on a truckload delivery if the transit time is expected to increase by one hour. The random delay has an average of $31.04 per hour per truckload delivery.

CHAPTER 1 INTRODUCTION

1.1 Background

Freight delay has been an increasingly severe issue. In 2006, 226 million hours of truck delay took place at bottlenecks where congestion recurrently happened (Cambridge Systematics, 2008). Note that delay at bottlenecks only accounts for about 40 percent of the total truck delay, while the other 60 percent is due to nonrecurrent or transient congestion according to Cambridge Systematics (2005). Congestion and delay add to the 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 a 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.

In order to address the freight delay and prioritize freight projects, public-sector researchers and planners need to know the impact of delay on stakeholders. This input information is important for fully understanding the benefit of transportation improvement projects and for justifying infrastructure investments. However, to date, freight planning decisions are made in the absence of defensible cost/benefit analyses. 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, a question is typically asked: what is the value of delay in freight transportation?

The value of delay study is essentially a special value of time study, which has been studied for carriers for decades. Estimates typically consider the direct costs to carriers because of delay in traffic (Wynter, 1995), which include fuel cost, truck operation cost such as truck/trailer lease and maintenance, and driver wage and benefit. The American Transportation Research Institute (ATRI, 2011) suggests that an additional one hour of truck driving time results in an extra $18.59 for fuel and oil and $59.61 for all vehicle-related operational costs such as wear and tear. However, this direct assessment method does not consider indirect impacts in terms of lost productivity to the carrier fleet. For example, the time spent in congestion affects carriers' ability to schedule freight shipments and reduces their fleet capacity for serving more clients.

However, we also have to examine the delay impact on shipper operations to get a comprehensive understanding about the value of delay. The shippers interact with each other through transportation. For example, shippers (i.e., suppliers) ship according to the needs of their customers such as delivery time windows and requirements on shipping mode, etc. Wholesalers make 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. For example, a longer and less reliable transit time for orders requires more 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. This research project studies the value of delay to shippers by examining additional costs to them.

This is a complex topic of study. One of the difficulties comes from the absence of a homogenous effect of delay on business since the impact depends on numerous factors such as the value of goods, schedule characteristics (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 in getting shippers' value of delay is that the production managers themselves do not have a thorough picture of this impact either. The exact impact is not clear to shippers in the first place.

1.2 Research Objectives

We have identified specific objectives as follows:

- Study how freight delay incurs costs to shippers and how the cost varies with the shipper's operational characteristics.
- Propose study methodologies to quantify the shippers' VOD.
- Conduct a pilot survey among a limited number of shippers for model testing.
- Identify issues related to shippers' participation in this study.
- Apply inventory management models and analyze the impact of highway delay.
- Identify VOD and make recommendations.

1.3 Study Methodology

This research project considers three ways to look into the impact of congestion on shippers: individual interviews, survey and analysis, and analytical study of inventory management. First, three half-structured on-site interviews were conducted with shipping managers in different industries to obtain insights into their daily logistics operations and subjective assessment of delay impact. These interviews provided insights about the impacts on logistics operations. In fact, the interview helped us develop the idea of investigating delay effects from different perspectives, such as from the shipment-sending end or shipment-receiving end. The interviews also supported our decision to employ the willingness-to-pay method to measure VOD for shippers.

Our second way concerned a more comprehensive survey of major manufacturers and wholesalers within Texas and Wisconsin. Specifically, the AHP and WTP methods were applied to the survey data to prioritize and quantify the impacts of congestion for shippers. AHP is a structured technique that specially prioritizes alternatives. The participants were asked to assess the delay components (i.e., en route delay, delay at the collection point, at the transfer point, and at the delivery point) on a scale from 0 to 10, with 0 being the least relevant and 10 being the most important. Through pair-wise comparisons for each combination of two components, AHP indicated that the en route transportation delay is the most influential factor that affects the stakeholders' operations. This finding supported our subsequent adoption of WTP in evaluating the value of highway congestion delay from the perspective of the shipping end. The application of WAP suggested a value of $56 per hour for travel time on shippers' operations. It should be noted that this value does not include the cost to carriers/truckers. In addition, travel time reliability has its economic value. A value of $0.4 per percentage delay was estimated for travel time reliability. The percentage represents the hypothetical delay time divided by normal travel time, which is specified by the individual.

Third, an analytical inventory model was used to examine the value of delay with regard to the mean and reliability of transit time from the perspective of the shipment-receiving end. This analytical exploration was intended to overcome the supply chain managers' lack of understanding of delay impact. Congestion and delay have significant impacts on shippers' operations regarding inventory level and order size. As mentioned earlier, the inventory management practices vary with industry. Therefore, we conducted analyses for each individual industry. The industry-specific impacts are listed in section 4.2. For example, shippers in the chemical industry have an additional $13.89 expense on a truckload delivery if the transit time is expected to increase by one hour. The random delay that represents reliability has an average of $31.04 per hour per truckload delivery.

1.4 Report Organization

This report is organized as follows:

- Chapter 2 reviews the existing literatures on the VOD topic to identify sources of costs resulting from late delivery, as well as to examine the appropriate methods for quantifying the impacts of late delivery to shippers.
- Three on-site interviews were conducted with logistics managers to get an in-depth understanding of how they perceive the impact of delay. Results are summarized in Chapter 3.
- Chapter 4 employs inventory models to analytically estimate the theoretical value of delay to shippers from the perspective of the shipment-receiving end.
- Based on the interview results in Chapter 3, Chapter 5 designs a stated preference survey to collect data about shippers' perception of the value of delay.
- Chapter 6 develops an analytical hierarchy process method and a multinomial logit model to assess the value of transportation delay and the relative priority of transportation delay over a series of delay components.
- Finally, Chapter 7 concludes the study and proposes future research directions to estimate the value of delay.

CHAPTER 2 LITERATURE REVIEW

The continued rise in traffic congestion aggravates the delay of freight delivery and incurs additional business costs. Section 2.1 investigates what additional costs would be. Section 2.2 summarizes the literature that attempts to estimate the cost of delay to businesses, especially to shippers. And Section 2.3 discusses the major challenges and issues in quantifying the cost of delay.

2.1 Costs of Delay

Traffic congestion, which leads to additional travel time on the road, often contributes to late delivery, requires the temporary shift of unloading personnel, and incurs additional working hours. It also reduces the customers' satisfaction. Section 2.1.1 examines the additional direct costs. On the other hand, shippers may have anticipatory operations to mitigate the impacts of traffic delay, such as an increase in fleet size, redesign of warehouses, etc. Therefore, Section 2.1.2 investigates these mitigation measures.

2.1.1 Impacts of Highway Congestion on Business Operations

Similarly to passenger travel, additional travel time for freight shipments caused by highway congestion leads to extra fuel and oil costs for truck operation. According to a recent study released by the American Transportation Research Institute (ATRI, 2011), the marginal fuel and oil costs for one hour of truck driving is $18.59. And the total truck operation cost is estimated to be $59.61 per hour, which includes other vehicle-based costs, such as truck/trailer lease and maintenance, and driver-based costs, such as driver wage and benefit. Therefore, the transportation cost increases directly as a result of traffic delay if the shippers use private fleets, and increases indirectly due to a higher transportation rate charged by for-hire or private carriers.

Logistics considers freight on the transportation network as in-transit inventory with a holding cost (McKinnon, 1998). In this sense, a longer travel time lengthens the stockholding period and therefore incurs greater in-transit inventory cost. However, McKinnon (1998) argues 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 the total inventory does not change.

Shippers who receive a late delivery are likely to have their operations distributed in a variety of ways. Freight delivery and unloading are scheduled with maximum efficiency if the workload is distributed evenly during work hours (McKinnon, 1998). 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. The staff might need to work beyond regular hours, which raises operational costs (O'Mahony and Finlay, 2004). This is an issue especially significant to cross-docking operations, where departing trucks have to wait for loading from the late-arriving trucks (McKinnon, 1998).

The late deliveries also cause a shortage of materials for production. Because the just-in-time (JIT) strategy reduces inventory and the associated cost of stock keeping, 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, the JIT production can be delayed or stopped (Blanchard, 1996).

As a reactive behavior, in order to reduce the risk of stock-out, a certain amount of inventory is kept on site. This amount of inventory is also known as safety stock, and its amount is estimated based on the lead time, uncertainty about the lead time, customer demands, and uncertainty about the demands during the lead time (Ballou and Srivastava, 2007). A larger safety stock is necessary if delay happens more frequently. This larger inventory leads to a higher inventory-carrying cost.

For freight senders, a single late delivery may not affect their operation significant. However, their level of customer service is jeopardized if the deliveries do not satisfy the time windows required by customers since late deliveries affect various operations of receivers directly as indicated above. Therefore, freight shippers that provide unreliable deliveries are risking loss of customers and the corresponding sales (Ballou and 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 the contract, especially in a constant delay situation.

Another possible opportunity cost to freight shippers comes from the loss of the ability to consolidate multiple outbound shipments facing the uncertainty of journey times (Fowkes et al., 2004). In particular, if the outbound vehicle was late on its first delivery, it is very likely to miss its unloading schedule for the 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 also shrinks business market areas and reduces the agglomeration economies of business operation (Weisbrod et al., 2001). McConnell and Schwab (1990) suggest that traffic congestion along specific routes has important impacts on the size of the market reach for businesses, where better transportation accessibility increases the economy of scale in serving markets. Moreover, Evers et al. (1988) indicate that greater accessibility allows businesses to reach a greater variety of labor skills and input products, which increases businesses' productivity.

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

- Additional fuel, oil, and truck operation costs.
- Extra in-transit inventory holding costs.
- Interrupted work flows at unloading bays.
- A disturbed production schedule and lower productivity.
- Dissatisfied customers and potential lost sales.
- A large volume of on-site safety stock and high inventory holding costs.
- Potential loss of the opportunity to consolidate multiple outbound shipments.
- Lost business markets and reduced agglomeration economies.

2.1.2 Mitigation Measures of Business Operations

Businesses have developed and implemented measures to mitigate the effects of traffic congestion caused by late deliveries. One example in freight receiving—the separation of loading and unloading bays—is an effective way to alleviate the impact of traffic delay; a late delivery does not need to wait for unloading if loading trucks are in line. Such a design characteristic is particularly helpful for cross-docking operations (McKinnon et al., 2009), which are the most time-sensitive activities in a warehouse and require efficiency in unloading and loading. Another strategy to improve the operation efficiency in the presence of late deliveries is to enlarge warehouse space; the capacity of diverting staff and equipment from less time-sensitive operations to those requiring immediate loading/unloading is enhanced (McKinnon et al., 2009).

In addition to warehouse space design, one common measure to mitigate late delivery is to avoid peak travel periods by rescheduling delivery activities (Weisbrod and Fitzroy, 2008). Usually freight is sent and transported during nighttime or in the middle of the day (Browne and Allen, 1997). However, this schedule also adds constraints to shippers' operations such as production and unloading, likely causing additional cost.

Meanwhile, the longer average shipping time as a result of increasing highway congestion leads to less shipments delivered within a given period of time, and thereby more vehicles are necessary to fulfill the same amount of delivery assignments (McKinnon et al., 2008). For shippers with their own private fleet and for carriers, more vehicles mean more costs for purchase, maintenance, and operation.

Advanced information technology (IT) systems and material-handling equipment are also used prevalently to relieve the impacts of congestion. Khattak et al. (2008) reported that route guidance devices were used by 75 percent of surveyed shippers or carriers on their shipping vehicles to increase the ability to reroute through congested areas.

In the case of commuter travel, O'Mahony and Finlay (2004) studied the results of a business survey undertaken by the Irish Business and Employers Confederation on 584 companies about their mitigation measures for traffic congestion. The results revealed that relocation and outsourcing the distribution function are two major strategies that businesses adopt or would consider to mitigate the impacts on business operations. The survey also investigated the attitudes of businesses toward strategies to reduce commuting costs. Over 30 percent of the surveyed companies adopted flexible working hours for their staff, while over 10 percent of the companies allowed teleworking and encouraged the staff to use other transportation modes for commuting trips. The authors further studied the attitudes of different industries and suggested a variation of attitudes toward certain measures, such as relocation and outsourcing the distribution function among businesses of different sectors.

The mitigation measures considered by shippers/receivers and carriers to reduce the impact of congestions are:

- Redesign the facility, such as having separated loading and unloading bays and enlarging warehouse space.
- Schedule delivery during off-peak periods.
- Increase fleet size to fulfill shipment needs.
- Invest in advanced IT systems to enhance the ability to reroute.

- Relocate to a less congested area.
- Outsource the distribution function to third parties.

2.2 Quantification of Cost of Delay

2.2.1 Cost-Saving Method

The cost-saving method assumes that time savings during transportation lead to a reduction in the resources required to perform a given volume of output (Adkins et al., 1967). It holds that savings in time can be converted into an equivalent number of vehicles, by dividing the total time savings by the average use time of each vehicle. Each vehicle is associated with a cost for being used. Later studies improved this method by carefully examining the vehicle operating cost (Berwick and Dooley, 1997). The cost savings then become more reasonable by using the product of the vehicle operating cost per hour and total hours saved. Wages and associated welfare payments are considered as the greatest component within the cost, but additional costs such as the capital value of vehicles, depreciation, proportion of maintenance, licenses, insurance, and taxes are treated in various ways in the literature (e.g., the work of Fender and Pierce in 2011). This is because some costs (e.g., interest, taxes, and insurance) are annual fees, irrelevant to the total annual operational hours or miles traveled. They are levied per year or month, not per number of hours or miles operated. In summary, the value of time savings in this method is calculated as the vehicle operating cost.

2.2.2 Net Profit Method

The net profit method assumes unlimited potential demand so that savings in time will be fully used productively. When each journey is assigned with a profit, the total savings in time are converted into additional profit. In other words, the amount of increase in net profit for truck operators depends on the efficiency with which the travel time savings can be used to conduct additional business. This method is first seen in Haning and McFarland (1963) and is later further developed by Waters et al. (1995). It calculated minimum and maximum values of time according to low and high levels of utilization of travel time savings.

2.2.3 Willingness-to-Pay Method

The willingness-to-pay method measures perceived value of time by stakeholders such as truckers and shippers. By definition in economics, the WTP is the maximum amount of money a person would be willing to pay in exchange for receiving a good or avoiding something undesired. This method combines stated preference (SP) techniques and logit models. In an SP survey, hypothetical alternatives are described by several attributes such as transport time, transport cost, reliability of service, damage percentage, etc. Reliability is usually characterized by the duration and frequency of unexpected delays. Respondents thus are asked to select their preference from the given alternatives. In order to analyze the stated preference data, a stochastic discrete choice model such as a logit model is applied based on the random utility theory. Utility represents the relative likelihood of each alternative. A greater utility of the alternative indicates a higher probability of the alternative to be chosen. The equivalency between transport time and cost or reliability gives an estimate of the value of time. This method is widely used in the commercial value of time studies. Some examples include Geiselbrecht et al. (2008), Zamparini and Reggiani (2007), Frank and Els (2005), Wigan et al. (2000), and Kurri et al. (2000).

2.2.4 Prospect-Theory-Based Method

The prospect theory was proposed by Kahneman and Tversky (1979) originally to explain the different perceptions toward gains and losses, to a reference state. In particular, prospect theory assumes that people value losses more than gains of equivalent size. The marginal value of gains and losses decreases as the magnitude increases.

This theory has been applied to transportation research to estimate the value of time, especially to distinguish the travel time saved and travel delay. For example, the Dutch and United Kingdom stated preference surveys held between 1988 and 1997 (van de Kaa, 2010) found that the majority of interviewees' behavior exhibited a strong sign dependence, which is explained better by the principles of the prospect theory. Similarly, Masiero and Hensher (2010) also confirmed that the prospect theory provides a strong improvement in the model fitness when there is delay aversion and diminishing sensitivity on time savings or delays.

2.2.5 Lead-Time Inventory Method

Lead time is the time from the ordering decision until the ordered amount is available on the shelf. It is not only the transit time from an external supplier or the production time in the case of an internal order. It also includes order preparation time, administrative time at the supplier, and time for inspection after receiving the order (Axsater, 2000).

In most cases, increasing transportation costs can possibly reduce lead time. For example, using toll roads or special delivery over congested highways would be faster but more costly. Therefore, by estimating the potential savings due to faster supply, companies are capable of making their choices between a faster resupply with more expense and a slower delivery with less expense (Gross and Soriano, 1969, 1972). This trade-off allows us to investigate the value of time in the environment of freight systems.

There are two types of potential savings in inventory cost when the lead time is reduced. The first is due to the pipeline inventory, which is also called in-transit inventory. A shorter lead time indicates fewer products in the pipeline. Here the pipeline takes the form of a highway system, air route, or other modal transportation. Capital is caught in the pipeline inventory. The second type of potential savings is from inventory holding costs, in other words, from on-shelf inventory costs. This is an important research area in inventory control theory because larger inventory not only requires a larger warehouse but also demands more complicated maintenance and less accurate regular inventory checks. The recent work in this area includes Paknejad et al. (1992), Lee and Schwarz (2007), and Nasri et al. (2008). Unlike earlier work, these works treat demand and lead time as stochastic parameters.

2.3 Difficulties in Assessing the Cost of Delay

Though there are abundant efforts to quantify the VOD cost due to highway congestion, the accuracy of results is still doubtable due to the following barriers. First, it is difficult to separate the effects of traffic delay from other kinds of delay (McKinnon, 1999). For example, for a manufacturer, a late delivery caused by traffic congestion might delay the freight unloading because there are insufficient workers during off-working hours, where the delay may further cause production postponement and be passed on to the downstream customers. Due to the close interrelationships between different operations and different supply chain players, the congestion effects need to be isolated from other disturbances to logistical schedules. McKinnon (1999) suggested that an accurate delay reporting system is necessary to isolate the effect of traffic delay.

An accurate delay tracking and reporting system also helps estimate the cost of traffic delay for business operations. As indicated in *NCHRP Research Result Digest* 202 (1995), managers rarely associate monetary value with urban congestion because they do not explicitly track the congestion and its associated cost. Under such circumstances, an estimate of the value of delay by stated preference survey is likely to have large variation due to vastly different perceptions.

Furthermore, stated preference surveys may involve survey issues as indicated by Weisbrod et al. (2001). First, the effect of traffic congestion tends to be underestimated since the interviews could only be conducted on surviving businesses, while the businesses that are most adversely affected by congestion are likely to have closed up or moved out of the area. Therefore, the businesses remaining operating in a given location tend to be those either affected less by traffic congestion problems or those accustomed to congestion by adjusting their nature of operations and customer markets (Cambridge Systematics, 1993). In addition, business staff may have difficulties making decisions under hypothetical scenarios that are not familiar to them. Therefore, it may not be reasonable for a manager operating in a less congested area to estimate the cost for a severe delay.

Another barrier preventing an accurate estimation is that capital investment is devoted to improving multiple business operations rather than to merely alleviate delay and its impacts. Based on a series of intensive interviews with business managers, McKinnon (1999) found that investment in more advanced materials-handling equipment and IT systems may result in a stream of benefits, one of which is the mitigation of congestion effects. Therefore, it is unreasonable to attach all the capital cost to congestion relief, while it is also difficult to estimate the proportion of the capital cost attributable to the congestion issue.

The impact of congestion also depends on the geographical area and business type (Weisbrod et al., 2001; McKinnon, 1999; Khattak et al., 2008). Different business types tend to operate differently. Khattak et al. (2008) also suggest a significant variation of value of unexpected delay among geographical regions. They argue that the value is associated with each region, which has to do with the rerouting availability and the type of majority business in the region.

Barriers are summarized as follows:

- There are difficulties in separating the effects of traffic delay from other kinds of delay.
- The monetary value estimated by managers' perceptions is not likely to be accurate.
- Most of the mitigation measures are not merely designed to alleviate delay or the impact of delay.
- The businesses in different industries/geographical locations may have different perspectives on the value of delay.

CHAPTER 3 CASE STUDY

The complexity of business operations motivated us to use the case study in order to have a better understanding of business processes and for an in-depth understanding of the impacts of delay. A select number of shippers were interviewed. We hoped that the case studies would facilitate development of quantitative methods for the VOD.

3.1 Case Study Design

Specifically, the case studies have the following objectives:

- Understand shippers' commodity and operational characteristics.
- Explore how shippers value their freight delay and the factors they considered.
- Investigate shippers' strategies to mitigate freight delay and costs associated with it.
- Identify the factors that might prevent shippers from participation in our survey for VOD studies and their suggested means, if any, to overcome those difficulties/obstacles.

The case studies were conducted through on-site interviews. Two research assistants visited the shippers to perform the interviews. Each interview was scheduled to be between 40 minutes and one hour. Previous studies indicate that once a respondent is willing to cooperate for a case study, he or she is likely to share more information than the questionnaire required. Therefore, the interview was conducted with half of the questions predetermined and the other half open, to ensure important questions were covered and flexibility was given to interviewers.

The shippers to interview were selected as representative of major types of operations. Based on the literature review, the factors considered as important to this study are industry type (manufacturer versus wholesaler), transportation service used (private fleet versus for-hire carrier), and haul length (short versus long). Because the transportation service used is believed to have a significant correlation with the haul length, these two factors are combined to generate two levels only (i.e., shipping in short-haul length using its own fleet versus shipping in long-haul length using a contract carrier). Finally, it was proposed to select one shipper in each of the categories below to conduct the interview:

- A manufacturer using short-haul length (less than 50 miles) and owning its own fleet.
- A manufacturer using long-haul length (more than 50 miles) and using contract carriers.
- A wholesaler using long-haul length (more than 50 miles) and using contract carriers.

A total of 50 shippers in Texas and Wisconsin were selected from an online business database (Manta, 2011). The database provides business information such as industry type, employment size, and contact information. The research team made phone calls to each business. Three qualified businesses were determined, and all of them agreed to participate in the case study.

3.2 Case Study Results Summary

The case studies are summarized below with detailed business information for the shippers.

3.2.1 Brenham Wholesale Grocery Co.

Location: Brenham, Texas
Interview Time: July 14, 2011, 8:10 AM–9:10 AM
Interviewer: Qing Miao, research assistant, Texas A&M University; and Don Nash, intern, Texas A&M University
Interviewee: David Beckendorf, distribution manager, Brenham Wholesale Grocery Co.

Company Background

Brenham Wholesale Grocery (BWG) is a distribution company that delivers grocery items such as candy, drinks, and hair and beauty products. The company has its own fleet consisting of about 32 drivers with 28 trucks with a delivery radius of 250 miles. Mr. Beckendorf assigns loads to drivers.

Impact of Late Delivery

The deliveries are usually on time because they are scheduled at night to avoid peak-hour congestion. In the case of late deliveries, the company informs its customers early to allow them to reschedule their activities accordingly. This interviewee suggested a breakdown method to identify late delivery costs and to associate a late delivery with highway congestion. The suggested operation cost breakdown was vehicle operation cost per mile, maintenance cost, wage and benefits for warehouse workers, and other related costs. For BWG, the major additional cost that results from late outbound delivery is related to extra wages for drivers and vehicle operating expenses.

3.2.2 Fristam Pumps USA

Location: 2410 Parview Rd., Middleton, Wisconsin
Time: March 7, 2012, 9:30 AM–10:15 AM
Interviewer: Qi Gong, project assistant, University of Wisconsin–Madison
Interviewee: David Skora (608-831-5001), vice president, Finance and Administration, Fristam Pumps USA

Company Background

Fristam Pumps USA (FPUSA) was founded in 1868 and was taken over in 1909 by Wolfgang Stamp. Over the years, FPUSA has established itself as the manufacturer of sanitary stainless steel pumps. The customers of FPUSA are spread over the nation. Today, FPUSA's pumps, mixers, and blenders can be found in many beverage, brewing, bio-pharmaceutical, and food-processing companies. However, most of the suppliers of FPUSA are within Wisconsin.

The Relationship between Supplier Selection and the Shipment

Most of the suppliers of FPUSA are within Wisconsin, usually hours away from the factory. FPUSA has worked with its suppliers for over 20 years. FPUSA chooses its suppliers based on the following criteria ordered by priority:

1. Product quality.
2. Reliability of delivery.
3. Product price.
4. Other intangible attributes, such as brand name and management team.

The reliability of delivery is rather important to FPUSA. Random delays are more detrimental to its operation than delays that can be expected in terms of length and frequency since FPUSA could adjust its operations accordingly if a delay was expected. This is a major reason why FPUSA chooses most of its suppliers from within the state.

In order to keep track of the performance of the suppliers, FPUSA developed a scoring system. An early delivery or a later delivery lowers the score of the supplier. Once it is found that the supplier has certain problems, FPUSA discusses the problem with the supplier and may even consider stopping the purchase contract with the current supplier if the problems continue.

Because most of the suppliers are within the state, the transportation delay does not have much impact on the business operation, nor does it bear significant cost implications. The delivery delay is usually due to the production at FPUSA's suppliers. For example, the suppliers may run short of materials or parts during their production. Once a delay is unavoidable, the suppliers usually give FPUSA an early notice.

The JIT Operation and Order Management

Starting in 2000, FPUSA changed from large inventory keeping to just-in-time operation (e.g., lean manufacturing). Currently, the inventory on average turns about every two months. FPUSA does not keep any finished goods on hand or produce any products in advance since most of the products are customized. The reasons why FPUSA changed to a JIT operation include:

- The JIT strategy improves the efficiency of operation by reducing the efforts of checking and keeping large quantities and a variety of raw materials.
- The strategy saves inventory-keeping costs.

In spite of the fact that the transportation cost goes up due to more frequent shipping, the entire economic and operation benefits outweigh the transportation cost.

The orders are managed through its Materials Requirement Planning System. The system continuously monitors quantities of raw materials on hand, referred to as inventory position. Once the inventory position falls below a predetermined threshold, an order is placed to the suppliers.

Impact of Late Delivery to FPUSA

As mentioned earlier, expected late delivery is usually communicated to FPUSA in advance. The major impacts of late deliveries on FPUSA include the following:

- Loss of production time at FPUSA may cause delay of delivery at FPUSA's customers, a clear ripple effect.
- Temporary shutdown and reboot of a machine mean a cost. Either leaving the machine running idle or shutting down the machine until production is restored requires additional cost. According to FPUSA, each incidence of shutdown and reboot costs about $100.

Late Delivery Impact on FPUSA as a Sender

FPUSA indicated that late delivery indeed affected its customers' operation and possibly caused a cost to its customers. In one example, FPUSA previously produced concrete pumps with customers of construction companies, who usually expect orders to arrive on time and usually schedule their personnel and other equipment on site correspondingly. Late delivery from FPUSA to its construction customers resulted in equipment running idle and personnel waiting, which was a sizeable cost to the customers at times.

But such a delay happened very rarely because the construction sites were usually close to FPUSA. When the delay did happen, it was more likely due to the longer-than-expected production time instead of transportation congestion.

Another example is with a customer manufacturing canned tomato product. The tomato-canning industry is seasonal only, with business in the summer from June to September. Therefore, a late delivery of pumps likely incurs significant production time loss for canned-tomato production. For a smooth operation, the manufacturer keeps two pumps on site, using one as a backup.

Suggestion on Improving the Interview Response

At the request of the research team at the University of Wisconsin–Madison, the Middleton Association of Manufacturers initially helped contact FPUSA, which proved to be productive for the case study. The university research team followed up with FPUSA on scheduling an interview.

FPUSA recommended the following approaches to improve the response rate:

- Contact the potential respondents through an acquaintance.
- Include monetary incentives in the mail.
- Send invitation by university office, which may be easier to be accepted than other agencies or individuals.

3.2.3 Capitol Sand and Gravel Company

Location: 8355 Stagecoach Rd., Cross Plains, Wisconsin
Time: March 8, 2012, 3:00 PM–3:40 PM
Interviewer: Qi Gong, project assistant, University of Wisconsin–Madison
Interviewee: Michael Gallagher (608-798-3051), president, Capitol Sand and Gravel Company Inc.

Company Background

Capitol Sand and Gravel Company (CSG) began its business as a family-owned local trucking company hauling construction materials. Later, it started its own raw material manufacturing business line, which processes gravel and sand for construction companies. Nowadays, raw material manufacturing has become its major business. All of its customers are in Wisconsin, and 90 percent are within Dane County, only 15–20 miles away. The company business is primarily from April to November each year.

Incoming Freight

Since CSG is a raw material processer, all the production materials are raw gravel and sand, which are mixed and processed by CSG for construction use. The only inbound freight is equipment and parts used for processing raw materials. CSG keeps a maintenance record on its major parts and equipment. Unless CSG is in an emergency situation, it makes orders a few weeks or months before a part is expected to wear out. Therefore, the shipping delay does not affect its business operation much.

In addition, most of the inbound parts are standard items requiring no customization. Once an order is made by CSG, the parts are delivered overnight or within a maximum of two days. There is one exception in which a specific piece of equipment usually needs 6–8 weeks lead time because most of the distributors in the United States do not keep enough stock of it and the equipment has to be manufactured in Germany. This one exception indeed incurs loss of production for CSG.

Shipping Needs and Cost

The major customers of CSG, mainly construction companies, usually have their own trucks. They haul their ordered materials. CSG's retail customers usually use for-hire carriers to ship their orders. In a case where CSG has to ship the material using local trucking companies, it will put a request online to inform the carriers. The shipping price is based on a relatively stable hourly rate and the expected shipping time. CSG does not pay extra shipping fees to accommodate additional hours traveled if there is a late delivery.

Impact of Transportation on Business Operation

Usually CSG needs one day or less to prepare the materials and contact truckers for shipping. Therefore, it also requires its customers to give a one-day notice before the required delivery time. This one-day notice allows CSG to generally deliver materials on time. Occasionally, customers may ask for same-day delivery. In such a case, CSG may be late in delivery for a very short time, for example as little as one hour or less. Realizing the difficulty to deliver within such a short time, the customers do not penalize for a late delivery, nor will CSG charge any additional fee to its truckers. But a constantly late delivery may lead to loss of customers.

Mr. Gallagher indicated that the reliability and cost of shipping was nevertheless one major concern that impeded business expansion to outside Wisconsin. The construction companies want to use local raw material suppliers as much as possible. Over the last 10 years, the material costs for construction companies have been practically equal to transportation cost.

A Major Difficulty to Identify the Value of Delay

Because CSG orders parts or equipment long before they are actually needed, it does not specify a date by which the shipment should be delivered, so there is no term of late delivery in this case.

Suggestions on Survey Improvements

Mr. Gallagher said that the major reason he finished the survey was that the survey contents closely related to his business. If the survey is designed more specific to his company, the response is expected to improve.

He also indicated that if the survey had been sent out by the Wisconsin Department of Transportation, he would probably have looked at it more closely because the company is a member of the Wisconsin Transportation Builders Association.

3.3 Implications of Case Studies on Estimating the Value of Delay

Although we were not able to cover more shippers, the experience and insights provided by our respondents should suggest a commonly shared acknowledgment among all the shippers. This helped us understand the impacts of delay on logistics operations, which are important to measuring the value of delay for businesses.

Clearly, there are varied impacts of delay on shippers at both shipping and receiving. At receiving, a late delivery is likely to result in difficulty in rearranging labor forces and machine use to prevent idling (e.g., as in the case of FPUSA). Once a late delivery arrives, extra working hours may be required for unloading and to rush product under a tight schedule. In addition, constant or unexpected delays may cause inventory keeping to increase, which implies additional cost. This additional inventory cost will be explained in Chapter 4. At shipping, a late delivery can result in extra shipping cost in the case of a private fleet like BWG. In fact, the interview helped us understand delay effects from different perspectives. The estimation methodology for VOD is expected to be varied.

Other than the explicit costs of delay such as extra expense in drivers' wages, oil and fuel, and vehicle maintenance, the unreliability of shipping also affects the strategic operation of businesses and therefore leads to additional costs. For example, as indicated during the interview with FPUSA, the suppliers were selected based on the reliability of delivery so that most of their current suppliers were located within the same state to reduce the uncertainty over shipment time. This led to an opportunity loss for FPUSA to purchase goods from cheaper but non-local suppliers. The presence of the implicit cost suggests that the willingness-to-pay method might appear appropriate because it allows shippers to implicitly consider all related cost.

CHAPTER 4 VALUE OF DELAY INVENTORY ANALYSIS

The major cost of delay for shippers who receive shipments is the extra wages for unloading hours and inventory holding. Although wages can be estimated by the product of the wage rate and delay, the estimation of inventory holding cost due to late delivery is difficult. This chapter makes an effort to evaluate additional logistics cost caused by delay.

4.1 Cost Components

Shippers are assumed to operate to minimize logistics cost. The total logistics cost consists of three cost components: freight expense (trucking cost in particular), in-transit inventory cost, and warehouse inventory holding cost.

4.1.1 Trucking Cost

Although the trucking cost comes from both inbound and outbound shipments, most companies only pay for inbound shipments, while the outbound trucking expenses are paid by customers. Therefore, in this project, only inbound trucking cost is considered in minimizing the total logistics cost.

Let C_T be the inbound trucking cost and $f(Q)$ be an empirically estimated relationship between the freight rate and the unit lot size. For both conceptual and practical reasons, Tyworth and Zeng (1998) noted that $f(Q)$ is a nonlinear function of Q because the cost per unit shipped rises more than proportionally as the quantity shipped is reduced. For example, the carrier may offer discounts from published rates. By fitting the representative rate data published by a major trucking company in 1995, Tyworth and Zeng (1998) suggest a multiplication function to calculate trucking cost based on order size, annual demand, and weight of goods.

$$C_T = f(Q) \cdot D = 2.319 \cdot (Q \cdot w)^{-0.3325} \cdot w \cdot D \qquad \text{(Eq. 4.1)}$$

where Q is the order size (in units), D is the annual demand (in units), and w is the weight of the goods (in pounds).

Given the inflation from consumer price index CPI (Table 4.1) for each year, Eq. 4.1 is adjusted from year 1998 to year 2011 by a factor of 1.48:

$$C_T = f(Q) \cdot D = 3.43 \cdot (Q \cdot w)^{-0.3325} \cdot w \cdot D \qquad \text{(Eq. 4.2)}$$

Table 4.1 Inflation Rate from CPI

Year	Annual Inflation	Year	Annual Inflation
2011	3.16%	1999	2.19%
2010	1.64%	1998	1.55%
2009	−0.34%	1997	2.34%
2008	3.85%	1996	2.93%
2007	2.85%	1995	2.81%
2006	3.24%	1994	2.61%
2005	3.39%	1993	2.96%
2004	2.68%	1992	3.03%
2003	2.27%	1991	4.25%
2002	1.59%	1990	5.39%
2001	2.83%	1989	4.83%
2000	3.38%	1988	4.08%

4.1.2 In-Transit Inventory Cost

In-transit inventory cost is caused by capital tied up with inventory during the transportation process, product shrinkage, damage, and any temporary storage cost. Tyworth and Zeng (1998) showed that the annual in-transit inventory carrying cost was not only affected by mean transit time but also decided by the total shipping volume per year.

The total in-transit inventory carrying cost is described by the product of annual demand D, mean transit time μ_T, and in-transit inventory cost per unit per day, which is y divided by 365:

$$C_{transit} = \frac{\mu_T D}{365} y \qquad \text{(Eq. 4.3)}$$

where μ_T is the mean transit time (in days), y is the inventory cost in transit (dollar per unit per year), and D is the annual demands.

4.1.3 Inventory Holding Cost at Warehouse

We assume the continuous review (Q, R) model (Figure 4.1) is adopted at the warehouse. Whenever the installation stock (physical inventory there) 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 Q, if 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 selected too low, the firms 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 affected by the order size or its inverse—the number of orders per year. The annual total ordering cost is simply equal to the cost per order multiplied by the number of orders per year. Total warehouse cost is shown as follows:

$$C_h = (\frac{Q}{2} + s)h \cdot + p\frac{n(R)}{T} + \frac{K}{T}$$
$$= (\frac{Q}{2} + R - \mu_x)h \cdot + p\frac{n(R)}{T} + \frac{K}{T} \quad \text{(Eq. 4.4)}$$

where Q is the order size, s is the safety stock $s = R - \mu_x$, h is the inventory hold cost (dollar 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 $s = R - \mu_x$, $n(R)$ is the expected shortage per order cycle, R is the recorder 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 transit time, v_0 is non-transportation such as pre-ordering time and processing time, and μ_x is the mean demand x during lead time ($\mu_x = \mu_L \cdot \mu_D$).

Given this specification, the first item in the equation above represents the warehouse inventory holding cost, and the second and third items represent the shortage cost and order cost, respectively.

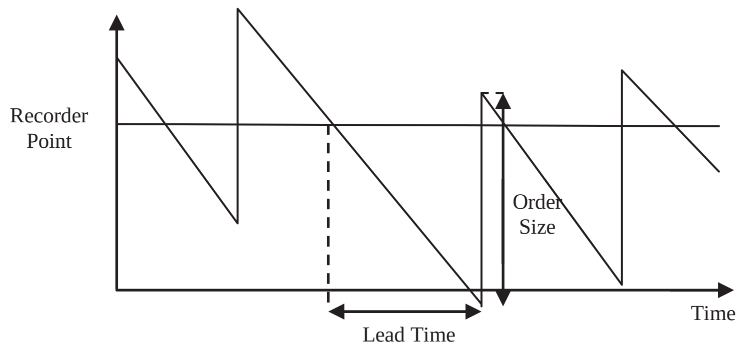

Figure 4.1 Illustration of (*Q*, *R*) Inventory Model

4.1.4 The Total Cost

By adding the three cost components listed in Eq. 4.2, Eq. 4.3, and Eq. 4.4, the following overall cost equation is obtained:

$$C_{overall} = C_T + C_{transit} + C_{holding}$$
$$= 3.43 \cdot (Q \cdot w)^{-0.3325} \cdot w \cdot D + \frac{\mu_T D}{365} y + (\frac{Q}{2} + R - \mu_x)h \cdot + p\frac{n(R)}{T} + \frac{K}{T} \quad \text{(Eq. 4.5)}$$

4.2 Numerical Tests

In general, the control parameters for a (*Q*, *R*) model depend on both the demand pattern and the lead time. The lead time variability often bears a negative impact on the inventory cost. Motivated by Bookbinder and Cakayildirim (1999), in which the random lead time can in fact be influenced by the decision maker, we conducted an analysis on the lead time effect from the perspective of mean transit time and its variations.

Beginning with a constant demand rate, lead time is treated as a random variable first in our test. For the purpose of not confusing readers by intricate distributions, only normal distribution is assumed here. A further development of the model allows us to examine the situation where both demand rate and lead time are random. The lead time demand, therefore, becomes a joint function of two normal distributions. Normal approximation is used to obtain mathematically tractable results.

Two types of services are considered during the test. The definitions of these two types can be found in the works of Tagaras (1989) and Xu et al. (2003). Type 1 service α presents the probability of not having stock-out:

$$\alpha = P(\text{actual lead time demand} \leq \text{inventory in stock when ordered}) \quad \text{(Eq. 4.6)}$$

where the actual lead time demand is the demand between placing an order and the actual arrival of the shipment. This is also known as an event-oriented performance criterion. The disadvantage of this type of service is that if a shipment fails to deliver before the occurrence of the stock-out, it does not matter how late it is.

Type 2 service, which is also called fill rate β, overcomes the above disadvantage by its quantity-oriented nature. It measures the expected amount of stock-out during a cycle. It is expressed by:

$$\beta = 1 - n(R) / \mu_x \quad \text{(Eq. 4.7)}$$

where $n(R)$ is the expected shortage per order cycle and μ_x is the expect cycle demand. In type 2 service, the influences of late shipments are different based on how late they are. A shipment having greater delay would contribute to more units of stock-out. Some technical details about type 2 service can be found in the work of Tyworth et al. (1996).

Four cases were tested based on different types of services and different random variables. The testing parameters were carefully selected from a comprehensive study done by LaLonde et al. (1988). In their research, 332 shippers and 123 warehouses provided useful information related to customer service, such as demand, lead time, and product value. These data were further categorized into nine industry groups. Shirley (2000) summarized their results by combining all the parameters into a master table. Table 4.2 shows the representative parameter for each industry type, adjusted by an inflation factor of 1.98 up to year 2011. Note that the warehouse holding cost, in-transit inventory cost, and shortage cost are based on the percentage of the unit item value. As the unit item value is adjusted by a factor of the inflation rate, these three cost parameters increase proportionally as well.

Table 4.2 Logistic Operation Data by Industry Type

		Food	Chemical	Pharma-ceuticals	Auto	Paper	Electronics	Clothing	Other Mfg.	Merchan-dise
		REPRESENTATIVE INDUSTRY								
DEMAND										
Mean of daily demand (units)	μ_D	121	26	9	16	13	29	16	21	4
Std. dev. of daily demand (units)	σ_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

4.2.1 Case 1: Type 1 Service with Random Lead Time and Deterministic Demand (α = 0.95)

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:

$$C_{overall} = 3.43\cdot(Q\cdot w)^{-0.3325}\cdot w\cdot D + \frac{\mu_T \cdot D}{365} y + (\frac{Q}{2} + R - \mu_x)h\cdot + p\frac{n(R)}{T} + \frac{K}{T}$$
$$= 3.43\cdot(Q\cdot w)^{-0.3325}\cdot w\cdot D + \frac{\mu_T \cdot D}{365} y + [\frac{Q}{2} + R - (\mu_T + v_0)\mu_D]h + p\cdot D\frac{n(R)}{Q} + D\frac{K}{Q}$$

(Eq. 4.8)

A type 1 service level of $\alpha = 0.95$ requires a certain level of reorder point R to ensure that the remaining inventory at the reorder point is sufficient to serve the 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 determined 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:

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

(Eq. 4.9)

where x represents the probability density function of the demand during lead time. By plugging Eq. 4.9 into the overall cost equation, we obtain:

$$C_{overall} = 3.43\cdot(Q\cdot w)^{-0.3325}\cdot w\cdot D + \frac{\mu_T \cdot D}{365} y + [\frac{Q}{2} + 1.645(\mu_D\sigma_T)]h + p\cdot D\frac{0.021\mu_D\sigma_T}{Q} + D\frac{K}{Q}$$
$$= 3.43D\cdot w^{0.6675}Q^{-0.3325} + (0.021\mu_D\sigma_T\cdot p + K)D\frac{1}{Q} + \frac{h}{2}Q + 1.645(\mu_D\sigma_T)h + \frac{\mu_T\cdot D}{365}y$$

(Eq. 4.10)

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 $C^*_{overall}$. However, the optimal order size Q is not affected by the change of mean transit time. The value of mean transit delay for the entire fleet is calculated by the following equation:

$$VOD_{fleet} = \frac{\partial C^*_{overall}}{\partial \mu_T} = \frac{D}{365} y \qquad \text{(Eq. 4.11)}$$

Table 4.3 summarizes the fleet value of mean transit delay. The 11-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 on December 22, 2011.

Table 4.3 Fleet Value of Mean Transit Delay for Case 1

		REPRESENTATIVE INDUSTRY								
		Food	Chemical	Pharma-ceuticals	Auto	Paper	Electronics	Clothing	Other Mfg.	Merchan-dise
Annual demand (units)	D	44165	9490	3285	5840	4745	10585	5840	7665	1460
In-transit holding cost ($/year)	y	3.70	37.83	17.25	16.21	6.83	2.70	9.27	8.62	7.37
Fleet VOD ($/day)	$(D/365)y$	655.97	1441.44	227.49	380.16	130.04	114.84	217.26	265.36	43.20
Fleet VOD ($/hr)	VOD_{fleet}	59.63	131.04	20.68	34.56	11.82	10.44	19.75	24.12	3.93

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 (15000 pounds per order in the largest case) are much less than any truck loading limit imposed by the Federal Highway Administration (Harwood, et al., 2003). Consequentially, there is only one vehicle associated with each order's transportation. The resulting single-vehicle value of mean transit delay is shown in Table 4.4.

Table 4.4 Single-Vehicle Value of Mean Transit Delay for Case 1

		REPRESENTATIVE INDUSTRY								
		Food	Chemical	Pharma-ceuticals	Auto	Paper	Electronics	Clothing	Other Mfg.	Merchan-dise
Annual demand (units)	D	44165	9490	3285	5840	4745	10585	5840	7665	1460
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
Trucks used per order		1	1	1	1	1	1	1	1	1
Annual truck usage	N	25	33	42	24	30	31	19	28	16
Single-vehicle VOD ($/hr)	VOD_{fleet}/N	2.39	3.97	0.49	1.44	0.39	0.34	1.04	0.86	0.25

From Table 4.4, it is found that the value of mean transit delay is extremely low for shippers. This can be explained by the fact that the prolonged mean transit time only incurs a minor change of in-transit holding cost to the shippers. Since they have contracts with their carriers, the carriers are actually paying for the extra truck operation cost such as fuel and salary, which is a major portion of the extra cost. The only thing shippers need to do is to order their supplies earlier. Bookbinder and Cakayildirim (1999) derived the expected inventory holding cost at the warehouse when an expedited lead time is shifted by a positive constant, with a deterministic demand. They found that it is the same cost as their original cost. Hence, in a general case, one can determine the optimal Q and s values as if no shift had occurred, and then calculate the optimal reorder point R by adding the shift parameter; the optimal Q needs no adjustment. Enlightened by this proof, it is easy to see that the change of mean transit time has little effect on the overall cost to shippers.

Unlike the effect of mean transit time, the change in transit time variation has a significant impact on the order size decision. As a consequence, the overall cost is altered accordingly, in addition to the change in the transportation (freight) cost and in-transit inventory cost. Table 4.5 summarizes the value of delay from the perspective of variation, where delay is calculated by the expectation:

$$\begin{aligned} E(delay) &= \int_0^{\mu_T} 0 f(t)dt + \int_{\mu_T}^{\infty} (t-\mu_T) f(t)dt \\ &= \int_{\mu_T}^{\infty} (t-\mu_T) f(t)dt \\ &= \sigma_T L(0) \\ &= 0.399\sigma_T \end{aligned} \qquad \text{(Eq. 4.12)}$$

Thus:

$$VOD_{fleet} = \frac{\partial C^*_{overall}}{\partial E(delay)} = \frac{\Delta C^*_{overall}}{\Delta E(delay)} = \frac{C^{*\,post\text{-}change}_{overall} - C^{*\,no\ change}_{overall}}{E^{post\text{-}change}_{delay} - E^{no\ change}_{delay}} \qquad \text{(Eq. 4.13)}$$

where the overall cost is:

$$C_{overall} = 3.43D \cdot w^{0.6675} Q^{-0.3325} + (0.021\mu_D\sigma_T \cdot p + K)D\frac{1}{Q} + \frac{h}{2}Q + 1.645(\mu_D\sigma_T)h + \frac{\mu_T \cdot D}{365} y \qquad \text{(Eq. 4.14)}$$

Table 4.5 shows that the chemical industry has the highest value of delay based on transit time variation ($46.08 per hour per vehicle) among nine industrial sections, followed by the food industry and then the automotive industry. Regular merchandise has the lowest value, which is $2.69 per hour per vehicle.

Table 4.5 Value of Delay Based on Transit Time Variation for Case 1

		REPRESENTATIVE INDUSTRY								
		Food	**Chemical**	**Pharma-ceuticals**	**Auto**	**Paper**	**Electronics**	**Clothing**	**Other Mfg.**	**Merchan-dise**
DEMAND										
Mean of daily demand (units)	μ_D	121	26	9	16	13	29	16	21	4
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
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
VOD										
VOD ($/hr) μ_T to σ_T^-		673.81	1521.24	162.70	247.06	135.85	120.49	136.96	175.71	43.03
VOD ($/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. fleet VOD		673.77	1520.69	162.50	246.93	135.81	120.44	136.91	175.55	43.03
Annual truck usage	N	25	33	42	24	30	31	19	28	16
Single-vehicle VOD ($/hr)		26.95	46.08	3.87	10.29	4.53	3.89	7.21	6.27	2.69

4.2.2 Case 2: Type 1 Service with Random Lead Time and Random Demand (α = 0.95)

In case 2, the demand is also normally distributed with a mean μ_D and standard deviation σ_D. The derivation of the overall cost function is very similar to the function in the first case, except the demand during lead time becomes a product of two random normal variables. This is expressed by (Blumenfeld, 2001):

$$\sigma_x{}^2 = \mu_D{}^2\sigma_T{}^2 + \sigma_D{}^2(\mu_T + v_0)^2 + \sigma_T{}^2\sigma_D{}^2 \qquad \text{(Eq. 4.15)}$$
$$\mu_x = \mu_D(\mu_T + v_0)$$

For the same reason, for $\alpha = 0.95$, Z is found to be 1.645 from the standard normal table. This gives $R = \sigma_x Z + \mu_x = 1.645 \cdot \sqrt{\mu_D{}^2\sigma_T{}^2 + \sigma_D{}^2(\mu_T + v_0)^2 + \sigma_T{}^2\sigma_D{}^2} + \mu_D(\mu_T + v_0)$. From the standard loss table, the value of $L(Z)$ is $L(Z) = L(1.645) = 0.021$. Thus:

$$\begin{aligned} n(R) &= \int_0^R 0\, f(x)dx + \int_R^\infty (x-R) f(x)dx \\ &= \int_R^\infty (x-R) f(x)dx \\ &= \sigma_x L(Z) \\ &= 0.021 \cdot \sqrt{\mu_D{}^2\sigma_T{}^2 + \sigma_D{}^2(\mu_T + v_0)^2 + \sigma_T{}^2\sigma_D{}^2} \end{aligned} \qquad \text{(Eq. 4.16)}$$

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

(Eq. 4.17)

Unlike the first case, the equation above shows that the mean transit time has an influence on both warehouse inventory holding cost and in-transit inventory cost, 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. The following equation shows the necessity of calculating optimal Q before obtaining the value of mean transit delay, where Q is unavoidable in the expression of $\partial C^*_{overall} / \partial \mu_T$:

$$VOD_{fleet} = \frac{\partial C^*_{overall}}{\partial \mu_T}$$

$$= (0.021pD\frac{1}{Q} + 1.645 \cdot h)\frac{\partial\sqrt{\mu_D{}^2\sigma_T{}^2 + \sigma_D{}^2(\mu_T + v_0)^2 + \sigma_T{}^2\sigma_D{}^2}}{\partial \mu_T} + \frac{D}{365}y$$

$$= (0.021pD\frac{1}{Q} + 1.645 \cdot h)\frac{\sigma_D{}^2(\mu_T + v_0)}{\sqrt{\mu_D{}^2\sigma_T{}^2 + \sigma_D{}^2(\mu_T + v_0)^2 + \sigma_T{}^2\sigma_D{}^2}} + \frac{D}{365}y$$

(Eq. 4.18)

Table 4.6 summarizes the value of mean transit time for case 2.

Table 4.6 Value of Mean Transit Delay for Case 2

		REPRESENTATIVE INDUSTRY								
		Food	**Chemical**	**Pharma-ceuticals**	**Auto**	**Paper**	**Electronics**	**Clothing**	**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
Fleet VOD ($/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
Fleet VOD ($/hr)	VOD_{fleet}	225.17	493.77	58.68	88.27	44.23	36.34	49.36	59.76	12.36
Annual truck usage	N	24	29	36	22	27	28	18	25	16
Single-vehicle VOD ($/hr)	$\frac{VOD_{fleet}}{N}$	9.38	17.03	1.63	4.01	1.64	1.30	2.74	2.39	0.77

Table 4.7 summarizes the value of delay based on variations for case 2. In fact, since it is difficult to directly take a derivative of the overall cost with respect to expected delay in any of the four cases, the equation used in case 1 has to be consistently applied to obtain the value of expected delay for all four cases. The only difference lies in the expression of the overall cost in each case. This being said, recall the equation with different overall costs for case 2:

$$VOD_{fleet} = \frac{\partial C^*_{overall}}{\partial E(delay)} = \frac{\Delta C^*_{overall}}{\Delta E(delay)} = \frac{C^{*post\text{-}change}_{overall} - C^{*no\ change}_{overall}}{E^{post\text{-}change}_{delay} - E^{no\ change}_{delay}} \qquad \text{(Eq. 4.19)}$$

where

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

(Eq. 4.20)

Table 4.7 Value of Delay Based on Transit Time Variation for Case 2

		REPRESENTATIVE INDUSTRY								
		Food	**Chemical**	**Pharma-ceuticals**	**Auto**	**Paper**	**Electronics**	**Clothing**	**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)	σ_D	72.6	15.6	5.4	9.6	7.8	17.4	9.6	12.6	2.4
LEAD TIME										
Constant order processing days	v_0	2.00	2.00	2.00	2.00	2.00	2.00	1.00	1.00	1.00
Mean transit time (days)	μ_T	2.50	5.00	3.00	4.00	3.00	4.00	4.00	4.00	4.00
Std. dev. of transit time (days)	σ_T	0.50	1.20	1.00	1.60	1.20	2.20	2.20	2.00	2.00
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
VOD										
VOD ($/hr) μ_T to σ_T^-		157.37	534.92	82.58	150.46	47.80	71.19	81.36	126.04	29.80
VOD ($/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. fleet VOD		174.00	587.76	89.78	162.11	52.53	76.77	87.74	134.33	31.79
Annual truck usage	N	24	29	36	22	27	28	18	25	16
Single-vehicle VOD ($/hr)		7.25	20.27	2.49	7.37	1.95	2.74	4.87	5.37	1.99

These results show that under the condition where lead time and demand are both random, the value of mean transit time becomes a significant number compared to case 1. Therefore, the shippers need to adjust their optimal policy to compromise the change in mean transit time. The value of delay for variation, however, has values that are less than half of that in case 1.

4.2.3 Case 3: Type 2 Service with Random Lead Time and Deterministic Demand (β = 0.95)

Service level 0.95 for type 2 means that 5 percent of the demand during lead time is not satisfied. This can be expressed by:

$$\frac{n(R)}{\mu_x} = \frac{\int_0^R 0 f(x)dx + \int_R^\infty (x-R) f(x)dx}{\mu_x} = \frac{\int_R^\infty (x-R) f(x)dx}{\mu_x} = \frac{\sigma_x L(Z)}{\mu_x} = 0.05 \qquad \text{(Eq. 4.21)}$$

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

$$L(Z) = 0.05\frac{\mu_x}{\sigma_x} = 0.05\frac{\mu_D(\mu_T + v_0)}{\mu_D \sigma_T} = 0.05\frac{(\mu_T + v_0)}{\sigma_T} \qquad \text{(Eq. 4.22)}$$

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

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

(Eq. 4.23)

Notice that Z is affected by μ_x, and μ_x is affected by μ_T, which makes it difficult to obtain the expression $\frac{\partial Z}{\partial \mu_T}$. Accordingly, it is not viable to calculate VOD_{fleet} for mean time change as:

$$\frac{\partial C^*_{overall}}{\partial \mu_T} = \frac{D}{365} y + \mu_D \sigma_T h \frac{\partial Z}{\partial \mu_T} + \frac{0.05}{T} D\mu_D p \qquad \text{(Eq. 4.24)}$$

We use an alternative equation based on a change of 20 percent mean transit time to run the test:

$$VOD_{fleet} = \frac{\partial C^{*}_{overall}}{\partial \mu_x} \approx \frac{\Delta C^{*}_{overall}}{\Delta \mu_x} = \frac{C^{*\,post\text{-}change}_{overall} - C^{*\,no\ change}_{overall}}{\mu_x^{\,post\text{-}change} - \mu_x^{\,no\ change}} \qquad \text{(Eq. 4.25)}$$

Table 4.8 summarizes these results. The value of delay based on transit time variation is summarized in Table 4.9 for case 3.

The similarity between the value of delay based on transit time variation in Table 4.5 and Table 4.9 is due to the same lead time demand pattern. The minor difference is caused by the different service level requirements.

4.2.4 Case 4: Type 2 Service with Random Lead Time and Random Demand (β = 0.95)

In case 3, it has already been found that for $\beta = 0.95$, $n(R) = 0.05\mu_x$ and. Also, in case 2, we proved that $\sigma_x^{\,2} = \mu_D^{\,2}\sigma_T^{\,2} + \sigma_D^{\,2}(\mu_T + v_0)^2 + \sigma_T^{\,2}\sigma_D^{\,2}$ and $\mu_x = \mu_D(\mu_T + v_0)$. Combining these equations, $L(Z)$ is expressed as follows in case 4:

$$L(Z) = 0.05\frac{\mu_x}{\sigma_x} = 0.05\frac{\mu_D(\mu_T + v_0)}{\sqrt{\mu_D^{\,2}\sigma_T^{\,2} + \sigma_D^{\,2}(\mu_T + v_0)^2 + \sigma_T^{\,2}\sigma_D^{\,2}}} \qquad \text{(Eq. 4.26)}$$

By obtaining the corresponding Z value from the standard loss table, $C_{overall}$ for case 4 is expressed as:

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

(Eq. 4.27)

Table 4.10 shows the value of mean transit delay based on a change of 20 percent mean transit time. Table 4.11 shows the value of delay based on transit time variation.

Table 4.8 Value of Mean Transit Delay for Case 3

		REPRESENTATIVE INDUSTRY								
		Food	**Chemical**	**Pharma-ceuticals**	**Auto**	**Paper**	**Electronics**	**Clothing**	**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)	σ_D	72.6	15.6	5.4	9.6	7.8	17.4	9.6	12.6	2.4
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
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										
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
VOD										
VOD ($/hr) μ_T to σ_T^-		121.38	271.57	49.69	64.10	23.81	19.64	31.86	45.97	5.29
VOD ($/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. fleet VOD		121.41	270.02	49.25	63.64	23.94	19.78	32.05	45.57	5.32
Annual truck usage	N	20	22	26	18	21	22	15	20	15
Single-vehicle VOD ($/hr)		6.07	12.27	1.89	3.54	1.14	0.90	2.14	2.28	0.35

Table 4.9 Value of Delay Based on Transit Time Variation for Case 3

		REPRESENTATIVE INDUSTRY								
		Food	Chemical	Pharma-ceuticals	Auto	Paper	Electronics	Clothing	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)	σ_D	72.6	15.6	5.4	9.6	7.8	17.4	9.6	12.6	2.4
LEAD TIME										
Constant order processing days	v_0	2.00	2.00	2.00	2.00	2.00	2.00	1.00	1.00	1.00
Mean transit time (days)	μ_T	2.50	5.00	3.00	4.00	3.00	4.00	4.00	4.00	4.00
Std. dev. of transit time (days)	σ_T	0.50	1.20	1.00	1.60	1.20	2.20	2.20	2.00	2.00
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	2168	436	126	322	224	481	401	388	98
Z for σ_T		−0.100	0.240	0.490	0.650	0.235	0.635	0.635	0.780	0.780
Overall cost ($) for σ_T	C^*	52080	101015	6461	20076	8436	7309	14309	12347	4628
Order size for σ_T^-	Q	2168	436	126	322	224	481	401	388	98
Z for σ_T^-		−0.295	0.070	0.345	0.510	0.070	0.495	0.495	0.650	0.650
Overall cost ($) for σ_T^-	$C^*_{(-)}$	51969	100219	6388	19856	8366	7158	14137	12140	4572
Order size for σ_T^+	Q	2168	436	126	322	224	481	401	388	98
Z for σ_T^+		0.050	0.360	0.605	0.755	0.360	0.740	0.740	0.880	0.880
Overall cost ($) for σ_T^+	$C^*_{(+)}$	52212	101845	6542	20310	8513	7469	14490	12566	4688
VOD ($/hr)										
VOD μ_T to σ_T^-		254.08	755.37	83.19	157.21	66.29	78.17	88.73	117.90	31.99
VOD μ_T to σ_T^+		298.92	788.21	91.74	166.30	72.96	82.75	93.93	125.15	33.95
Avg. fleet VOD		276.50	771.79	87.47	161.76	69.63	80.46	91.33	121.53	32.97
Annual truck usage	N	20	22	26	18	21	22	15	20	15
Single-vehicle VOD		13.82	35.08	3.36	8.99	3.32	3.66	6.09	6.08	2.20

Table 4.10 Value of Mean Transit Delay for Case 4

		REPRESENTATIVE INDUSTRY								
		Food	**Chemical**	**Pharma-ceuticals**	**Auto**	**Paper**	**Electronics**	**Clothing**	**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)	σ_D	72.6	15.6	5.4	9.6	7.8	17.4	9.6	12.6	2.4
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
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										
Order size for μ_T	Q	2168	436	126	322	224	481	401	388	98
Z for μ_T		1.015	1.030	1.055	1.080	1.030	1.080	1.080	1.120	1.120
Overall cost ($) for μ_T	C^*	56760	116409	7255	21659	9827	8434	15585	13420	4919
Order size for μ_T^-	Q	2127	419	120	310	219	466	391	371	96
Z for μ_T^-		1.015	1.035	1.075	1.110	1.035	1.100	1.100	1.160	1.160
Overall cost ($) for μ_T^-	$C^*_{(-)}$	55524	110941	6792	20813	9537	8115	15139	12831	4823
Order size for μ_T^+	Q	2208	453	133	334	229	495	410	404	99
Z for μ_T^+		1.010	1.020	1.040	1.070	1.020	1.070	1.070	1.100	1.100
Overall cost ($) for μ_T^+	$C^*_{(+)}$	57966	121719	7710	22535	10106	8764	16045	14029	5024
VOD										
VOD ($/hr) μ_T to σ_T^-		224.78	497.03	70.06	96.18	43.90	36.26	50.73	66.90	10.97
VOD ($/hr) μ_T to σ_T^+		219.25	482.72	69.03	99.56	42.37	37.49	52.18	69.24	11.89
Avg. fleet VOD		222.02	489.88	69.55	97.87	43.13	36.87	51.46	68.07	11.43
Annual truck usage	N	20	22	26	18	21	22	15	20	15
Single-vehicle VOD ($/hr)		11.10	22.27	2.67	5.44	2.05	1.68	3.43	3.40	0.76

Table 4.11 Value of Delay Based on Transit Time Variation for Case 4

		REPRESENTATIVE INDUSTRY								
		Food	Chemical	Pharma-ceuticals	Auto	Paper	Electronics	Clothing	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)	σ_D	72.6	15.6	5.4	9.6	7.8	17.4	9.6	12.6	2.4
LEAD TIME										
Constant order processing days	v_0	2.00	2.00	2.00	2.00	2.00	2.00	1.00	1.00	1.00
Mean transit time (days)	μ_T	2.50	5.00	3.00	4.00	3.00	4.00	4.00	4.00	4.00
Std. dev. of transit time (days)	σ_T	0.50	1.20	1.00	1.60	1.20	2.20	2.20	2.00	2.00
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	2168	436	126	322	224	481	401	388	98
Z for σ_T		1.015	1.030	1.055	1.080	1.030	1.080	1.080	1.120	1.120
Overall cost ($) for σ_T	C^*	56760	116409	7255	21659	9827	8434	15585	13420	4919
Order size for σ_T^-	Q	2168	436	126	322	224	481	401	388	98
Z for σ_T^-		1.010	1.015	1.035	1.055	1.015	1.055	1.055	1.080	1.080
Overall cost ($) for σ_T^-	$C^*_{(-)}$	56701	115875	7204	21499	9778	8324	15460	13244	4872
Order size for σ_T^+	Q	2168	436	126	322	224	481	401	388	98
Z for σ_T^+		1.015	1.040	1.075	1.110	1.040	1.110	1.110	1.160	1.160
Overall cost ($) for σ_T^+	$C^*_{(+)}$	56805	116929	7313	21853	9874	8568	15737	13620	4974
VOD ($/hr)										
VOD μ_T to σ_T^-		135.55	506.20	58.32	113.85	45.67	57.02	64.73	99.86	27.09
VOD μ_T to σ_T^+		102.20	493.99	66.66	137.91	44.56	69.14	78.48	114.12	30.96
Avg. fleet VOD		118.88	500.10	62.49	125.88	45.12	63.08	71.60	106.99	29.03
Annual truck usage	N	20	22	26	18	21	22	15	20	15
Single-vehicle VOD		5.94	22.73	2.40	6.99	2.15	2.87	4.77	5.35	1.94

4.3 Discussion

The (Q, R) inventory model was adopted for this analysis. It sheds light on other practices such as the periodic review policy of inventory management. To summarize the results, Table 4.12 provides the average value of delay for all four cases, categorized according to industrial group, in terms of mean transit time and its variations.

Table 4.12 Average Single-Vehicle Value of Delay

		REPRESENTATIVE INDUSTRY								
	Case	Food	Chemical	Pharma-ceuticals	Auto	Paper	Electronics	Clothing	Other Mfg.	Merchan-dise
Value of delay for mean transit time ($/hr)	1	2.39	3.97	0.49	1.44	0.39	0.34	1.04	0.86	0.25
	2	9.38	17.03	1.63	4.01	1.64	1.30	2.74	2.39	0.77
	3	6.07	12.27	1.89	3.54	1.14	0.90	2.14	2.28	0.35
	4	11.10	22.27	2.67	5.44	2.05	1.68	3.43	3.40	0.76
	Avg.	**7.24**	**13.89**	**1.67**	**3.61**	**1.31**	**1.06**	**2.34**	**2.23**	**0.53**
Value of delay for variation ($/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 5 A PILOT SURVEY

5.1 Objective of the Survey

The survey aimed to provide data not only for evaluating the value of time due to en route highway delay from the perspective of shippers, but also for ranking different delay components.

5.2 Sample Design

To quantify the value of delay due to transportation congestion, the stated preference survey method is implemented in 12 hypothetical scenarios. In each scenario, two alternatives with different combinations of shipping characteristics (i.e., shipping delay and additional shipping cost) are offered for the respondents to select from, based on their preferences. The first alternative runs a late delivery. The second alternative has on-time delivery with an additional monetary cost. The amount of delay in the first alternative and the additional cost in the second alternative vary among these 12 hypothetical scenarios.

The survey also documents the shippers' characteristics, which include industry type and normal travel time specified for a typical shipment (also denoted as the average trip length per truck). In addition, survey participants' ranking of the importance of four different delay components was collected for later use in the AHP. Detailed information about the survey design can be found in the survey cover letter in Appendix A, and a sample survey questionnaire is in Appendix B.

CHAPTER 6 VALUE OF DELAY TO SHIPPERS

6.1 Descriptive Analysis

A total of 600 surveys have been sent by the writing of this report. The response rate is about 4 percent. About 24 AHP records have been created, and 288 WTP records have been created for regression analysis.

6.2 Analytic Hierarchical Process

Multiple factors contribute to the late delivery of shipments, such as unexpectedly longer production time, delay at a distribution center, and congestion during transportation. To investigate the importance of congestion to late delivery, we have made efforts to prioritize and measure the relative importance of the contributing various factors through an analytic hierarchy process.

6.2.1 Methodology

The analytic hierarchy process is a structured technique initially proposed by Satty (1977) for prioritizing a set of alternatives. Since the AHP provides a systematic approach to convert qualitative judgments into numerical values, it has also been applied to the areas of decision making and alternative ranking.

Usually, the AHP decomposes a decision or priority problem into a hierarchy of independent sub-problems in its first step. For example, a problem of prioritizing several investment projects can be decomposed into a series of prioritization problems by different criteria, such as investment risk, expected return, and liquidity. To prioritize alternatives, a series of pair-wise comparisons are conducted for each combination of two alternatives under each criterion. In each comparison, the less important/favored alternative is marked by the decision maker and then assigned a numerical value of 1 by default, while the other alternative is assigned a greater value based on its relative importance or superiority compared with the less important alternative. The pair-wise comparison scale used in Satty’s study is shown in Table 6.1.

Table 6.1 The Analytic Hierarchy Process Pair-Wise Comparison Scale

Intensity of Importance	Definition	Explanation
1	Equal importance	Two elements contribute equally to the problem
3	Moderate importance	Experience and judgment moderately favor one element over another (one element is moderately more important than the other)
5	Strong importance	Experience and judgment strongly favor one element over another (one element is strongly more important than the other)
7	Very strong importance	One element is favored very strongly over another; its dominance is demonstrated in practice
9	Extreme importance	The evidence favoring one element over another is of the highest possible order of affirmation
Intensities of 2, 4, 6, and 8 can be used to express intermediate values.		

After evaluating the relative importance for each pair of alternatives with respect to criterion *c*, we organized the results into a judgment matrix:

$$A_c = \begin{bmatrix} a_{c,11} & a_{c,12} & \dots & a_{c,1n} \\ a_{c,21} & a_{c,22} & \dots & a_{c,2n} \\ \dots & \dots & \dots & \dots \\ a_{c,n1} & a_{c,n2} & \dots & a_{c,nn} \end{bmatrix} \quad \text{(Eq. 6.1)}$$

where $a_{c,ij}$ represents the evaluated relative importance of the alternative *j* as compared to the alternative *i* under criterion *c*. For example, if the alternative *i* is assigned a numerical value of 1 (i.e., is recognized as less important), and the alternative *j* is assigned a greater value *t* (i.e., is recognized as more important), then $a_{c,ij} = t$. On the other hand, if the alternative *j* is assigned 1 and the alternative *i* is assigned a greater value *t*, then $a_{c,ij} = 1/t$. It is obvious that a_{ij} has the following properties:

1. $a_{c,ij} > 0$
2. $a_{c,ij} = 1/a_{c,ji}$
3. $a_{c,ii} = 1$

After construction of the judgment matrix A_c, the absolute importance or priority of each alternative is estimated as the eigen vector W_c of the judgment matrix A_c:

$$A_c W_c = \lambda_{\max c} W_c \quad \text{(Eq. 6.2)}$$

where $W_c = [w_{c.1}, w_{c,2}, \dots, w_{c,n}]$ is the eigen vector of the matrix A_c with $w_{c,i}$ representing the importance or weight of the alternative *i* with respect to the criterion *c*, and λ_{max} represents the maximum eigen value among all eigen values of the matrix A_c.

By repeating such pair-wise comparisons in each sub-problem, the importance of each alternative *i* under each criterion *c* is obtained. To estimate the overall importance w_i for each alternative *i* to the problem or decision of interest, it is necessary to first understand the importance of each criterion to the overall problem. This is accomplished by the same technique used to estimate the importance of alternatives. The only difference is that the criteria themselves are treated as alternatives.

Denote the importance of a criterion *c* as w_c. Then the overall importance w_i of an alternative *i* is obtained as the sum of its importance under each criterion weighted by the importance of the criterion:

$$w_i = \sum_c w_c w_{c,\,i} \qquad \text{(Eq. 6.3)}$$

6.2.2 Application of the AHP to Estimate the Importance for Different Delay Components

As discussed above, a late delivery to a customer could result from several factors, which in turn interact with each other and aggravate the delay. For example, an unexpectedly longer production results in a late delivery of finished goods to carriers, who may in turn have to schedule shipping at rush hour and increase its exposure to congestion. To investigate the importance of various factors on a final late delivery, the AHP approach has been employed to prioritize and measure the relative importance for various factors.

Figure 6.1 represents the AHP structure used in this study. The various factors that possibly lead to shipment delay are first grouped into the following four components by shipment stage in which a factor is most likely to happen:

- En route delay: The delay happens in the transportation process due to factors such as congestion, traffic accidents, etc.
- Delay at the collection point: The shipment leaves the shipper's site later than expected due to factors such as delay of production, stock-out of goods to send, a shortage of drivers/vehicles to deliver the goods, etc.
- Delay at the transfer point: The delay happens at the dock, airport, or distribution center where shipments are consolidated, distributed, and/or transferred from one transportation mode to another. A direct shipment from shippers to carriers is free of the risk of being delayed at the transfer point.
- Delay at the delivery point: Even after a shipment has arrived at the customer's site, there might still be a time span before it is actually delivered due to the lack of warehouse space or unloading bays, etc.

The goal is to rank these four delay components. It should be noted that a decomposition of the goal here is unnecessary, given the relatively simple and clear structure of the problem.

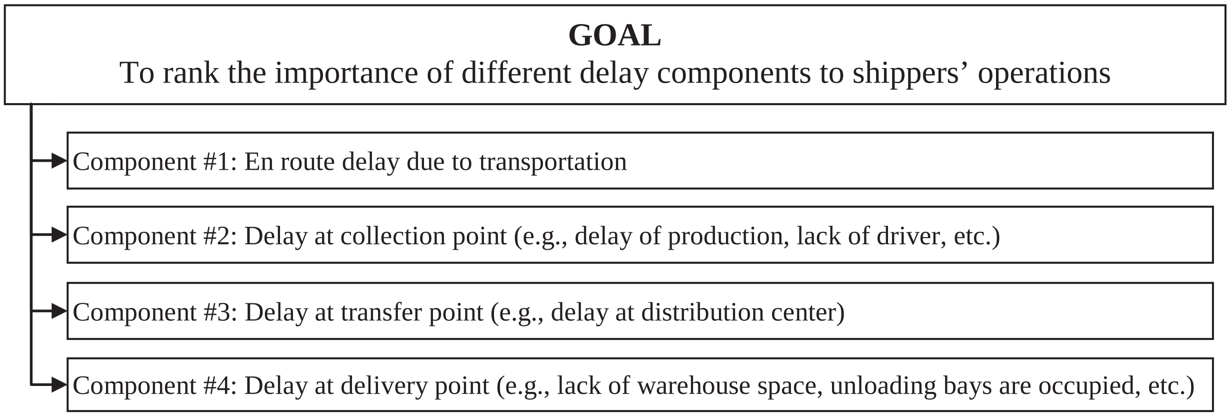

Figure 6.1 Analytic Hierarchy Process Structure for Delay Component Ranking

With the four components listed in Figure 6.1, a total of 12 comparisons need to be completed by each respondent. In order to reduce the survey burden, the original pair-wise comparison design was revised into a numeric rating scale design, where each respondent is required to rate the importance of each delay component on a scale from 0 to 10, with 0 being the least important and 10 being the most important. The design is shown in Figure 6.2.

Ranking Delay Components

Please assess the following delay factors using a number from 0 to 10 with "0" being least relevant and "10" being most important.

Aspect of the delay	Circle a number indicating importance (0-10 scale)
Delay <u>due to transportation</u>	Least … Most 0 1 2 3 4 5 6 7 8 9 10
Delay <u>at collection point</u> (e.g., delay of production, lack of driver, etc.)	Least … Most 0 1 2 3 4 5 6 7 8 9 10
Delay <u>at transfer point</u> (e.g., delay at distribution center)	Least … Most 0 1 2 3 4 5 6 7 8 9 10
Delay at <u>delivery point</u> (e.g., lack of warehouse space, unloading bays are occupied, etc.)	Least … Most 0 1 2 3 4 5 6 7 8 9 10

Figure 6.2 Survey Design for Ranking Delay Components

Given the rating for each component, the relative importance between two components is estimated as the ratio between their rates. Before estimating the relative importance, the rating number is first rescaled into a number between 1 and 11 by adding 1 to the original rating number to avoid a ratio comparison with 0. Then the relative importance of the component j as compared to the component i is obtained as the ratio of their adjusted ratings.

6.2.3 AHP Analysis Results

A total of 24 completed responses have been collected in the shipper surveys. According to the AHP estimation method discussed in Section 6.2.1 , the importance of delay components is estimated for each respondent as the eigen vector *w*, where each element in *w* represents the relative weight or importance for each corresponding delay component. The second column in Table 6.2 summarizes the average relative importance for each delay component for 24 respondents. The third column shows the average importance rate obtained from the questionnaire without scaling.

Table 6.2 Importance of Different Delay Components

Delay Component	Average Relative Importance Based on AHP	Average Importance Rate from Original Questionnaire
En route delay	29.2%	6.21
Delay at collection point	29.1%	5.94
Delay at transfer point	18.6%	3.89
Delay at delivery point	23.1%	4.47

The results indicate that the importance obtained from the AHP analysis is consistent with the original importance rating results. The transportation delay is the most important factor that affects the stakeholders' operation, with delay at the collection point ranking as the second most important issue. The results reveal that the delay at the transfer point is not likely to cause significant impact to their operation. One possible reason is that some of the shippers deliver goods directly to their customers without using a distribution center or an intermediate facility.

The results have important implications on the analysis of the value of delay. First, the importance of en route delay justifies the emphasis of measuring the value of delay caused by extra time spent during the transportation process, making the WTP method appropriate for the analysis. On the other hand, the relative importance of different delay components provides a weight basis on which the monetary value of delay could be split by the stage of delivery. Though the estimate of value of delay in each stage by this split method is not accurate, a rough examination of the magnitude of the impact of delay that occurs in different processes could be obtained, which is not available otherwise.

6.3 Multinomial Logit (MNL) Model

In the stated preference survey, the participants were asked to select their own preference between two options. One option is to travel on a congested road with a certain amount of delay. The other option is to pay an extra service fee, such as a toll, to avoid congestion. Their non-congestion travel time is also recorded for use in the analysis.

We consider the following utility function:

$$U_i = \alpha C_i + \beta TT_i \quad \text{(Eq. 6.4)}$$

where U_i is the utility for individual i; C_i is the extra payment to avoid congestion, such as tolling; and TT_i is the actual travel time affected by non-congestion travel time NT_i and delay D_i. Note that $TT_i = NT_i + D_i$; α and β are the coefficients.

Assume option 1 is the congestion-free service. The likelihood of choosing the congestion-free service is:

$$P_i(U_i^1) = e^{U_i^1} / (e^{U_i^1} + e^{U_i^2}) = e^{\alpha C_i^1 + \beta TT_i^1} / (e^{\alpha C_i^1 + \beta TT_i^1} + e^{\alpha C_i^2 + \beta TT_i^2}) \quad \text{(Eq. 6.5)}$$

By using the maximum likelihood method to fit our data of participants' choices, we obtain the parameters presented in Table 6.3.

Table 6.3 MNL Model Results

	Coefficient of Payment	Coefficient of Actual Travel Time	Value of Time ($/Minute)	Value of Time ($/hr)
All Companies	0.01896	0.01763	0.92985	55.7911

In Table 6.3, the value of time is equal to the coefficient of actual travel time divided by the coefficient of payment. Since we are particularly interested in the value of delay, which is the value of being late in dollars per hour, we reconsider another utility function:

$$U_i^{'} = \alpha C_i + \beta D_i \quad \text{(Eq. 6.6)}$$

We observe that the likelihood of choosing the congestion-free service is therefore:

$$P_i(U_i^{1'}) = e^{U_i^{1'}} / (e^{U_i^{1'}} + e^{U_i^{2'}}) = e^{\alpha C_i^1 + \beta D_i^1} / (e^{\alpha C_i^1 + \beta D_i^1} + e^{\alpha C_i^2 + \beta D_i^2}) \quad \text{(Eq. 6.7)}$$

Multiply the nominator and denominator by $e^{\beta NT_i}$, and the above equation changes into:

$$P_i(U_i^{1'}) = e^{\beta NT_i} e^{U_i^{1'}} / e^{\beta NT_i} (e^{U_i^{1'}} + e^{U_i^{2'}}) = e^{\alpha C_i^1 + \beta (NT_i + D_i^1)} / (e^{\alpha C_i^1 + \beta (NT_i + D_i^1)} + e^{\alpha C_i^2 + \beta (NT_i + D_i^2)}) \quad \text{(Eq. 6.8)}$$

Due to the assumption that $TT_i = NT_i + D_i$, we can see that $P_i(U_i^{1'})$ is exactly the same as $P_i(U_i^1)$. This means that maximizing the likelihood of either utility would also maximize the likelihood of the other one. In fact, we tested $U_i' = \alpha C_i + \beta D_i$ with our data and got the coefficients in Table 6.4.

Table 6.4 New Results of MNL Model

	Coefficient of Payment	Coefficient of Actual Travel Time	Value of Time ($/Minute)	Value of Time ($/hr)
All Companies	0.01896	0.01763	0.92985	55.7911

This result shows that if we assume the value of delay has a uniform value for every company, the two utilities above are equivalent. In other words, the value of time and the value of delay are the same. However, in reality this assumption is rarely true. Different companies have their own characteristics. These characteristics may be not the same, such as the length of the trip/travel or the tightness of the delivery/pickup window.

The concept of the value of time is first used for commuter vehicles, which usually take 20–60 minutes traveling from home to work or a restaurant/store. Commuters' value of time or value of being late is pretty consistent because the majority of them have a value that is near the population mean. On the other hand, in the freight area, travel time ranges from one hour to a few days. No significant portion of the trips gathers around the population mean. A unified value of time or value of being late cannot embrace all the trips within freight transportation. We propose the following utility function to address this problem, using percentage delay instead of the absolution value:

$$U_i' = \alpha C_\mathrm{i} + \beta PD_\mathrm{i} \qquad \text{(Eq. 6.9)}$$

where PD_i is the percentage delay based on the individual congestion-free travel time. For example, a 30-minute delay with five hours of travel time makes $PD_i = 10$ (10 percent). Then we can find the value of percentage delay in Table 6.5.

Table 6.5 Value of Reliability Using MNL Model

	Coefficient of Payment	Coefficient of Percentage Delay	Dollar per Percentage Delay
All Companies	0.04004	0.01410	0.35215

This result allows us to calculate the value of delay in each particular case. For example, in urban freight transport, a 30-minute delay during one hour of travel accounts for up to 50 percent of the total time. The value of delay in this case would then be $0.35215*50/30 minutes = $17.6075/30 minutes = $35.215/hour. In contrast, in inter-city transportation, a 30-minute delay during five days of travel would only indicate a value of delay of $0.293 per hour.

CHAPTER 7 DISCUSSIONS AND FINAL REMARKS

This research project examined the impacts of congestion on shippers' operations. Initially, three on-site interviews were conducted to help us identify the major effects of highway delay. The insights provided by these logistics managers were used to develop a comprehensive survey for major manufacturers and wholesalers within Texas and Wisconsin. A total of 600 surveys were sent out with a response rate of about 4 percent. About 24 records were created for the AHP, and 288 WTP records were created for regression analysis.

The AHP indicates that en route transportation delay is the most important component of delay, followed by delay at the item collection point. The AHP also reveals that delay at transfer points is not considered significant. One possible reason is that direct shipping bypasses distribution centers.

With the AHP results and WTP data from the SP surveys, the multinomial logit model was applied to conduct regression tests in order to evaluate the value of highway congestion delay (considered equivalent to en route transportation delay). The parameters obtained from these tests indicated a value of $56 per hour when all participants are considered together in the analysis. Additionally, given the different characteristics in the survey such as base travel time of each participant, a $0.4 per percentage delay is also calculated for transportation time reliability. This value allows us to calculate the value of delay under each scenario. For example, in urban freight transport, a 30-minute delay during one hour of travel accounts for up to 50 percent of the total time. The value of delay in this case would then be $0.35215*50/30 minutes = $17.6075/30 minutes = $35.215/hour. In contrast, in inter-city transportation, a 30-minute delay during five days of travel would only render a value of delay of $0.293 per hour.

Using a continuous review (*Q*, *R*) policy, an analytical inventory model is used to examine the value of delay with respect to the mean transit time and its variations, respectively. Nine industry groups were investigated separately. Two different demand and lead time patterns were considered with two different types of services.

Table 7.1 summarizes the range of values of delay for the mean transit time in a descending order. Table 7.2 summarizes the range of values of delay considering transit time variation.

In general, future work would include a wider survey distribution for the purpose of expanding the data source, which could potentially benefit the regression analysis by allowing additional groupings. Another improvement can be achieved by searching the newest representative industrial parameter. This would lead to an updated value of delay through our analytical inventory model.

Table 7.1 Range of Values of Delay for Mean Transit Time

	REPRESENTATIVE INDUSTRY								
	Chemical	Food	Auto	Clothing	Other Mfg.	Pharma-ceuticals	Paper	Electronics	Merchan-dise
Range ($/hr)	3.97 | 22.27	2.39 | 11.10	1.44 | 5.44	1.04 | 3.43	0.86 | 3.40	0.49 | 2.67	0.39 | 2.05	0.34 | 1.68	0.25 | 0.76
Avg. ($/hr)	**13.89**	**7.24**	**3.61**	**2.34**	**2.23**	**1.67**	**1.31**	**1.06**	**0.53**

Table 7.2 Range of Values of Delay Based on Transit Time Variation

	REPRESENTATIVE INDUSTRY								
	Chemical	Food	Auto	Clothing	Other Mfg.	Pharma-ceuticals	Paper	Electronics	Merchan-dise
Range ($/hr)	20.27 | 46.08	5.94 | 26.95	6.99 | 10.29	4.77 | 7.21	5.35 | 6.27	2.40 | 3.87	1.95 | 4.53	2.74 | 3.89	1.94 | 2.69
Avg. ($/hr)	**31.04**	**13.49**	**8.41**	**5.74**	**5.77**	**3.03**	**2.99**	**3.29**	**2.21**

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APPENDIX A SURVEY COVER LETTER

Re: Highway Freight Delay Survey

Dear Mr.(Ms.) **______**,

Welcome to the survey! This survey is part of a study to identify costs to shippers due to highway traffic delay. The study is funded by the Center for Freight and Infrastructure Research and Education (CFIRE) at the University of Wisconsin and the University Transportation Center for Mobility at Texas A&M University. The findings will potentially be used by freight planners to develop congestion relief projects and toll policies. Telling us your true feelings is important to the success of this survey. Please feel free to forward this survey to your colleagues if you believe they are more able to estimate the impact of traffic delay to your operation.

We are committed to maintaining the confidentiality of your information. No individual specific information will be released to the public. The collective information will be tabulated for analysis and policy making only.

Please put the finished survey questionnaire in the stamped envelope and mail it back.
If you have any questions, please feel free to let us know. You are also welcome to write down your overall comments and suggestions in the survey.

Sincerely,

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APPENDIX B SURVEY QUESTIONNAIRE

A Survey of Shippers

1. **Please briefly describe your business operations.**

   Industry type (select the appropriate one):
   ☐ Raw materials (mining, quarrying, oil/gas extraction, agriculture, forestry, fishing, and hunting)
   ☐ Manufacturer
   ☐ Wholesaler
   ☐ Warehouse
   ☐ Other, please specify________________________

   Materials/goods purchased: _________________________ Products sold: __________________________

   Approximate workforce size (head count): ______________ Annual amount of sales: ___________________

2. **If you receive freight shipments on a regular basis, please answer the following questions.**

   How often does a late inbound shipment occur (out of 10 times)?
   ☐ It does not matter ☐ 0 ☐ 1-2 ☐ 3-4 ☐ 5-6 ☐ 7-8 ☐ 9-10

   What do you typically do to counter late deliveries to you? (Please select all that apply.)
   ☐ Increase safety stock
   ☐ Provide incentives for on-time deliveries
   ☐ Other, please specify ____
   ☐ Do nothing

3. **If you send freight shipments on a regular basis, please select appropriate options concerning shipment operations to your <u>major customers</u> (defined as the customers to which you send the greatest tonnage of goods).**

   Transportation mode used (select all that apply):
   ☐ Truck ☐ Rail ☐ Air ☐ Sea ☐ Other, please specify__________________

   Type of carrier used (select all that apply):
   ☐ Own fleet ☐ Leased fleet ☐ For-hire ☐ Third-party logistics ☐ Other, please specify ________

   Typical shipping length: ☐ 0 to 50 miles ☐ 50 to 300 miles ☐ 300+ miles

   How is a delivery time typically defined by your major customers?
   ☐ Within certain week(s)
   ☐ Within certain day(s)
   ☐ Within certain hour(s) of a day
   ☐ Other, please specify___________

   How often is a late outbound shipment delivered to your major customers (out of 10 times)?
   ☐ It does not matter ☐ 0 ☐ 1-2 ☐ 3-4 ☐ 5-6 ☐ 7-8 ☐ 9-10

   What do you typically do to counter late deliveries to your major customers? (Please select all that apply.)
   ☐ Inform receivers
   ☐ Provide incentives for on-time deliveries
   ☐ Other, please specify____
   ☐ Do nothing

4. **Would you help us identify typical cost categories to shippers that are due to highway congestion?**

Transportation Service Selection for a Typical Shipment

5. Typical shipment to your major customer

To your major customer, about how many hours is the average travel time from your location? _______ hours

Please answer the questions below regarding a typical shipment to your major customer (if it is hard to define a typical shipment, please answer the questions regarding your most recent shipment to the customer):

Approximate dollar amount of the shipment: $___________
Approximate transportation cost/charge for the shipment: $_________
Average or typical shipment size: ________ (circle one) tons/items/liters/m^3/ft^3/other ______

6. For the typical shipment reported in Section 5, please select the transportation service you prefer from two hypothetical carriers under each of the 12 choice situations below

Choice Situation	For the typical shipment reported above, the transportation services are described below for Carrier A	Carrier B	I would choose Carrier A	or Carrier B
1	- 30 minutes later than delivery time window required - same charge as reported	- On-time delivery - Additional $20 charge	☐	☐
2	- 60 minutes later than delivery time window required - same charge as reported	- On-time delivery - Additional $30 charge	☐	☐
3	- 120 minutes later than delivery time window required - same charge as reported	- On-time delivery - Additional $40 charge	☐	☐
4	- 30 minutes later than delivery time window required - same charge as reported	- On-time delivery - Additional $60 charge	☐	☐
5	- 60 minutes later than delivery time window required - same charge as reported	- On-time delivery - Additional $150 charge	☐	☐
6	- 120 minutes later than delivery time window required - same charge as reported	- On-time delivery - Additional $360 charge	☐	☐
7	- 30 minutes later than delivery time window required - same charge as reported	- On-time delivery - Additional $30 charge	☐	☐
8	- 60 minutes later than delivery time window required - same charge as reported	- On-time delivery - Additional $50 charge	☐	☐
9	- 120 minutes late than delivery time window required - same charge as reported	- On-time delivery - Additional $140 charge	☐	☐
10	- 30 minutes later than delivery time window required - same charge as reported	- On-time delivery - Additional $70 charge	☐	☐
11	- 60 minutes later than delivery time window required - same charge as reported	- On-time delivery - Additional $120 charge	☐	☐
12	- 120 minutes late than delivery time window required - same charge as reported	- On-time delivery - Additional $200 charge	☐	☐

Now suppose the two carriers charge the same amount of money for the shipment as reported in Section 5 but carrier A will have a larger delay with uncertainty, and carrier B will have a smaller delay with certainty. Would you choose carrier A or B?

Choice Situation	For the typical Carrier A	Carrier B	I would choose Carrier A	or Carrier B
1	5% chance of having 240 minutes delay, 95% chance of on time	10 minutes of delay with certainty	☐	☐
2	5% chance of having 240 minutes delay, 95% chance of on time	15 minutes of delay with certainty	☐	☐
3	5% chance of having 240 minutes delay, 95% chance of on time	20 minutes of delay with certainty	☐	☐
4	10% chance of having 180 minutes delay, 90% chance of on time	10 minutes of delay with certainty	☐	☐
5	10% chance of having 180 minutes delay, 90% chance of on time	15 minutes of delay with certainty	☐	☐
6	10% chance of having 180 minutes delay, 90% chance of on time	20 minutes of delay with certainty	☐	☐
7	80% chance of having 30 minutes delay, 20% chance of on time	20 minutes of delay with certainty	☐	☐
8	80% chance of having 30 minutes delay, 20% chance of on time	25 minutes of delay with certainty	☐	☐
9	80% chance of having 30 minutes delay, 20% chance of on time	28 minutes of delay with certainty	☐	☐
10	90% chance of having 20 minutes delay, 10% chance of on time	10 minutes of delay with certainty	☐	☐
11	90% chance of having 20 minutes delay, 10% chance of on time	15 minutes of delay with certainty	☐	☐
12	90% chance of having 20 minutes delay, 10% chance of on time	18 minutes of delay with certainty	☐	☐

Comments (if any):

Ranking Delay Components

Please assess the following delay factors using a number from 0 to 10, with 0 being least relevant and 10 being most important.

Aspect of the delay	Circle a number indicating importance (0-10 scale)
Delay due to transportation	Least 0 1 2 3 4 5 6 7 8 9 10 Most
Delay at collection point (e.g., delay of production, lack of driver, etc.)	Least 0 1 2 3 4 5 6 7 8 9 10 Most
Delay at transfer point (e.g., delay at distribution center)	Least 0 1 2 3 4 5 6 7 8 9 10 Most
Delay at delivery point (e.g., lack of warehouse space, unloading bays are occupied, etc.)	Least 0 1 2 3 4 5 6 7 8 9 10 Most

Please add any comments you wish to make:

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