CFIRE

Environmental and Energy Benefits of Freight Delivery Consolidation in Urban Areas

CFIRE 03-19
March 2013

National Center for Freight & Infrastructure Research & Education
Department of Civil and Environmental Engineering
College of Engineering
University of Wisconsin–Madison

Authors: Jane Lin[a,b], Qin Chen[a], Kazuya Kawamura[c]

[a,] Department of Civil and Materials Engineering, and
[b] Institute for Environmental Science and Policy,
[c] Department of Urban Planning and Policy,
University of Illinois at Chicago

Principal Investigator: Jane Lin, Ph.D., Associate Professor, UIC

DISCLAIMER

This research was funded by the National Center for Freight and Infrastructure Research and Education. The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the information presented herein. This document is disseminated under the sponsorship of the Department of Transportation, University Transportation Centers Program, in the interest of information exchange. The U.S. Government assumes no liability for the contents or use thereof. The contents do not necessarily reflect the official views of the National Center for Freight and Infrastructure Research and Education, the University of Wisconsin, the Wisconsin Department of Transportation, or the USDOT's RITA at the time of publication.

Technical Report Documentation Page

1. Report No. CFIRE 03-19	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Environmental and Energy Benefits of Freight Delivery Consolidation in Urban Area		5. Report Date **March 2013** 6. Performing Organization Code
7. Author/s Jane Lin, Qin Chen, and Kazuya Kawamura		8. Performing Organization Report No.
9. Performing Organization Name and Address National Center for Freight and Infrastructure Research and Education (CFIRE) University of Wisconsin-Madison 1415 Engineering Drive, 2205 EH Madison, WI 53706		10. Work Unit No. (TRAIS) 11. Contract or Grant No. **DTRT06-G-0020** **168k044**
12. Sponsoring Organization Name and Address Research and Innovative Technology Administration U.S. Department of Transportation 1200 New Jersey Avenue, SE Washington, DC 20590		13. Type of Report and Period Covered **Final Report [1/1/2010 – 8/31/2012]** 14. Sponsoring Agency Code
15. Supplementary Notes **Project completed for USDOT's RITA by CFIRE.**		

16. Abstract

Among new, innovative city logistics strategies, delivery cooperation has received increasing academic and practical attention mostly in Europe and Japan. The idea is to establish cooperation among the suppliers, carriers and the customers through Urban Consolidation Center (UCC), a public facility usually located at the city boundary; with proper consolidation of loads and routing, the goods are then sent to the customers in the urban area with cleaner vehicles and less vehicle miles traveled (VMT). In this study, we investigated the feasibility of UCC in an urban setting at the tactical level with respect to total logistics cost and environmental impact. In other words, whether UCC could reduce the logistics cost which involves the monetary costs for activities from production to consumption, while maintaining acceptable level of energy consumption and vehicular emissions.

It is found that under certain conditions, UCC may become a favorable last-mile urban delivery solution to the current one without a UCC. Especially the benefits of UCC strategies become significant when the customer rent cost is high and UCC terminal operation cost is low. UCC becomes more beneficial as the economic scale is greater (i.e., higher numbers of customers and suppliers). In addition, public subsidy for UCC terminals would make urban cooperative delivery more competitive, resulting in lower truck VMT and emissions in the urban area.

17. Key Words UCC, logistics cost, energy consumption, emissions, Continuum Approximation	18. Distribution Statement **No restrictions. This report is available through the Transportation Research Information Services of the National Transportation Library.**		
19. Security Classification (of this report) **Unclassified**	20. Security Classification (of this page) **Unclassified**	21. No. Of Pages 298	22. Price **-0-**

Form DOT F 1700.7 (8-72) **Reproduction of form and completed page is authorized.**

(This page is intentionally left blank)

Table of Contents

EXECUTIVE SUMMARY 9

1. INTRODUCTION 13

1.1 Background: problem statement and research significance 13

1.2 Study objectives 14

1.3 Study approach 15

2. LITERATURE REVIEW 16

2.1 Last-mile problem and green supply chain 16

2.2 Overview of existing delivery consolidation studies 17

2.3 Logistics cost components 19

2.4 Logistics operating factors in the last-mile problem 19

2.5 Typical modeling approaches 20

2.6 Data requirements 22

3. METHODOLOGY 24

3.1 Framework 24

3.2 Distribution network model 25

3.2.1 Introduction to CA method 25

3.2.2 Problem setting and assumptions 28

3.2.3 Problem formulation 30

3.2.4 Data description 36

3.2.5 Parameter estimation 38

3.3 Emission estimation model 40

3.3.1 Introduction to MOVES 40

3.3.2 Emission factors generated by MOVES 41

3.3.3 Emission calculation 44

4. ANALYSIS RESULTS 44

4.1 Long-haul distance cost 44

4.2 Effect of number of suppliers and number of customers on cost 48

4.2.1 Effect of Market Penetration 48

        4.2.2 Effect of Delivery Network Size 49
    4.3 Cost as function of customer density 51
    4.4 Cost as function of customer demand rate 52
    4.5 Cost sensitivity to customer rent cost and UCC terminal operation cost.............................54
    4.5 Cost as a function of vehicle capacity...56

5. CONCLUSIONS 56

6. REFERENCES...59

Tables

Table 1.Data requirements in delivery channel problems[1] 23
Table 2 Summarize of scenarios 25
Table 3 Summary of the Parameters Used in the Model Formulation 30
Table 4. Optimal Results for UCC Strategies B1 and B2 35
Table 5. Key information recorded in the Texas Commercial Vehicle Survey travel log 36
Table 6 Key information recorded in the Food Environment Atlas 37
Table 7 Key input parameters to MOVES 41
Table 8 PM2.5 emission rates and energy consumption rates 43

Figures

Figure 1 Study Framework 24
Figure 2 Delivery Strategies. 28
Figure 3 PM2.5 emission rate curve by speed for single-unit short-haul truck 41
Figure 4 PM2.5 emission rate curve by speed for combination short-haul truck 42
Figure 5 Energy consumption rate curve by speed for single-unit short-haul truck 42
Figure 6 Energy consumption rate curve by speed for combination short-haul truck 43
Figure 7 Cost as a Function of Long-haul Distance 45
Figure 8 Energy Consumption and PM2.5 Emissions as a Function of Long-haul Distance. 45
Figure 9 Total Logistics Costs under Different UCC Terminal Costs. 46
Figure 10 Cost as a Function of Long-haul Distance and UCC Location. 47
Figure 11 Energy consumption as a Function of Long-haul Distance and UCC Location. . 48
Figure 12 PM2.5 emissions as a Function of Long-haul Distance and UCC Location. 48
Figure 13 Cost as a Function of Number of Suppliers 49
Figure 14 Cost as a Function of Number of Suppliers and Customers 50
Figure 15 Energy consumption as a Function of Number of Suppliers and Customers 50
Figure 16 PM2.5 emissions as a Function of Number of Suppliers and Customers 51
Figure 17 Cost as a Function of Customer Density 51
Figure 18 Energy consumption and PM2.5 emissions as a Function of Customer Density . 52
Figure 19 Cost as a Function of Customer Demand Rate 53
Figure 20 Energy consumption and PM2.5 emissions as a Function of Customer Demand Rate 53
Figure 21 Effects of UCC Terminal Operation Cost and Customer Rent Cost 54
Figure 22 Energy consumption of UCC Terminal Operation Cost and Customer Rent Cost 55
Figure 23 PM2.5 emissions of UCC Terminal Operation Cost and Customer Rent Cost ... 55
Figure 24 Cost as a Function of Inbound Vehicle Capacity and UCC Location 56

EXECUTIVE SUMMARY

Introduction

Among new, innovative city logistics strategies, delivery cooperation has received increasing academic and practical attention mostly in Europe and Japan. The idea is to establish cooperation among the suppliers, carriers and the customers through Urban Consolidation Center (UCC), a public facility usually located at the city boundary; with proper consolidation of loads and routing, the goods are then sent to the customers in the urban area with cleaner vehicles and less vehicle miles traveled (VMT). Although creating a terminal increases the operating cost at the facility, it may be compensated by reducing VMT with the right economies of scale, stocking cost at the customer end, and emissions and congestion in urban area.

What is UCC?

Urban Consolidation Center (UCC) is a public urban freight infrastructure that serves essentially the same functionalities as urban transshipment center, urban distribution center (UDC), and city logistik (the phase used in Germany). Large long-haul trucks from different suppliers come to the UCC and goods are consolidated and transferred to smaller trucks, a process known as transshipment, before being delivered into the city. Thereby number of truck trips is reduced and congestion and pollution are alleviated.

Study Objective

In this study, we investigated the feasibility of UCC in an urban setting at the tactical level with respect to total logistics cost and environmental impact. In other words, whether UCC could reduce the logistics cost which involves the monetary costs for activities from production to consumption, while maintaining acceptable level of energy consumption and vehicular emissions.

Methodology

In this study, two delivery strategies are considered: Strategy A - delivery without UCC; and Strategy B - delivery with UCC. Furthermore, within Strategy B, two sub-strategies are considered: B1 - delivery with UCC, and no coordination between inbound and outbound shipments at the consolidation point, and B2 - Delivery with UCC and coordination between inbound and outbound shipments at the consolidation point.

There are two major model components used in finding the delivery efficiency in various strategies: 1) a distribution network model to find the optimal schedule and routing plan, the optimal vehicle activity as well as the optimal cost; 2) an emission estimation model to obtain the value of energy consumption and emissions from freight vehicles.

The distribution network model employs the Continuum Approximation (CA) method. Specifically, the schedule plan involves the decision of shipment size for each customer, delivery frequency, and dispatching time; the routing plan determines the tour pattern and number of stops. In the emission estimation model, MOVES model is used to calculate the PM2.5 emission rates and the energy consumption rate.

Major Findings and Policy Implications

It is found that under certain conditions, UCC may become a favorable last-mile urban delivery solution to the current one without a UCC. Especially the benefits of UCC strategies become significant when the customer rent cost is high and UCC terminal operation cost is low. In terms of energy consumption and PM2.5 emissions, B1 seems to be almost always doing better than Strategy A, while B2 is better off than Strategy A only when high customer rent cost is achieved.

UCC becomes more beneficial as the economic scale is greater (i.e., higher numbers of customers and suppliers). Interestingly, our analysis shows otherwise for energy consumption and PM2.5 emissions. That is, Strategy A saves more energy and emits less PM2.5 than Strategy B1 (or B2), and the saving increases as the number of customers decreases and as the number of suppliers increases.

Furthermore, direct delivery strategy becomes more cost effective in longer distance. Similarly, moving the UCC location closer to suppliers would reduce the total logistic cost. On the other hand, the study shows that UCC without coordination (B1) almost always generates higher energy consumption and PM2.5 emissions.

Cooperative delivery via UCC may also provide flexibility in vehicle size to meet city ordinance about truck size, curfew and environmental issues. Moreover, considering the policy option of congestion pricing and other truck restrictions in the urban areas, cooperative delivery may become an even more appealing option for its flexibility and reliability, which may bring significant savings especially to the receivers.

(This page is intentionally left blank)

1. INTRODUCTION

1.1 Background: problem statement and research significance

Due to the modern manufacturing practice, the increasing demand and the need for good service quality from customers, higher frequency of deliveries and larger quantities of freight shipments coming from, bound to or transiting through urban areas are needed. According to the Federal Highway Administration (FHWA), in the United States total vehicle miles of travel (VMT) increased by 21% in the urban areas from 1996 to 2006. In particular, the share of freight vehicles increased from 4.8% to 5.2%, indicating the faster growth of freight traffic in the urban areas. Increased urban freight traffic competes with passenger vehicles for roadway capacity and parking space, and hence significantly contributes to congestion and environmental problems (e.g., emissions and noise). For example, heavy vehicles account for 23.8% of total highway transportation energy consumption (U.S. DOT/FHWA, 2003), 33% of mobile source nitrogen oxides (NOx) emissions and 18% of NOx emissions from all sources (U.S. DOT, 2005). These problems arising in the final part of the supply chain are referred to as the last-mile problem.

In European and Asian countries, various strategies providing solutions to the last mile problem have been studied or even field-tested (EU, 2003, OECD, 2003, CIVITAS, 2004). One such strategy, delivery consolidation through cooperation among the stakeholders (also known as urban cooperative delivery, urban consolidation or City Logistik), has been deployed successfully in some European and Asian countries(Kohler, 2001, Pattier, 2005, Taniguchi and Nemoto, 2003). In this delivery consolidation strategy, suppliers ship their goods to an Urban Consolidation Center (UCC) (also known as Urban Distribution Center (UDC), or city terminal in the literature); with proper consolidation of the loads and routing, the goods are then delivered to customers with minimum required frequency and the shortest routing distance.

The key for success of this type of operation is to establish cooperation among suppliers, carriers and customers, and to better utilize the shipping resources (e.g., shipping capacity, storage space). In addition to enhancing efficiency, Taniguchi and Thompson (2002) pointed out that delivery consolidation could significantly reduce urban congestion and vehicle emissions. For example, London Heathrow Airport Consolidation Centre (UK) consolidates deliveries for 40 retailers in airport terminal 5 with a 3rd party logistics company reducing 66% delivery trips,1.35kg less CO2 emissions per week and monetary saving of 370,000 EUR per year, while maintaining the 95% on-time delivery rate.

However, not all of the delivery consolidation projects survived after several years of operation, due primarily to financial reasons. For example, the urban distribution center project in Leidin, Netherlands was not financially sustainable with increased monetary costs after 3 years of operation, although it reduced the truck trips by 40% and hence the vehicle emissions.

The above empirical findings motivate us to find out what operational factors may make urban delivery consolidation more attractive than otherwise, and how these factors affect the effectiveness of delivery consolidation in terms of cost savings and environmental benefits. The former, aiming at minimizing costs and maximizing profits, is important from the business point of view; and the latter, aiming at reducing emissions, saving energy, as well as reducing number of trucks and congestion in urban area, is important from a sustainability perspective.

1.2 Study objectives

The objective of this study is to examine the effectiveness of delivery consolidation in terms of air pollutant emissions, energy use, and costs to businesses. This research strives to investigate the following research questions:

1) ***What is the monetary benefit/cost of delivery consolidation to businesses?***

Currently it is not yet well understood how well delivery consolidation may work. That is, what operational factors make delivery consolidation more attractive than without consolidation, and how these factors affect the cost effectiveness of consolidation in the monetary term. These are important questions from the business point of view. In the current literature such effects are empirically observed from individual case studies and not analytically quantified. In this study, we attempt to formulate a mathematic model to quantify the relationship between operational factors and logistics costs.

A quantitative method is used to investigate the relationship between operational factors and monetary cost in the last-mile delivery process. The proposed modeling tool is capable of analyzing the effects of various factors on logistics cost, which may not be possible to observe in a field case study, and such a tool is easy to be adapted to a different logistics chain in a different metropolitan region by modifying the input parameters.

2) ***What is the social benefit of delivery consolidation in terms of reduction in total emissions and life cycle energy demand?***

The last mile problem is complicated for multiple stakeholders’ involvement in the system. Generally, from the business point of view, minimizing the cost and gain profits as much as possible is the major concern. On the other hand, to achieve long-term sustainability in the living environment in urban areas, curbing or even reducing truck traffic and consequently congestion, pollution and noise is to be desired. In this study, additional to the cost analysis, the energy consumption and PM2.5 emissions are estimated. MOVES model is used to generate the emissions rates in this study.

3) ***How will the answers to the questions above be affected by the size of delivery vehicles, market penetration and network topology?***

In this study, the effects of a wide range of factors (e.g., the consolidation facility location, the market penetration, the size of delivery network, the customer density and demand, facility rent cost, as well as vehicle size) will be investigated on the choice of delivery strategies based on the pre-defined evaluation criteria.

In addition, the framework and method can be used in future studies to conduct the following analysis:

- Simulate more complex consolidation schemes (e.g. schemes that do not require city terminal) and distribution channels (e.g. direct delivery from warehouse to home)
- Simulate larger scale real urban areas with different commodities and logistics chains

1.3 Study approach

This study compares economic and environmental impacts for a hypothetical generic urban area with and without delivery consolidation. Performance measures such as the logistics cost, the vehicle miles traveled (VMT), the amount of energy consumption and PM2.5 emissions, are estimated separately for two strategies: Strategy A - delivery without consolidation and Strategy B - delivery with consolidation. The estimation is done in a two-step procedure.

In the first step, a tactical level (as opposed to the operational level) optimization model with the objective of minimizing the logistics cost is used to obtain the optimal scheduling and routing plan. Here the logistics cost involves the costs for activities from production to consumption and can be broken down into the stationary cost components such as facility rental cost and the motion cost components such as transportation cost. It is worth pointing out that in this study costs include all incurred components regardless of who pays for them.

Then the amount of energy consumption and PM2.5 emissions are calculated from the optimal results obtained from the first step. And the effectiveness of delivery consolidation is evaluated by comparing the performance measures between the two strategies. To account for the uncertainties related to the factors that may prove critical to the effectiveness of consolidation center, a set of scenarios that represent various combinations of key factors of interest, including customer density, demand quantity, UCC location, and vehicle fleet used for shipments, are constructed.

The tactical level optimization problem is modeled using the Continuum Approximation (CA) method without the need for detailed data about the suppliers and the customers, which is often unavailable in practice. It relies on the spatial and temporal density and distribution of customer demand rather than the precise information at every exact customer location. This method requires less input data, computational efforts and provides a close form solution, especially when the number of data points (both suppliers and customers) is large. It is a useful tool in gaining insight into the interconnection between factors and cost components without needing the precise supplier and customer information at every exact location.

2. LITERATURE REVIEW

2.1 Last-mile problem and green supply chain

The last mile can be defined as the final leg in consumer delivery service whereby the cargo is delivered to the recipient, either at the recipient’s home or collection point (Gevaers et al., 2011). A typical logistic chain is organized as follows: raw materials are sent to the supplier’s manufacture place, from where the finished products are shipped to the warehouse (either owned by the supplier or the logistics provider); then the finished products are delivered to the end consumers, either through traditional outlets such as retail stores or supermarkets, or directly to consumers’ homes. Typically the last mile concerns the delivery process from the warehouse to the final consumers.

Different culture, local economic, geographic characteristics greatly affect the logistics decisions and delivery process. For example, in many developing countries in Asia and Africa, street vendors occupy street space, selling goods from fresh food to electronics, making the already congested roads even harder to get through; small private carriers use man labor and old delivery vehicles for low efficient transport and handling, generating large amount of emissions and noise and greatly affecting the living environment (Dablanc, 2011). In historical cities in EU and Japan, narrow streets make delivery trucks difficult to get into the urban area, and the limited parking space forces loading and unloading activities to take place on street and thus block traffic. In the US cities such as Los Angeles and Chicago, freight trucks are contributing significant amount of air pollution and noise in the city.

During the last three decades, the efficiency of supply chains has increased dramatically. For example, in the U.S., the share of the logistics-related expenditure of the GDP dropped from about 16.2% in 1981 to 8.7% in 2002 (FHWA, 2005). Available data suggests that the most significant improvements likely have occurred in the movement of retail and high-value goods, which account for 30 percent of the weight and 85 percent of the value of freight moved in the U.S. (Section 1909 Commission Staff, 2007). Since high-value goods are more likely to be shipped in smaller batches (e.g., just-in-time) to reduce the inventory cost, this trend has led to a rapid growth in the number of trips made by truck at a fraction of the full capacity, i.e., 49 percent growth in trucks over 10,000 pounds and 62 percent growth in their vehicle miles of travel over the last 15 years (Section 1909 Commission Staff, 2007). Similar findings are noted in other studies (Gray, 1992, 2002; Halldórsson et al., 2009). On the other hand, due to the continuing growth of e-commerce combined with the ever-increasing expectation by consumers for shorter time lag between purchase and delivery, this trend is likely to continue into the foreseeable future. It is estimated that total domestic trucking VMT will increase by over 60%

between 2000 and 2020 (AASHTO, 2003). Additional truck traffic will further increase the congestion in the urban areas. Their energy and environmental impacts will only become greater (Vachon and Klassen, 2006). It is therefore imperative that viable strategies to minimize truck traffic in congested areas be studied and implemented.

The concept of green supply chain and logistics is part of the so called green economy which is holistically viewed as a component of the ecosystem in which it resides. A green economy is one that results in improved human well-being and social equity, while significantly reducing environmental risks and ecological scarcities. A green economy is an economy or economic development model based on sustainable development and knowledge of ecological economics. But in a time of severely constrained state and city budgets, it is unlikely that "green" projects, initiatives and investments will be authorized without rigorous cost-benefit analysis and justification for the investment and its ultimate sustainability. Furthermore, in the last mile city logistics literature, there exists a gap of addressing environmental costs in the total logistics cost. It is therefore one of the goals of this research to investigate and develop sound last mile strategies that balance among the economic output, carbon footprint, and energy input.

2.2 Overview of existing delivery consolidation studies

To deal with the last-mile problems, various so-called city logistics strategies have been proposed and even field tested at both tactical level and operational level over the past two decades, mainly in EU and Japan. The aim of those strategies was to optimize the logistics and transportation activities of private companies in urban areas and at the same time provide co-benefits to mitigate traffic congestion, energy consumption, and adverse environmental impact within the framework of a market economy (Taniguchi and Tamagawa, 2005).

Delivery consolidation is viewed by some to be the best way to achieve sustainable last-mile development (Wisetjindawat, 2010) by reducing freight trips and energy consumed for deliveries. For example, the consolidation system in Freiburg, German reduced truck trips by 33% and travel time by 48% for the participants (Kohler, 2001). The joint distribution system in Fukuoka, Japan, first implemented in 1978,decreased the truck VMT and total hours of parking within the 370,000 square mile area by 87%and 17% respectively (Ogata, Accessed March 21, 2008).

The idea is to establish cooperation among suppliers, carriers and customers, and to consolidate deliveries at a public urban freight infrastructure called Urban Consolidation Center (UCC). In the literature, UCC serves essentially the same functionalities as urban transshipment center, urban distribution center (UDC), and city logistik (the phase used in Germany). Large long-haul trucks from different suppliers come to the UCC and goods are consolidated and transferred to smaller trucks, a process known as transshipment, before being delivered into the city. Thereby number of truck trips is reduced and congestion and pollution are alleviated.

Browne et al. (2005) defined UCC as principally a logistics facility located in close proximity to a geographic area to serve consolidated deliveries within that area. By inserting an UCC into the urban delivery network typically at the urban fringe, the logistics activities are split into two parts: activities outside the urban limit (i.e., before UCC) and those within (i.e., after UCC). Optimal strategies may be considered separately to utilize resources in both parts according to their characteristics. In practice, cooperation from the private sector is necessary, which implies some form of incentives to the private sectors.

Delivery consolidation and UCC started receiving attention as early as in the 1970s. A feasibility case study on a consolidation terminal was conducted in Columbus, Ohio between 1972 and 1974. The study result showed that the UCC would operate with financial benefits, but it was never put into practice (Browne et al, 2005). In the 1990s, about 80 German cities launched the city logistik scheme (the German terminology for cooperative delivery via UCC) (Visser et al., 1999). However, most of them but five cities (Aachen, Bremen, Essen, Frankfurt, and Regensburg) no longer have UCC in operation (Browne et al 2005). Following Germany, Switzerland launched five pilot UCC projects in 1996 and none of them are in operation today mainly because of the constrained demand and no public regulations involved (BESTUFS 2007).

In recent years, studies on delivery consolidation or UCCs under the concept of city logistics schemes were carried out in the United States (see Regan and Colob, 2003; Holguin-Veras, 2007; Kawamura and Lu, 2007) and UK (Browne et al 2005, 2007). In 2005, under the support of the UK government, the researchers at University of Westminster reviewed the UCC cases and concluded that the early failed UCC projects were due to no coordination between the private and the public sectors. According to Browne et al. (2005), renewed UCCs schemes are being implemented mainly by private actors, such as in France and Sweden or through public-private partnerships, particularly in Italy and UK. Some of them seem to be working out well and the others are not, which suggests that there are factors at work in certain context and not in the others (Ademe, 2004; BESTUFS, 2007; Civitas, 2006).

Throughout the literature, there are several key points for implementing the UCC:

First, it should be noted that much of the urban freight is already consolidated at the intra-company level or contracted by parcel carriers, so limited or even negative benefits may be perceived by those companies, which could hinder the adoption of UCC (BESTUFS, 2007; Browne et al, 2005; Wisetjindawat, 2010).

Secondly, private sectors are most concerned about reducing costs while maintaining a satisfactory level of service, especially associated with the last mile activities. Any effective strategies should directly address the total logistics cost and monetary benefits (Quak and Tavasszy, 2011, Browne et al., 2005).

Thirdly, the lack of willingness to cooperate is because of the fierce competition; and the suppliers are afraid of disclosing competitive information about order quantities, products, customers to their competitors. In such cases, if cooperative delivery is used, delivery responsibility should be contracted to a well organized 3rd party logistics (BESTUFS, 2007; Panero et al., 2011).

Lastly, some large urban areas may require more than one UCC to handle the wide variety of goods moving in and out of the city (Wisetjindawat,2010).

2.3 Logistics cost components

In the last mile problem, the logistics cost components involve transportation, inventory, facility and handling, and information (Chopra and Meindl, 2003).

Transportation cost consists of the costs incurred during delivery using various transportation modes, including the costs incurred during transfer and waiting at intermediate stops. For example, if a peddle-run delivery rather than a one-to-one direct delivery is used, the stop cost at each additional stop is considered part of the transportation cost.

Inventory cost is the holding cost for safety stock and the holding cost during transfer (also known as pipeline inventory cost). Usually it is proportional to the product quantities and the holding time.

Facility and handling cost consists of the terminal operating cost and the cargo handling fee during the loading/unloading process. Generally speaking, adding an additional facility in the logistics chain (an intermediate stop during the last-mile) leads to an increase in facility and handling cost. It also plays an important role in shifting the inventory cost, depending on the facility location. For example, if the rent rate at the intermediate facility is much cheaper than at the supplier/customer end, then the total inventory cost in the last-mile could be reduced.

Information cost is the cost paid for the new technology and information system, e.g., energy saving vehicles, GPS tracking system, and label tracking system, etc.

2.4 Logistics operating factors in the last-mile problem

Logistic decisions universally depend on the characteristics in the last mile problems such as geographic characteristics, customer requirements, market penetration and policy regulations (Dablanc and Rakotonarivo, 2009).

Geographical Area and Market penetration and density

Customer density plays an important role in distribution network design. If the average distance between customer points is large, delivery cost increases. Additionally, market penetration and product sales volume in a given market, is crucially important for attracting sufficient participators to achieve the economics of scale.

Demand level and market size

Gevaers (2009) found that in the case of delivery to supermarkets and shops, demand level and market size are important economic parameters in the context of last-mile deliveries. If just one package needs to be delivered to a customer, cost will increase substantially because of the empty miles involved. And if just one supplier for a particular type of commodity exists in the region (monopoly), it always makes profit regardless what delivery decisions are made.

Vehicle fleet and technology

Vehicle fleet can significantly affect the operating cost in many ways including fuel consumption, loading factor, loading method and vehicle age and type (Gavaers, 2011). Another important factor is the information and communication technology used to monitor the fluctuation of demand, stock level, and traffic conditions. Hence, quick and accurate response can be made to save cost.

Public restriction and policy

Public sectors are concerned about the living environment in the urban areas. Policies and regulations towards alleviating congestion, emissions, and safety problems have been implemented in many cities. Those policies (i.e., truck route, delivery hour restriction and off-peak delivery) tend to lower the delivery efficiency and increase the operating cost for carriers. Thus, adopting cooperative delivery may save money by better utilizing resources.

2.5 Typical modeling approaches

There are two types of problems when modeling the preference of using delivery consolidation or not. One is to study the interactive decisions among the stakeholders (usually the decision games between the supplier and the carrier, or the public sector and private sector) by using game theory methods and the activity-based methods. The other is to study the preference by comparing the total optimal cost. For this type of problem, mathematical models (e.g., mixed integer programming) are usually employed. For our study purposes, we are interested in the latter problem. In the rest of the section, we will thus focus on the literature addressing the second type of problem.

Regan et al. (2003) used survey data in 2001 to study the preference of using a shared freight facility in California, by examining the results of an ordered probit demand model. The results showed that a reasonably large number of trucking companies would likely use such facilities – in particular, long distance carriers and those providing service to rail terminals are the most likely users. IT adoption and use of third party logistics services are also indicators of likely users of shared use facilities. Marcucci (2007) conducted a stated-preference study to investigate how transportation decisions were made by customers or shippers in response to the potential demand at the urban consolidation center in the city of Fano, Italy. The results showed that certain types of commodity such as food and grocery items and certain types of business such as stores with less storage space would more likely use consolidation service. It should be pointed out that both studies rely on survey data which are usually quite expensive and case (regional) specific. While they are able to provide good empirical evidence and insight to cooperative delivery strategies, it is unclear to what degree the findings and experience learnt could be shared in other regions or even countries.

Among analytical methods, mathematical programming is commonly used in supply chain and logistics analysis, in particular, evaluation of freight delivery costs. For example, Quak et al. (2007) conducted a factorial design using VRP(vehicle routing problem) software to quantify the impact of vehicle restriction and time window regulations on delivery cost. Figliozzi (2007) adopted a VRP model to understand the impact of congestion on urban delivery tour efficiency. While these models are able to unveil the relationships between a set of factors and the variable of interest quantitatively, they often require a large amount of discrete input data at every customer point and considerable computing time. In actuality, detailed discrete input data is often unavailable or hard to get. Furthermore, Continuum Approximation (CA) provides an alternative to the above-mentioned mathematical programming as a useful tool when planning a new service or an expansion of an existing one (Langevin et al. 1995). CA relies on the spatial and temporal density and distribution of customer demand rather than the precise information at every exact customer location. Discrete data are approximated with a continuous function which provides a close form solution, especially when the number of points is large.

Daganzo is the first to apply this CA method to delivery problems to analyze different logistics costs and trade-offs between cost components. In one study, Daganzo (1984a) analyzed the routing strategy of a traveling salesman problem in different shapes of the service area and obtained a near optimal routing strategy. In another study, Daganzo (1984b) partitioned the service region into clusters with different shapes, and proposed a “cluster-first, routing-second” methodology to approximate route length. This work on route length approximation led to Daganzo and Newell (1986) proposing the application of CA approaches to solving vehicle routing and facility location problems, which up to that point had always been formulated as a mixed-integer programming problem and solved heuristically with detailed inputs data. More recently, Daganzo (2005) summarized his previous applications of the CA method on one-to-many delivery problems with or without transshipment.

There are few applications of the CA method to delivery consolidation. Base on the model developed by Daganzo (2005), Roca-Riu and Estrada (2011) applied the CA method to a collaborative delivery case study at L’Hospitalet de Llobregat in Barcelona, Spain, a relatively small and dense urban area with a high customer density and relatively short distances between origins and destinations. The study focused on the transportation cost alone with equal size stores. They concluded that at least 40% of the companies were needed to commit to the collaborative strategy in order to recover the cost of the consolidation facility. However, the conclusion could be quite different if total logistics cost is considered as it encompasses many cost components which may often times trade off one another internally (Anand et al.,2011). Considering the total logistics cost in an urban delivery problem, Kawamura and Lu (2007) explored the feasibility of consolidated distribution systems under varying population density and service area size in shoes delivery. They concluded that the current multiple-stop traditional delivery system was rational from an industry standpoint and that the decision was relatively insensitive to factors such as population density and service area size.

Campbell (1995) used the CA approach to estimate the change in vehicle emissions due to large truck restrictions during peak periods. Campbell concluded that large truck restrictions meant to ease congestion and improve air quality could be counterproductive. Rather than switching to off-peak operating hours (the desired effect), shippers may instead simply increase the use of smaller trucks in their distribution systems. This could result in increase in the total amount of pollutants, or little or no change.

2.6 Data requirements

For urban freight problems, one of the major research obstacles is the limited data sources available publicly. There are national level surveys of freight transport activities in many countries (for example, the continuing survey of road goods transport in UK, the Freight Analysis Framework in the U.S.). Although these surveys cover urban areas, they usually do not provide detailed urban freight activities. Allen and Browne (2008) summarized the reasons as follows: 1) in any particular urban area, the sample size drawn from the national survey is relatively small; 2) disaggregating the data from the overall dataset is often difficult; and 3) the type of data collected in national surveys does not provide the detailed information required for urban freight analysis.

During the past two decades, there have been data collection efforts made in some urban areas by private sectors for specific purposes, mostly in UK, followed by the U.S., Netherlands, Germany and Italy (Victoria and Walton, 2004; Allen and Browne,2008; Patier and Routhier, 2008). However, these data often suffer from the following drawbacks:

1) Small samples compared to personal travel data and traffic counts;
2) Data collected in one study are often not suitable for other studies because of the specific survey purpose and design for that study only;
3) Detailed data are generally not public available due to the ownership and confidentiality issues; they are only available in the form of summary statistics or other aggregation forms;
4) Majority of urban freight surveys are funded by the public sector and are not well maintained after the project;

5) Some project reports are written in their native language which must be translated into English, and some reports only have limited copies or are even missing.

Generally speaking, data needs vary between urban freight transportation problems, depending on the planning and policy framework, the established practice in data collection, and the availability of previously collected data (Ogden 1992). **Table 1** summarizes the data requirements and the example data sources in distribution channel problems.

Table 1.Data requirements in delivery channel problems[1]

Data requirement	Example	Data Source in this study
Vehicle Information	Vehicle type Vehicle age Vehicle weight Container type Mileage	-Texas Commercial Vehicle Surveys -VIUS
Trip details and patterns	Number of stops/tour Number of tours/day Location of stops Purpose/type of stops Distance between stops Travel time/speed Type of goods Fuel consumption Trip start/end time	-Texas Commercial Vehicle Surveys -Food Environment Atlas
Goods flows supplier/ customer (Origin/ destination)	Quantities of goods Type of goods Location of O/D Operation cost at O/D Delivery requirement	-Texas Commercial Vehicle Surveys -Food Environment Atlas
Vehicle loading /unloading activity	Load/unload location Load/unload duration Type of machine Vehicle dwell time	-Texas Commercial Vehicle Surveys
Ordering and stockholding arrangements	Whether stock is held Size of storage space Order lead time Storage cost Handling cost	-Texas Commercial Vehicle Surveys -Other data sources

[1] This table is adapted from Allen and Browne (2008)

3. METHODOLOGY

3.1 Framework

Figure 1 depicts the flow chart of major components in this study. The objective of this study is to investigate the efficiency of cooperative delivery strategies (i.e., delivery with or without cooperation) using the proposed evaluation modeling framework. Given a delivery strategy, after defining the basic settings (the inputs) and selecting the cost function (objective selection), two major modules are used to calculate the pre-defined evaluation criteria: 1) a distribution network model to find the optimal schedule and routing plan, the optimal vehicle activity as well as the optimal cost; 2) an emission estimation model to obtain the value of energy consumption and emissions from freight vehicles. By feeding the framework with different delivery strategies, we can evaluate the delivery efficiency with respect to the pre-defined evaluation criteria.

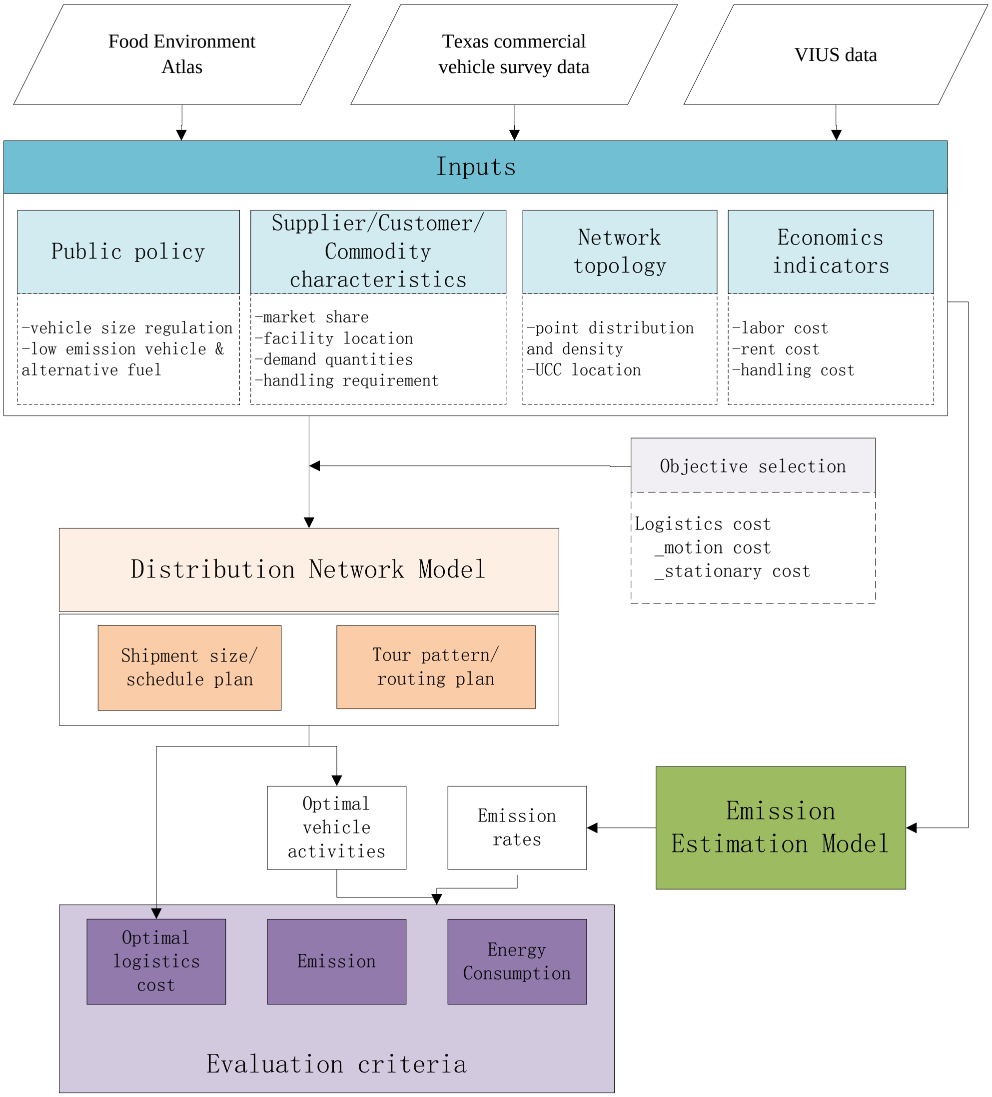


Figure 1 Study Framework

In this study, two delivery strategies are considered: Strategy A - delivery without UCC; and Strategy B - delivery with UCC. Furthermore, within Strategy B, two sub-strategies are considered: B1 - delivery with UCC, and no coordination between inbound and outbound shipments at the consolidation point; and B2 - Delivery with UCC and coordination between inbound and outbound shipments at the consolidation point. The pre-defined evaluation criteria are the logistics cost, energy consumption and PM2.5 emissions.

The objective function is to minimize the total logistics cost, which includes the motion cost component and the stationary cost component. The distribution network model employs the Continuum Approximation (CA) method. Specifically, the schedule plan involves the decision of shipment size for each customer, delivery frequency, and dispatching time; the routing plan determines the tour pattern and number of stops. In the emission estimation model, MOVES model is used to calculate the PM2.5 emission rates and the energy consumption rate.

The proposed research framework is intended for a tactical level investigation. With the day-to-day demand and road network information available one can also solve for detailed scheduling and routing plan at the operational level, which has been well established in the literature. Therefore it will not be addressed in this study.

Table 2 identifies a number of key factors influencing the efficiency of delivery strategies and defines the corresponding policy scenarios to be tested later in the study.

Table 2 Summarize of scenarios

Scenarios	Description
1	Impact of long-haul distance: with fixed UCC location
2	Impact of long-haul distance: with variable UCC location
3	Impact of market penetration
4	Impact of network size
5	Impact of customer density
6	Impact of customer demand rate
7	Impact of customer rent cost and UCC terminal cost
8	Impact of vehicle size regulation

3.2 Distribution network model

3.2.1 Introduction to CA method

In this research, Continuum Approximation (CA) method is used to build the distribution channel model at the tactical level. CA is a useful tool when planning a new service or the expansion of an existing one. As described in Chapter 2.5, CA has a number of desirable features that makes it a good tool for the proposed research at the tactical level. Compared to the traditional OR methods (e.g., mixed integer program), this method requires only the spatial and temporal densities and the average distribution of customer demand rather than the precise information on every exact location. Discrete data can be approximated by continuous function with close form solutions, especially when the number of points is large.

We define the model objective as minimizing the total logistics cost, then choose the schedule and routing plan to optimize the objective and calculate the number of stops per tour, dispatching frequency, logistics cost and vehicle miles traveled (VMT) for further evaluation.

In this section, we introduce the cost components formulation, then present the Continuum Approximation method through a one-to-one delivery problem. (Daganzo and Newell, 1986; Daganzo,2005)

The logistics cost in this study is defined as various cost components arising from logistics operation in the last-mile process, including costs related to motion (i.e., during transportation) and costs related to stationary (i.e., during storage). All the costs incurred are counted regardless of who pays them, and are measured as cost per item. (Item is the basic unit for shipped goods, it can be lbs, gallon, or pallet, etc) It is not crucial that the cost of the specific action be allocated to the "correct" category, as all costs are included and none are double counted in the analysis.

Motion costs are captured by the ***transportation cost*** and the ***handling cost.*** The former includes items movement cost from one point to another; the latter includes packaging cost and loading/unloading cost.

Transportation cost can be counted in the following way:

Fixed cost per shipment $C_f = (1+n_s)*C_s + C_d*d$,

where n_s is the number of stops per shipment; d is the total distance traveled per shipment; C_s is the stopping cost ($/stop) and C_d is the transportation cost per vehicle-mile ($/vehicle-distance)

Variable cost per shipment $= C_v * v$,

where C_v is the added transportation cost per extra item carried ($/item); v is the shipment size.

Handling cost includes loading individual items onto a container (i.e. box or pallet), moving the container to the vehicle, and reversing these operations at the destination. The handling cost is proportional to the shipment size, therefore

Handling cost per shipment $= C_s^{'} * v$

Where $C_s^{'}$ is the added handling cost of carrying an extra item ($/item). Then, the motion cost per shipment $= C_f + C_v * v + C_s^{'} * v$

We use $\overline{H}$ to represent the average dispatch headway, and use D' to capture the customer demand rate. With the fact that $v = D^{'} * \overline{H}$, the motion cost can be expressed as a function of the average headway.

Motion cost per item= $C_f \, / \, D^{'}\overline{H} + (C_v + C_s^{'})$

Stationary costs include ***rent costs*** and ***waiting costs***. The former captures the rent for the space, machinery needed to store the items in place, plus any maintenance costs (i.e. security and utilities) directly related to the provision of storage space. The latter includes the opportunity cost of the capital tied up in storage, and the item value lost while waiting.

Rent cost is the cost of the space and facilities needed to hold the maximum accumulation. Therefore, it should be proportional to the maximum accumulation, the item size, as well as the storage requirements.

Rent cost/item= $C_r(\textit{max accumulation})/\mathrm{D}^{'} = C_r * H_{\max}$

Where C_r is the rent cost per item per unite time ($/item-time) and $H_{\max}$ represents the maximum dispatching headway during evaluation period.

Waiting cost, also called inventory cost, is the cost associated with delay to the items. It is captured by the product of the total wait done by all items and a constant, C_i ,the penalty paid for holding one item for one time unit.

Waiting cost/item= $C_i(\textit{average wait / item}) = C_i * (H_{\max} + t_m)$

Where C_i is the waiting cost per item per unite time ($/item-time) and t_{m} represents the transportation time between origin and destination. Therefore, ***the stationary cost/item***= $(C_r + C_i) * H_{\max} + C_i * t_m$

To minimize the stationary cost, it is better to dispatch regularly, and the lower bound for $H_{\max}$ is $\overline{H}$.

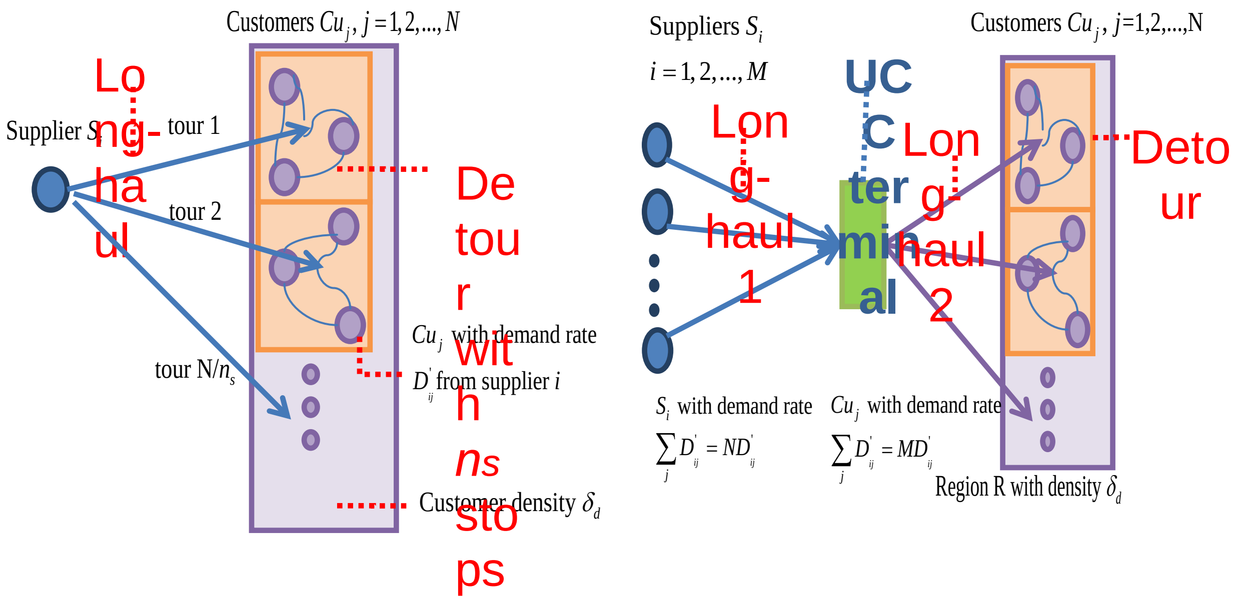
In a one-to-one delivery problem (i.e. from supplier's distribution center to the customer's warehouse), the total logistics cost is the sum of motion cost (transportation and handling) and stationary cost (storage and waiting). Since only one customer exists in this problem and it doesn't require routing decision, we solve the problem for the optimal headway (the scheduling plan).

Total logistics cost/item= $C_f \, / \, D^{'}\overline{H} + (C_v + C_s^{'}) + (C_r + C_i) * \overline{H} + C_i * \mathrm{t}_m$

This problem takes the form of economic order quantity (EOQ), which can be expressed as $\{A/\bar{H} + B\bar{H} + C\}$, where A, B, C are parameters and $\bar{H}$ is the decision variable. We can solve the problem easily by hand or excel and get the optimal headway $\bar{H} = \sqrt{C_f / D'(C_i + C_r)}$

3.2.2 Problem setting and assumptions

Suppose there are M suppliers S_i (i=1,2,…,M) located outside of the study (urban) area that supply same commodity to a set of customers Cu_j (j= 1,2,…,N) – retail stores- in the study area. In other words, each supplier ships the required quantities to all N customers according to the total demand and their market shares. The total demand rate of a customer Cu_j for all suppliers is D'_j. Suppose that the UCC facility location, the customer demand rate, and the truck fleet information are known. Considering the limited storage space in the city and the demand for just-in-time delivery, each supplier Si chooses the scheduling and routing strategies that minimize the systemic cost while satisfying the customer demand. Specifically, the scheduling decision involves the shipment size and the dispatching time, and the routing decision involves the number of customers served in a tour (i.e., chained trips from base back to base) and the service coverage area. **Figure 2** depicts typical traditional delivery and cooperative delivery strategies.



(A) Traditional Delivery Strategy (B) Cooperative Delivery with a UCC Strategy

Figure 2 Delivery Strategies.

In the traditional delivery strategy (denoted as Strategy A), the total logistics cost contains two components: the motion cost and the stationary cost. The motion cost component consists of transportation cost, stop cost and goods waiting cost during transportation; the stationary cost component includes facility rent and storage cost, and goods waiting cost at the facility. Considering the general case that the rent and storage cost is much higher at the customer's establishment in the city than at the supplier's distribution center that is typically located outside the urban area, it is not unreasonable to neglect the rent cost at the supplier's end in the total logistics cost. So the stationary cost considered in Strategy A in this paper occurs only at the customer end. Because each shipper makes decisions independently, the traditional strategy can be formulated as M parallel one-to-many distribution problems.

In the cooperative delivery with UCC strategy (denoted as Strategy B), the total logistics cost has another component in addition to the abovementioned two: the stationary cost at the UCC terminal. Because cooperation exists among the suppliers, the total logistics cost can be divided into three parts: (i) inbound cost, which corresponds to the motion cost component from the suppliers to UCC and the UCC terminal stationary cost associated with the inbound shipment (e.g., the terminal rent and storage cost related to the inbound headways); (ii) UCC terminal cost, which corresponds to the terminal-specific stationary cost (e.g., the handling and storage cost regardless of the headways); and (iii) outbound cost, which corresponds to the motion cost from the UCC terminal to the customers and the UCC terminal stationary cost associated with the outbound shipment (e.g., the terminal rent and storage cost related to the outbound headways). Thus the total logistics cost is the summation of a one-to-one distribution problem for the inbound portion and a one-to-many distribution problem for the outbound portion, plus the UCC terminal-specific cost. The detailed mathematical formulation will be described in Chapter 3.2.3.

In this study, the traditional delivery and cooperative delivery strategies are illustrated through the example of delivery of non-perishable grocery items among grocery stores in an urban area. There are three reasons for choosing the delivery of non-perishable grocery items as an illustrative case. Firstly, they are easy to quantify by weight. Secondly, they are typically shipped exclusively (i.e., not mixed with non-grocery items). And thirdly, they have been studied in the literature so their delivery patterns and attributes are relatively well known, which enables us to conduct reasonableness check and obtain realistic parameter values for our study.

Note that the grocery stores (i.e., customers) considered in the study are small to medium size independent grocery stores as opposed to chain supermarkets and wholesale stores, which have their own logistics operation, often time already consolidated by some measures; and therefore the kind of consolidation strategy examined here is of little benefit to them. On the other hand, home delivery to the end users is very dynamic in nature; and it is hard to quantify the demand accurately. In fact, home delivery is a whole other research area in itself. Therefore, this study only considers the delivery ending at small or medium local grocery stores.

The following are necessary model assumptions for the problem formulation that is presented later in Chapter 3.2.3:

- The customers are homogeneous and uniformly distributed in the study are with the same demand rate for each supplier. That is, $D_{ij}^{'} = D^{'}$, and $\sum_{i} D_{ij}^{'} = D_{j}^{'}$.
- Each customer is served by all suppliers, and each supplier serves all customers in the study area.
- The demand rate is constant over time, which means $D_{ij}^{'}$ does not change over time.
- The number of customers (N) in the study area is large (N>>the square of the number of stops per tour). In other words, multiple delivery tours are needed to serve all of the customers.
- The commodity to be delivered is non-perishable grocery items. So it can be assumed that the items' waiting cost (also known as inventory cost) is relatively small compared to the other cost components and hence is ignored in the analysis. This assumption also implies that the rent cost dominates the inventory cost at the customer end, thus minimizing the maximum accumulation of the items at the store will result in the minimum stationary cost at the customer end.
- Vehicles have a maximum load of $V_{\max}$. The above assumption about low waiting cost also implies that vehicles always set out with maximum load in this study since it is obviously more economical.
- A vehicle tour accounts for the truck activity that consists of the following: departs from the base (a depot or a distribution center), serves one or more customers, then goes back to the base. It is assumed that there is no reverse flow, which means the vehicle does not collect items during the tour and bring them back to the base.
- There is no restriction on tour length.
- The study area can be partitioned into rectangles or circles.

3.2.3 Problem formulation

The model formulation is an extension to Daganzo's work on Logistics Cost Functions (1986 and 2005), with necessary modifications that are described below. The parameter notations with the adopted values used in our analysis are given in **Table 3**. Explanation on how the parameter values were determined is presented in Chapter 3.2.5.

Table 3 Summary of the Parameters Used in the Model Formulation

Notation	Explanation	Unit	Lower Bound	Upper Bound	Typical Value
δ_d	Customer density	per sq miles	1.43	49.03	25
$D^{'}$	Customer demand rate	lbs/customer-day	59.69	3246	1550
r	Long-haul distance in traditional	Mile	50	500	250

	delivery				
$r1$	Supplier-UCC long-haul distance	Mile			230
$r2$	UCC-customer long-haul distance	Mile			20
K	Dimension less parameter[i]				0.82
V_{max}	Vehicle capacity	Lbs	7272	22238	9238
M	Number of suppliers	/			5
N	Number of customers	/			500
C_r	Customer rent cost	\$/lbs-day	0.39	4.5	0.5
C_{h1}	Long-haul transportation cost	\$/mile			0.63
C_{h2}	local transportation cost	\$/mile			1.83
C_s	Fixed stop cost (e.g. regardless of the item quantities)	\$/stop			16.34
C'_s	Variant stop cost (e.g. as a function of the item quantities)	\$/lbs			0.005
C_r^0	Fixed terminal rent cost	\$/order			0.02
C_r^t	Variant terminal rent cost	\$/lbs			0.0868
C_f^0	Terminal handling cost (fixed)	\$/order			0.184
C_f^t	Terminal handling cost (varied)	\$/lbs			0.004
H^t	Minimum terminal process time	Day			0.083
n_s	Number of stops in a delivery tour	(decision variable in the model)			
v	Shipment size from one supplier to one customer	(decision variable in the model)			

Strategy A: Without UCC

The traditional delivery problem (Strategy A) is treated as an M-parallel one-supplier-to-many-customer distribution problem. As illustrated in Figure 1(A), supplier S_i serves all customers in the study area without discrimination, and ships goods directly to the customers with a number of multiple-stop tours. With the assumptions that N is a large number and that the customers are homogeneous, the study area can be partitioned into an integer number of identical subareas. Each subarea is served by one delivery tour. Furthermore, each customer Cu_j (j=1,…,N) is assumed to have the same demand rate for supplier S_i. Therefore, the number of stops is equal in every delivery tour.

We introduce the following auxiliary variables to representing the cost components of long-haul motion cost (α_{1A}), detour motion cost (α_{2A}) and stationary cost (α_{4A}):

---

[i] K is a dimensionless parameter, which only depends on the metric to reflect the detour distance. It is an approximate VRP distance without the precise location of each customer. K=0.82 in the L1 Metric, see Daganzo (2005) Appendix 1 for the proof.

$\alpha_{1A} = 2rC_{d1} + C_s$

$\alpha_{2A} = C_{d2} k \delta_d^{-0.5} + C_s$

$\alpha_{4A} = C_h M / D^{'}$

Normalize by the shipment size per tour, the total logistics cost per unit without UCC can be formulated as follows:

$$Z_A = C_s^{'} + \alpha_{1A} / n_s v + \alpha_{2A} / v + \alpha_{4A} v \tag{1}$$

$$St.\ n_s v \le Vmax \tag{2}$$

$$n_s \ge 1 \tag{3}$$

Constraints (2) and (3) ensure that the shipment size per tour cannot exceed the vehicle capacity, and at least one customer is served in the tour. It is a simple quadratic program which can be solved either by hand or commercial software. Solving the problem with the fully loaded truck condition, i.e., $n_s v = Vmax$, we have the following:

1) If the optimal shipment size $v^* = \sqrt{\alpha_{2A} / \alpha_{4A}} \le Vmax$, then

Optimal total logistic cost	$Z_A^* = C_s^{'} + \alpha_{1A} / Vmax + 2\sqrt{\alpha_{2A}\alpha_{4A}}$
Optimal motion cost	$Z_A^{t*} = C_s^{'} + \alpha_{1A} / Vmax + \sqrt{\alpha_{2A}\alpha_{4A}}$
Optimal stationary cost	$Z_A^{h*} = \sqrt{\alpha_{2A}\alpha_{4A}}$

2) If the optimal shipment size $v^* = \sqrt{\alpha_{2A} / \alpha_{4A}} \ge Vmax$, then

Optimal total logistic cost	$Z_A^* = C_s^{'} + (\alpha_{1A} + \alpha_{2A}) / Vmax + \alpha_{4A} Vmax$
Optimal motion cost	$Z_A^{t*} = C_s^{'} + (\alpha_{1A} + \alpha_{2A}) / Vmax$
Optimal stationary cost	$Z_A^{h*} = \alpha_{4A} Vmax$

Strategy B: With UCC

As shown in Figure 1(B), in the cooperative delivery problem (Strategy B), UCC consolidates the quantities according to the demand by *N* customers from *M* suppliers, and then disseminates the quantities to all customers in the study area. In this case, we assume that UCC is located outside of the study area and the average distance from the supplier to UCC is r_1, and the average distance from UCC to the customer is r_2. The number of suppliers and customers reflects the economic scale of using UCC.

The following auxiliary variables are introduced in Strategy B:

Inbound motion cost $\alpha_{1Bi} = 2r_1C_{d1} + C_s$,

Inbound stationary cost $\alpha_{4\mathrm{Bi}} = C_hM \,/\, ND^{'}$,

Outbound long-haul motion cost $\alpha_{1Bo} = 2r_2C_{d1} + C_s$,

Outbound detour motion cost $\alpha_{2Bo} = C_{d2}k\delta_d^{-0.5} + C_s$,

Outbound stationary cost $\alpha_{4\mathrm{Bo}} = C_h \,/\, D^{'}$,

UCC terminal rent and handling cost (varied part over quantities) $\alpha_5 = C_f^t + C_r^tH_t$,

UCC terminal rent and handling cost (fixed part over quantities) $\alpha_6 = C_f^o + C_r^o$.

Normalized by the shipment quantities per tour, the total logistic cost with UCC can be formulated as follows:

$$Z_B = Z_{Bi} + Z_{Bo} + Z_{Bt} \tag{4}$$

Where $$Z_{Bi} = C_s^{'} + \alpha_{1Bi} \,/\, v_i + \alpha_{4Bi}v_i \tag{5}$$

$$Z_{Bo} = C_s^{'} + \alpha_{1Bo} \,/\, n_sv_o + \alpha_{2Bo} \,/\, v_o + \alpha_{4Bo}v_o \tag{6}$$

$$Z_{Bt} = C_r^t \max[H_i, H_o] + \alpha_5 + \alpha_6 \,/\, ND^{'} \tag{7}$$

$$St.\ \ v_i \le Vmax \tag{8}$$

$$v_on_s \le Vmax \tag{9}$$

$$n_s \ge 1 \tag{10}$$

Equations (5),(6) and (7) represent the inbound cost, outbound cost and the UCC terminal cost; while (8) and (9) ensure that the shipment size is less than vehicle capacity. Equation (10) indicates at least one customer is served during each outbound delivery. In equation (7), the first term is the terminal rent cost as a function of storage time, usually the largest time gap between the inbound shipment and the next outbound shipment. Thus, if one prefers frequent service while the other operates with a long headway, the cost at the UCC terminal will increase, contributing to an increase in the total logistics cost. Therefore, two types of cooperative delivery are discussed next:

No coordination between inbound and outbound trips at UCC (Strategy B1): Inbound trips to UCC and outbound trips from UCC are assumed to be non-coordinated under this scenario. In other words, these two delivery activities occur independently. In this case, the optimization results can be obtained separately for inbound and outbound deliveries. Thus optimal results can be obtained by solving the two quadratic problems (5) (8) and (6)(9)(10) separately as shown in **Table 4**.

For inbound trips, if the optimal unit shipment size v^* is larger than the vehicle capacity, equation

$$(2r_1C_{d1} + C_s)N / M \geq V_{max}{}^2C_h / D' \qquad (10)$$

then constraint (5) must be satisfied. This indicates that when the ratio of the number of customers to that of suppliers, demand rates, as well as the long-haul distance are large, it is possible for the inbound unit shipment size to exceed the vehicle capacity, i.e., constraint (8). In that case, the optimal shipment size is set equal to the vehicle capacity.

Similarly, when the demand rates are high and the customer density is low, it is possible for the outbound shipment size to be greater than the vehicle capacity, if no constraint applied. In that case, the optimal outbound shipment size would equal to the vehicle capacity.

Coordinated inbound and outbound trips at UCC (Strategy B2): Under this strategy, inbound and outbound trips are synchronized in terms of their headway (or dispatching frequency). Thus, the single quadratic problem (5)-(10) is solved. The optimal results for both Strategy B1 and B2 are presented in **Table 4**.

Table 4. Optimal Results for UCC Strategies B1 and B2

	Condition	**Optimal cost**	**Expressions**
Strategy B1	$v_i \le V_{max}$ and $v_o \le V_{max}$	Total logistics cost	$Z^{*}_{B1} = 2C^{'}_{s} + 2\sqrt{\alpha_{1Bi}\alpha_{4Bi}} + 2\sqrt{\alpha_{1Bo}\alpha_{4Bo}} + \alpha_{1Bo} / V_{max} +$ $\mathrm{C}^{t}_{h} \max[\sqrt{\alpha_{1Bi}\alpha_{4Bi}} M / ND^{'}, \sqrt{\alpha_{2Bo}\alpha_{4Bo}} / D^{'}] + \alpha_5 + \alpha_6 / ND^{'}$
		Motion cost	$Z^{t*}_{B1} = 2C^{'}_{s} + \sqrt{\alpha_{1Bi}\alpha_{4Bi}} + \sqrt{\alpha_{1Bo}\alpha_{4Bo}} + \alpha_{1Bo} / V_{max}$
		Stationary cost	$Z^{h*}_{B1} = \sqrt{\alpha_{1Bi}\alpha_{4Bi}} + \sqrt{\alpha_{1Bo}\alpha_{4Bo}} + \mathrm{C}^{t}_{h} \max[\sqrt{\alpha_{1Bi}\alpha_{4Bi}} M / ND^{'}, \sqrt{\alpha_{2Bo}\alpha_{4Bo}} / D^{'}] + \alpha_5 + \alpha_6 / ND^{'}$
	$v_i \ge V_{max}$ and $v_o \le V_{max}$	Total logistics cost	$Z^{*}_{B1} = 2C^{'}_{s} + (\alpha_{1Bo} + \alpha_{1Bi}) / V_{max} + \alpha_{4Bi} V_{max} + 2\sqrt{\alpha_{2Bo}\alpha_{4Bo}}$ $\mathrm{C}^{t}_{h} \max[V_{max} M / ND^{'}, \sqrt{\alpha_{2Bo} / \alpha_{4Bo}} / D^{'}] + \alpha_5 + \alpha_6 / ND^{'}$
		Motion cost	$Z^{t*}_{B1} = 2C^{'}_{s} + (\alpha_{1Bo} + \alpha_{1Bi}) / V_{max} + \sqrt{\alpha_{2Bo}\alpha_{4Bo}}$
		Stationary cost	$Z^{*}_{B1} = \sqrt{\alpha_{2Bo}\alpha_{4Bo}} + \mathrm{C}^{t}_{h} \max[V_{max} M / ND^{'}, \sqrt{\alpha_{2Bo} / \alpha_{4Bo}} / D^{'}] + \alpha_5 + \alpha_6 / ND^{'}$
	Else[ii]	Total logistics cost	$Z^{*}_{B1} = 2C^{'}_{s} + (\alpha_{1Bo} + \alpha_{1Bi} + \alpha_{2Bo}) / V_{max} + (\alpha_{4Bi} + \alpha_{4Bo}) V_{max} + \mathrm{C}^{t}_{h} V_{max} / D^{'} + \alpha_5 + \alpha_6 / ND^{'}$
		Motion cost	$Z^{*}_{B1} = 2C^{'}_{s} + (\alpha_{1Bo} + \alpha_{1Bi} + \alpha_{2Bo}) / V_{max}$
		Stationary cost	$Z^{h*}_{B1} = (\alpha_{4Bi} + \alpha_{4Bo}) V_{max} + \mathrm{C}^{t}_{h} V_{max} / D^{'} + \alpha_5 + \alpha_6 / ND^{'}$
Strategy B2	$v_i \le V_{max}$ and $v_o \le V_{max}$	Total logistics cost	$Z^{*}_{B2} = 2C^{'}_{s} + \alpha_{1Bo} / V_{max} + 2\sqrt{(\alpha_{1Bi} + \alpha_{2Bo} N / M)(\alpha_{4Bi} + \alpha_{4Bo} M / N + \mathrm{C}^{t}_{h} M / ND^{'})} + \alpha_5 + \alpha_6 / ND^{'}$
		Motion cost	$Z^{t*}_{B2} = 2C^{'}_{s} + \alpha_{1Bo} / V_{max} + \sqrt{(\alpha_{1Bi} + \alpha_{2Bo} N / M)(\alpha_{4Bi} + \alpha_{4Bo} M / N + \mathrm{C}^{t}_{h} M / ND^{'})}$
		Stationary cost	$Z^{h*}_{B2} = \sqrt{(\alpha_{1Bi} + \alpha_{2Bo} N / M)(\alpha_{4Bi} + \alpha_{4Bo} M / N + \mathrm{C}^{t}_{h} M / ND^{'})} + \alpha_5 + \alpha_6 / ND^{'}$
	Else[iv]	Total logistics cost	$Z^{*}_{B2} = 2C^{'}_{s} + (\alpha_{1Bo} + \alpha_{1Bi} + \alpha_{2Bo} N / M) / V_{max} + (\alpha_{4Bi} + \alpha_{4Bo} M / N + M\mathrm{C}^{t}_{h} / ND^{'}) V_{max} + \alpha_5 + \alpha_6 / ND^{'}$
		Motion cost	$Z^{t*}_{B2} = 2C^{'}_{s} + (\alpha_{1Bo} + \alpha_{1Bi} + \alpha_{2Bo} N / M) / V_{max}$
		Stationary cost	$Z^{h*}_{B2} = (\alpha_{4Bi} + \alpha_{4Bo} M / N + M\mathrm{C}^{t}_{h} / ND^{'}) V_{max} + \alpha_5 + \alpha_6 / ND^{'}$

[ii, iv] It is not possible for $v_i \le V_{max}$ and $v_o \ge V_{max}$ when M/N<=1. Proof is not provided here due to space limitation.

3.2.4 Data description

In this research, we have assembled and compiled the following data sets for estimating the model parameters.

Texas Commercial Vehicle Surveys (Nepal, Farnsworth and Pearson, 2007) was conducted by Texas Department of Transportation in counties of San Antonio, Amarillo, Valley, Lubbock and Austin during 2005 and 2006. The data set contains randomly selected samples from a combined database of field observations of privately operated certified commercial vehicles in the study areas, including a total of 13,802 trips made by 1,711 commercial vehicles, in which the food commodity accounts 25% of the total trips. Drivers or operators of the selected vehicles completed both a vehicle information form and a daily travel log on an assigned day. As shown in **Table 5**, the surveys record the trip information such as departure time, arrival time, location, commodity, quantities of drop size; and the vehicle information like vehicle type, fuel type, gross weight, odometers, etc.

Table 5. Key information recorded in the Texas Commercial Vehicle Survey travel log

Stop-level attributes	Description
Longitude and latitude	Stop coordinates
Departure time	Departure time at stop
Arrival time	Arrival time at stop
Loading/unloading cargo type	Cargo Classification: 1) Farm products, 2) Forest products, 3) Marine Products, 4) Metals and Minerals, 5) Food, Health, and Beauty Products, 6) Tobacco Products, 7) Textiles, 8) Wood Products, 9) Printed Matter, 10) Chemical Products, 11) Refined Petroleum or Coal Products, 12) Rubber, Plastic, and Styrofoam Products, 12) Clay, Concrete, Glass, or Stone, 14) Manufactured Goods/Equip, 15) Wastes, 16) Miscellaneous Shipments, 17) Hazardous Materials, 18) Transportation, 19) Unclassified Cargo, 20) Driver Refused to Answer, 21) Unknown to Driver, 22) Empty
Loading/unloading cargo weight	Total loading or unloading cargo weight
Activity type	Activity Options: Base Location/Return to Base Location, Delivery, Pick-up, Pick-up and Delivery, Maintenance (fuel, oil, etc.), Driver Needs (lunch, etc.), To Home, Others (specify), Refused/Unknown
Land use type of stop	Land Use Type Options: Office Building, Retail/Shopping, Industrial/Manufacturing, Medical/Hospital, Educational (12th Grade or less), Educational (College, Trade, etc.), Government Office/Building, Residential, Airport, Intermodal Facility, Warehouse, Distribution Center, Construction Site, Others (specify), Refused/Unknown.

Food Environment Atlas is a program supported by the U.S. Department of Agriculture, Economic Research Service. It aims at stimulating research in food choice and diet quality by providing public county-level statistics in community characteristics and food availability, including information such as demographic composition and population density, accessibility and proximity to a grocery store, number of stores available, and the demands at stores, etc. The statistics are generated with multiple data sources collected between 2006 and 2008. **Table 6** lists the key parameters recorded in this data set. The data is used to estimate the range of social economic parameters for this study.

Table 6 Key information recorded in the Food Environment Atlas

County level Indicators	Description
Access to food stores	# Households no car & >1 mi to store, 2006 % Households no car & >1 mi to store, 2006 # Low income & >1 mi to store, 2006 % Low income & > 1 mi to store, 2006 # Households no car & >10 mi to store, 2006 % Households no car & >10 mi to store, 2006 # Low income & >10 mi to store, 2006 % Low income & >10 mi to store, 2006
Availability of food stores	# Grocery stores, 2007 Grocery stores/1,000 pop, 2007 # Supercenters and club stores, 2007 Supercenters and club stores/1,000 pop, 2007 # Convenience stores no gas, 2007
Food at home	Lbs per capita fruit and vegetables, 2006 Ratio of per capita fruit&vegetables and prepared food, 2006 Lbs per capita packaged sweet snacks, 2006 Gals per capita soft drinks, 2006 Lbs per capita meat&poultry, 2006 Lbs per capita solid fats, 2006 Lbs per capita prepared food, 2006
Food price	Relative price of low-fat milk, 2006 Relative price of sodas, 2006 Relative price ratio low-fat milk/sodas, 2006 Price ratio green-leafy/starchy veg, 2006 Price ratio fruit/pkg sweet snacks, 2006 Price ratio fruit/pkg savory snacks, 2006 Price ratio wholegrain/refinedgrain, 2006
Local food	# Farms with direct sales, 2007 % Farms with direct sales, 2007 % Farm sales $ direct to consumer, 2007 $ Direct farm sales, 2007 $ Direct farm sales per capita, 2007

	# Farmers’ markets, 2009
	Farmers’ markets/1,000 pop, 2009
	# Vegetable acres harvested, 2007
	Vegetable acres harvested/1,000 pop, 2007
	Farm to school program, 2009
Socioeconomic Characteristics	% White, 2008
	% Black, 2008
	% Hispanic, 2008
	% Asian, 2008
	% Amer. Indian or Alaska Native, 2008
	% Hawaiian or Pacific Islander, 2008
	Median household income, 2008
	Poverty rate, 2008

The Vehicle inventory and usage survey (VIUS) is a public available data set collected by the U.S. Census Bureau. It provides data on the physical and operational characteristics of the nation's private and commercial truck population. Its primary goal is to produce national and state-level estimates of the total number of trucks. VIUS provides physical and operational characteristic data of nationwide private and commercial truck fleet. The physical characteristic data include weight, number of axles, overall length, body type, etc. for medium and heavy trucks. The operational characteristic data include commodities handled, distance traveled, mileage, etc. This survey was conducted every 5 years till 2002, as part of the economic census. VIUS 2002 is used to obtain the vehicle information at the state level for this research.

Other data sources include a study by Regan *et al (2005)* based on a survey carried out in spring 2001 of logistics managers in California, the research findings from Kawamura *(2000) (2007)*and Hayashi et al*(2005)*, 2011business facility rental information obtained from various Internet advertisement sources (e.g., the Crag’s list).

3.2.5 Parameter estimation

As stated in Chapter 1, a major research obstacle is the limited public available data sources for urban freight problems. With this problem, we combined several data sources which were described in Chapter 3.2.4 to estimate the parameters for this study.

Customer density The Food environmental Altas provides the grocery store density per capita and population density per square mile in 2008 in four counties: New York(Manhattan), Cook(Chicago), Los Angeles and San Francisco. The customer density is the product of the store density and population density. The results show that San Francisco has the lowest value and the New York has the highest value among the five counties, the range of the customer density is 1.43-49.02(store per sq mile).

Demand rate The Food Environmental Altas contains the grocery consumption in lbs per capita, and the direct sale percent which counts for the portion consumed via the grocery stores during the year 2006 for the same four counties. By dividing the product of the groceries consumptions and direct sale percent with the grocery store density per capita, we obtained the demand rate at the customer end (lbs/store-day) with the range from 59.69-3246. Note that this demand rate is the sum of the demand rate from all suppliers in the model, i.e., D'_j.

Long haul distance In spring 2001, University of California conducted a survey of Logistics managers of more than 700 trucking companies operating in California (Marcucci, 2008). The survey recorded the company's information and asked the intention of using shared freight facility. The results showed that the shared freight facility demand is highly correlated with the truck haul distance: The potential demand for using the shared freight facility is highest for carriers with hauls over 500 miles and lowest for carriers with hauls less than 50 miles. In the range of 50-500 miles, the carriers have neutral opinions in the choice. Therefore, for our study purpose, 50-500 miles is used as the range of the long-haul distance.

Vehicle capacity The Freight Analysis Framework 2 (FAF2) gives the average payload (measured in lbs) by Gross Vehicle Weight Group derived from VIUS 2002 for each state. The VIUS data provides the physical (e.g., weight, overall length, body type) and the operational characteristics (e.g., commodities handled, mileage) of nationwide private and commercial truck fleet. The VIUS data revealed that 99% of the truck trips for carrying food commodities were made by the Gross Vehicle Weight Groups 2 to 8, which corresponds to the payload range of 7,272 lbs to 35,101 lbs. The most frequently used truck group is Group 6 (single unit truck) with a payload of 9,238 lbs, followed by the truck group 7(combinational truck) with a payload of 22,238lbs. Therefore, we will use 9,238lbs as the standard vehicle capacity in this study, with an alternative capacity of 22,238lbs.

Store rent cost By looking up the merchandise renting cost from the advertisement online in the urban areas of the four counties mentioned above, we obtained the rent cost for stores with area between 10,000 and 15,000 sq ft. By dividing the rent cost by the demand rate, the store rent cost is in the range of be 0.39-0.68($/day-lbs).

Stop cost According to Kawamura (2000),the perceived value of time for truck operators =28.1 per hour; the Texas data show that over 95% of the dwell times are in the range of 10 to 60 minutes for the food commodity, therefore the range for fixed stop cost is 4.68 to 28.1 ($/stop). Moreover, with the pickup/drop size information available in the Texas data set, a regression model gives the value of the varied stop cost of 0.005($/lbs)

Distance cost The local average speed for commercial vehicle obtained from Texas data is 19.36 mph; The long-haul average speed can be roughly estimate from the highway potion considering speed limit and congested effects, which is 44mph. Applying the value of time for trucks, the value of distance costs for local and long-haul are 1.83 and 0.63 separately.

Other parameters The location of UCC terminal is assumed to be outside of the areas, which an average distance of 50 miles from the UCC terminal to the delivery regions is reasonable. Because there is no existing practice of UCC in the US, the UCC terminal cost components are hypothetic and generally comes from the rent cost of warehouse at suburbs area. We obtain the values of terminal operation cost used in Kawamura and Lu (2007) and vary them by 2% to 2000% to conduct a sensitivity analysis.

3.3 Emission estimation model

3.3.1 Introduction to MOVES

To evaluate the environmental impacts on delivery consolidation, US EPA emission model MOVES is used to generate the emission factors of various vehicle types at different speeds (US EPA, 2010). Based on different factors such as vehicle characteristics (e.g., fuel type, load weight, etc), vehicle activity characteristics (e.g., speed distribution, vehicle specific power) and other external factor (e.g., road type), MOVES classifies the vehicle activities into different activity bins and estimate the emission rates. A few correction factors are also applied to the emission rates to adjust for the influence of temperature, air conditioning, and fuel effects. For more details, please refer to Vallamsundar and Lin (2011).

In this study, two types of pollutant are included in the analysis: energy consumption, which is directly linked to the CO2 and PM2.5 emissions. It is worth mentioning that other pollutants (i.e. CO, PM10, NOx) can be incorporated in the similar fashion as to be presented below for further study.

Emission rate estimation in MOVES

MOVES implements a modal-based approach to estimate emissions. An important aspect of this approach is that vehicle activities can be “binned” into categories according to different factors affecting emissions. The bins that differentiate activities according to vehicle characteristics such as fuel type, engine type, model year, loaded weight, and engine size are labeled source bins. Operating mode bins differentiate the emissions according to second-by-second vehicle activity characteristics consisting of vehicle specific power (VSP) - a measure of the power demand placed on a vehicle under various driving modes and instantaneous speed distributions, and classified according to average speed, road type, and vehicle type. After classifying activities into different bins, MOVES assigns an emission rate for each unique combination of source and operating mode bin. Once the emission rate is assigned to each source and operating mode bin, the emission rates are aggregated to produce an overall emission rate for each source-use type. A few correction factors are also applied to the emission rates to adjust for the influence of temperature, air conditioning, and fuel effects. More detailed technical discussion of MOVES can be found in US EPA (2010)

To estimate the PM2.5 emission rate and the energy consumption rate in MOVES, a number of input parameters must be specified. **Table 7** summarizes the key inputs to MOVES for this study. Note that emissions are typically regionally specific and hard to generalize. Therefore, many of the input parameters shown in **Table 7** are Chicago (Cook County) based. But the estimation procedure is common to any geographical areas in the country.

Table 7 Key input parameters to MOVES

Input	Description
Season	Winter
Time of day/Day of Week	Mid-day, weekday
Analysis year	2011
Road type	-Urban Unrestricted Access or Arterials -Urban Restricted Access or Freeways
Pollutants	PM2.5, Energy consumption
Emission Processes	Running exhaust, crankcase running exhaust, brake and tire wear and tear
Vehicle type	Single Unit Short-haul Truck, Combination short-haul Truck
Vehicle speed	0-70 mph
Fuel type	diesel (Cook county specific)
Temperature	Cook county specific

3.3.2 Emission factors generated by MOVES

After running MOVES, an emission rate matrix by vehicle speed for each road type and vehicle type is obtained. The next step is to fit a continuous smooth curve between the emission rates and the vehicle speeds. To keep the environmental cost component in the objective function simple and solvable, polynomial power functions are fitted. Figures 3 - 6 show examples how well the curves are fitted to the estimated emission rates (from MOVES) in blue dots.

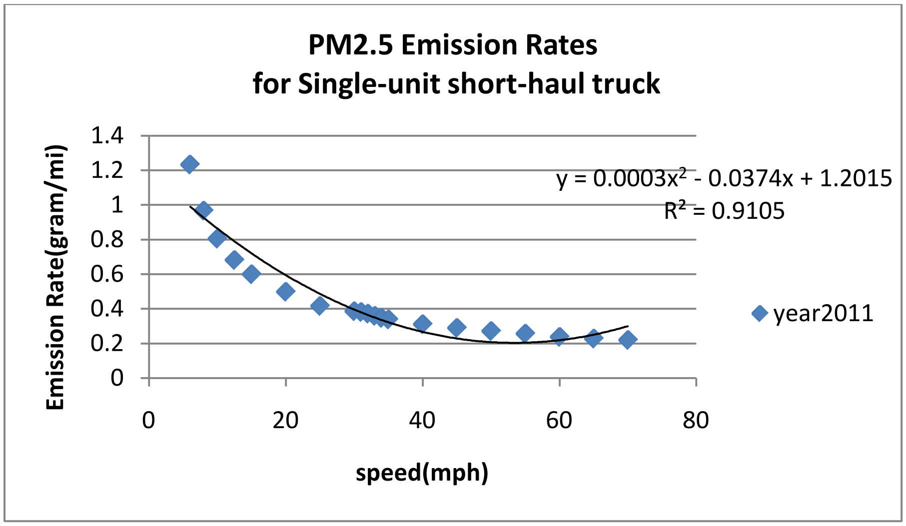


Figure 3 PM2.5 emission rate curve by speed for single-unit short-haul truck

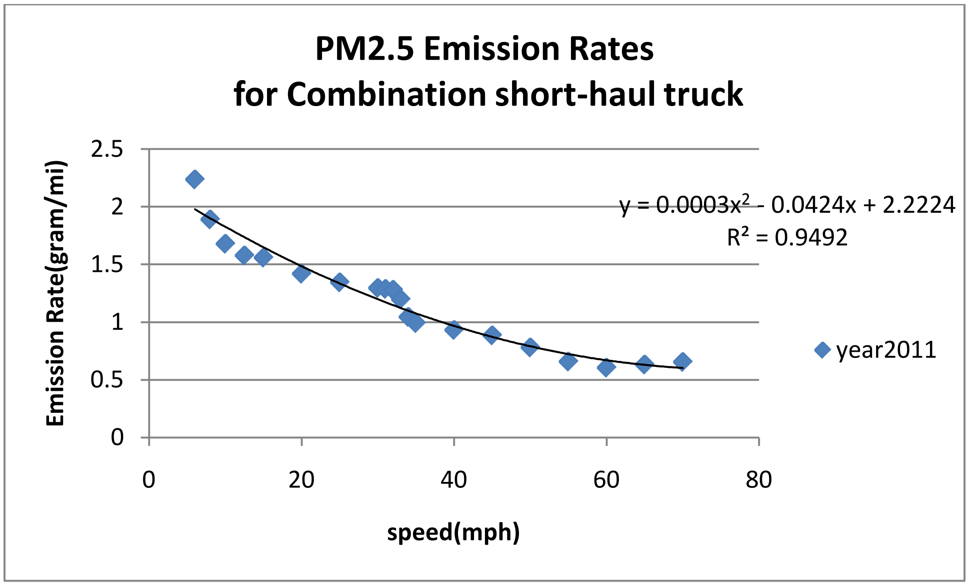


Figure 4 PM2.5 emission rate curve by speed for combination short-haul truck

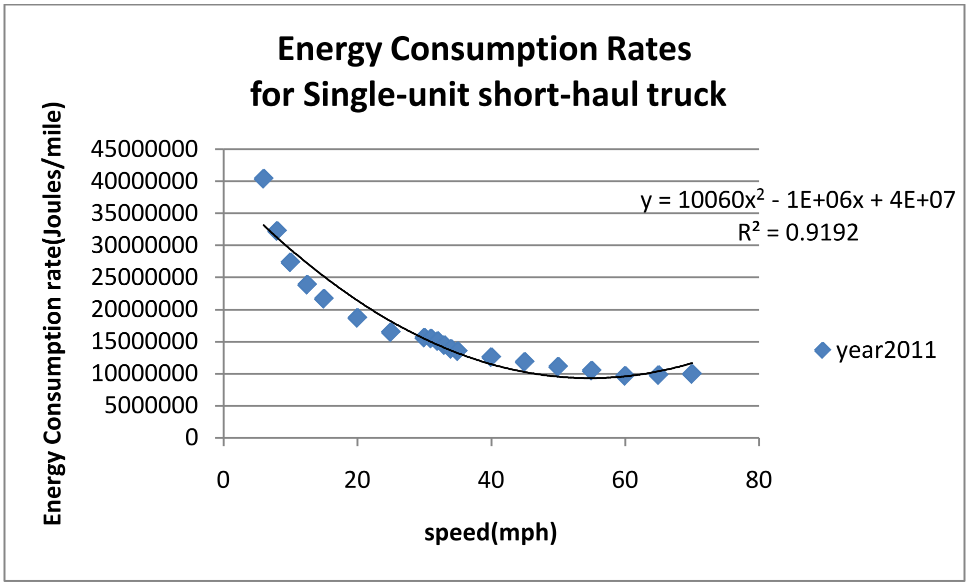


Figure 5 Energy consumption rate curve by speed for single-unit short-haul truck

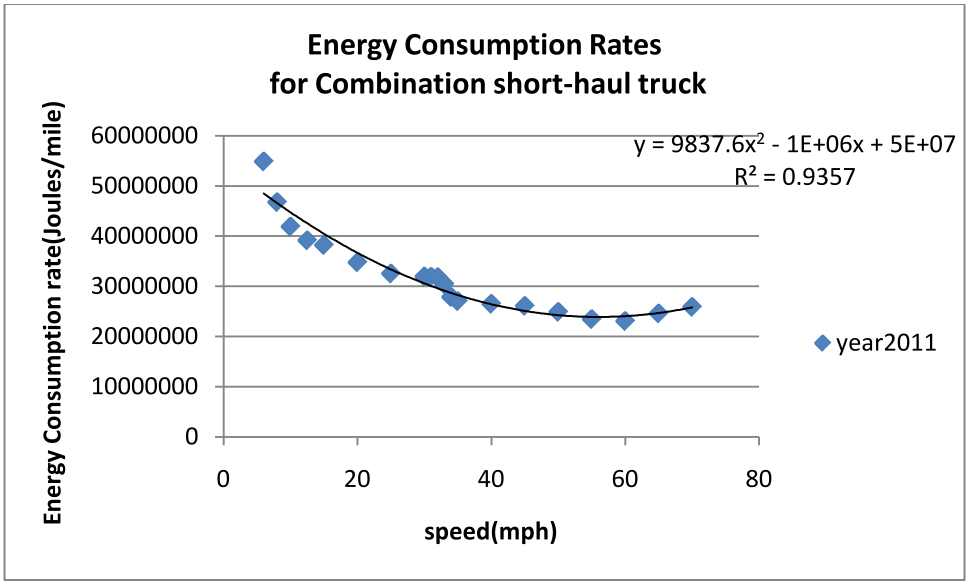


Figure 6 Energy consumption rate curve by speed for combination short-haul truck

Table 8 summarizes the final fitted curves for diesel engine truck emission rates in calendar year 2011. Here only the emission rates for two vehicle types are considered: single unit short-haul truck and combination short-haul truck. According to the Texas data, the local (arterial) average speed for commercial vehicle is 19.36 mph; The long-haul (freeway) average speed is assumed to be 44 mph after taking into account congestion effect.

Table 8 PM2.5 emission rates and energy consumption rates

Pollutant	**Vehicle type**	**Equation**	**R²**	**EF value at Speed=19.36mph (gram/mile)**	**EF value at Speed=44mph (gram/mile)**
PM2.5	Single unit truck	$y = 0.0003x^2 - 0.0374x + 1.2015$	0.9105	0.589879	0.1367
	Combination truck	$y = 0.0003x^2 - 0.0424x + 2.2224$	0.9492	1.513979	0.9376
Energy Consumption	Single unit truck	$y = 10060x^2 - 1E{+}06x + 4E{+}07$	0.9192	24410585	15476160
	Combination truck	$y = 9837.6x^2 - 1E{+}06x + 5E{+}07$	0.9357	34327227	25045594

3.3.3 Emission calculation

With the emission factors from **Table 8**, and the total vehicle miles traveled from the model described in Chapter 3.2.3, the total emissions can be estimated with the following equation:

$$Emission(p) = \sum_{veh,road} EF_{p,veh,road} * VMT_{veh,road}$$

Where p---pollutant type, PM2.5 or Energy consumption;

veh---vehicle type, single-unit truck or combination truck;

$road$---road type, freeway or arterial;

$EF_{p,veh,road}$ ---emission rate for pollutant p, vehicle type *veh*, and road type *road;*

$VMT_{veh,road}$ ---vehicle miles traveled for vehicle type *veh* and road type *road.*

4. ANALYSIS RESULTS

The CA models described in Chapter 3 are applied with the parameter values set in **Table 3**. Furthermore, a series of sensitivity analyses are performed on long-haul distance, number of suppliers and number of customers, customer density and demand, fleet size, and customer rent cost and UCC terminal cost, to evaluate the effects of these factors on the total logistics cost, energy consumption, and PM2.5 emissions. Results are presented and discussed in the following subsections. Note that, in order to reduce the number of plots presented, we introduce the *%change of a given evaluation criterion* (i.e., total logistics cost, energy consumption, and PM2.5 emissions) between strategies A(baseline) and B1 and B2(alternatives):

%change = [Baseline (A) - Alternative (B1 or B2)]/Baseline (A)

A positive number means A has a higher value than B1 or B2.

4.1 Long-haul distance cost

4.1.1 With Fixed UCC Location

The long-haul distance is assumed to vary between 50 miles and 500 miles with the average distance from UCC to the study area of 30miles. In Strategy A (**Figure 7**a), the stationary cost is constant but the motion cost increase linearly with the long-haul distance, leading to a linear increase of the total logistics cost. In the UCC strategies B1 and B2 (**Figure 7**b and **Figure 7**c), all cost components increase nonlinearly with long-haul distance and at a faster rate than in Strategy A. In strategies B1 and B2, vehicle miles traveled is presumed being saved over A. As the long-haul distance increases the saving of motion cost in UCC is reduced. When the UCC terminal cost exceeds the reduced saving in the motion cost, UCC strategies become less appealing than A.

Figure 8 gives the % change in energy consumption (**Figure 8**a) and PM2.5 Emissions (**Figure 8**b). The blue line plots the difference between strategies A and B1, and the red line shows the difference between strategies A and B2. The blue line is a convex one with the long-haul distance. It shows that B1 almost always generates higher energy consumption and PM2.5 emissions and the difference reaches the maximum point when the long-haul distance is around 150miles. On the other hand, B2 seems to always provide energy and emission benefits over A.

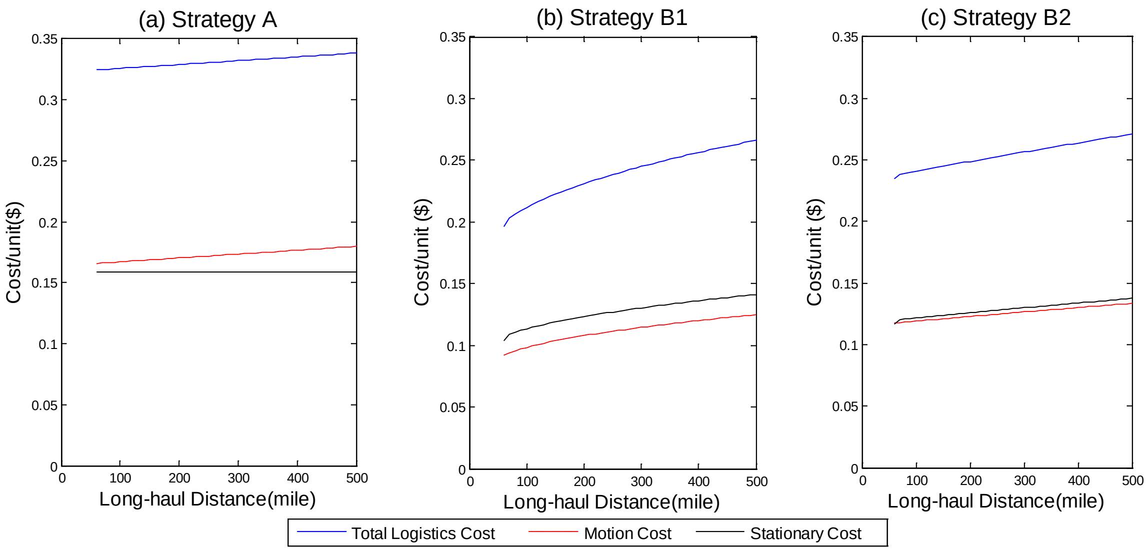


Figure 7 Cost as a Function of Long-haul Distance

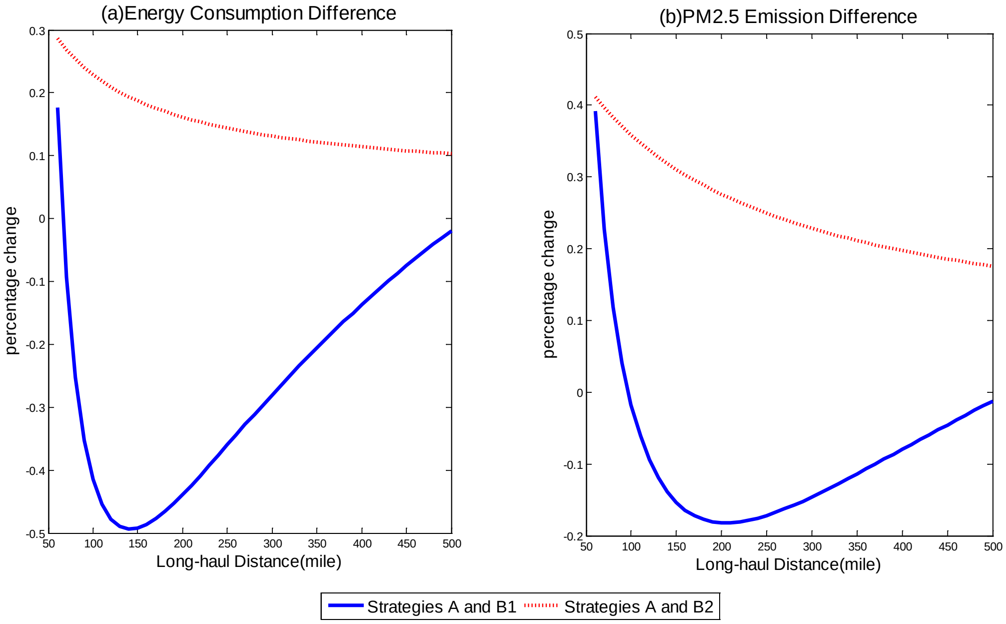


Figure 8 Energy Consumption and PM2.5 Emissions as a Function of Long-haul Distance.

Figure 9 compares the overall cost under two different UCC terminal operation costs. **Figure 9**(a) shows the total logistics costs, calculated with an assumed base terminal operation cost presented in **Table 3**. **Figure 9**(b) shows the total logistics costs calculated using the terminal operation cost that is twice the base one used in **Figure 9**(a).

When the long-haul distance is relatively short, Strategy B1 has the lowest total logistics cost among the three. However, beyond around 200 miles, Strategy B1 has higher cost than Strategy A, suggesting the limit in the long-haul distance for Strategy B1 to be appealing in terms of total logistics cost. When the terminal operation cost is low (in **Figure 9**(a)), the UCC strategies bring overwhelming cost benefits in the entire long-haul distance range considered here (i.e., 50-500 miles). This analysis illustrates the critical importance of terminal operation cost. A sensitivity analysis involving the terminal operation cost is presented in section 4.5.

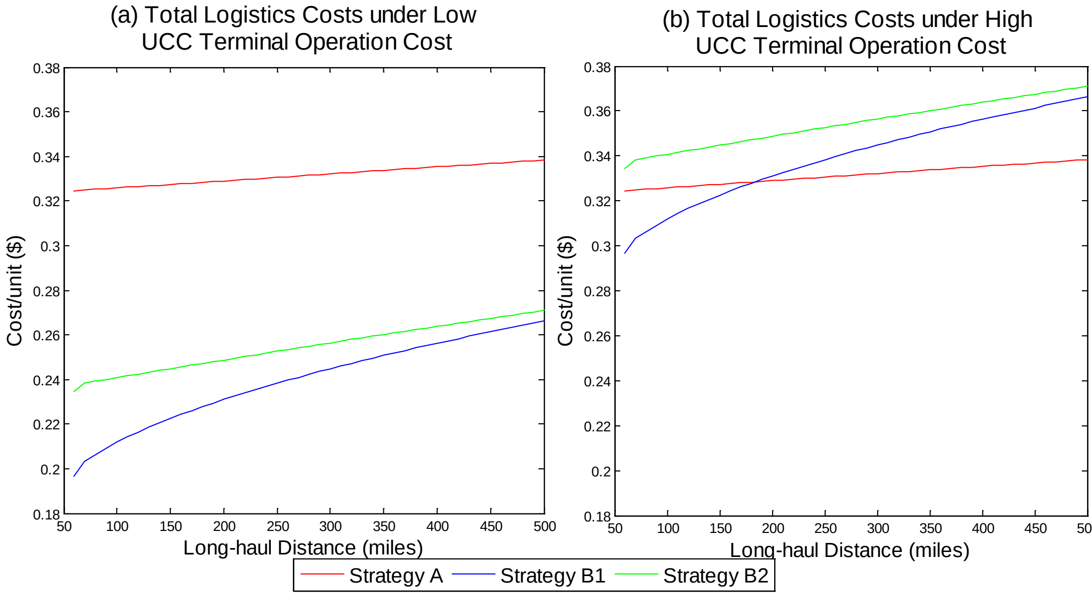


Figure 9 Total Logistics Costs under Different UCC Terminal Costs.

In the rest of the analyses presented in Chapter 4.2-4.6 (except for 4.5), the base UCC terminal operation cost is used. However, it is important to keep in mind that the advantage of UCC over Strategy A may diminish if the terminal operation cost increases.

4.1.2 With Variable UCC Location

In this analysis, the *long-haul distance* is assumed to vary between 50 and 500 miles and the *distance ratio*, defined as the ratio of inbound trip distance (r_1) and outbound trip distance (r_2), varies from 0.2 to 102.4. A small distance ratio means the UCC terminal is located close to the suppliers, while a large one represents the cases in which UCC terminal is close to the customers end.

Figure 10 shows that the total logistics costs for both Strategies B1 and B2 increase with long-haul distance as well as the distance ratio, suggesting that moving the UCC location closer to the suppliers would reduce the total logistic cost.

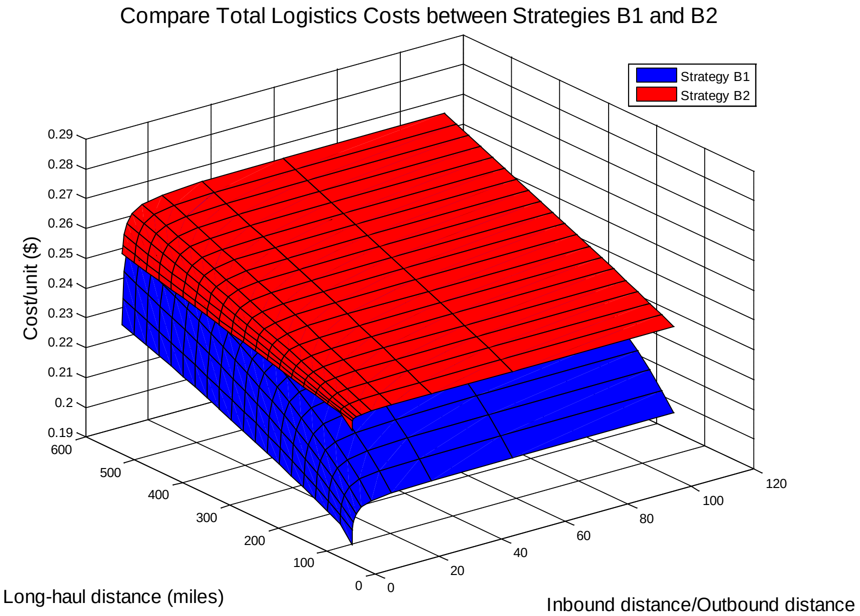
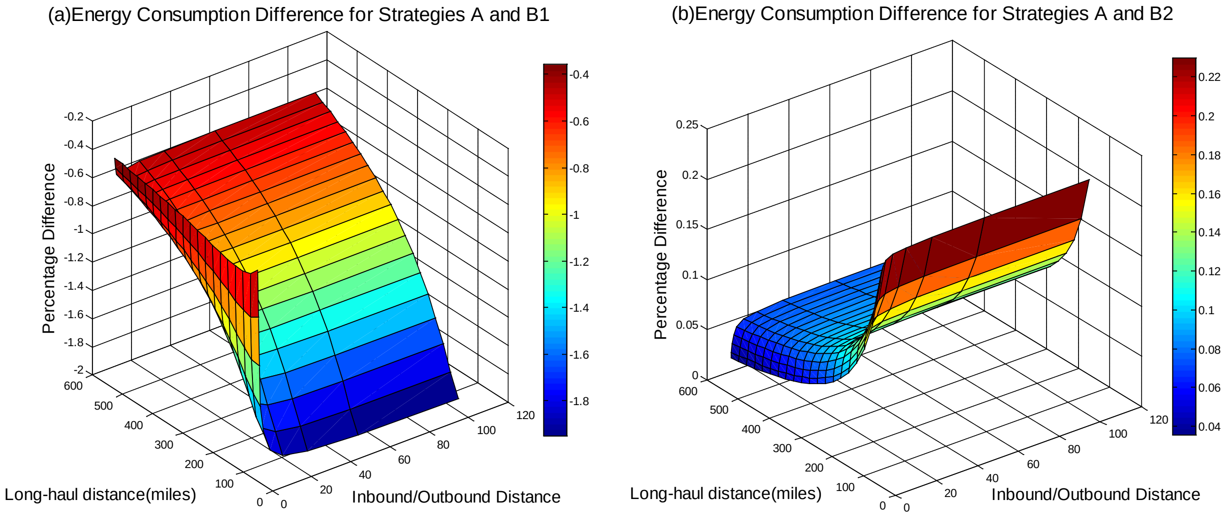


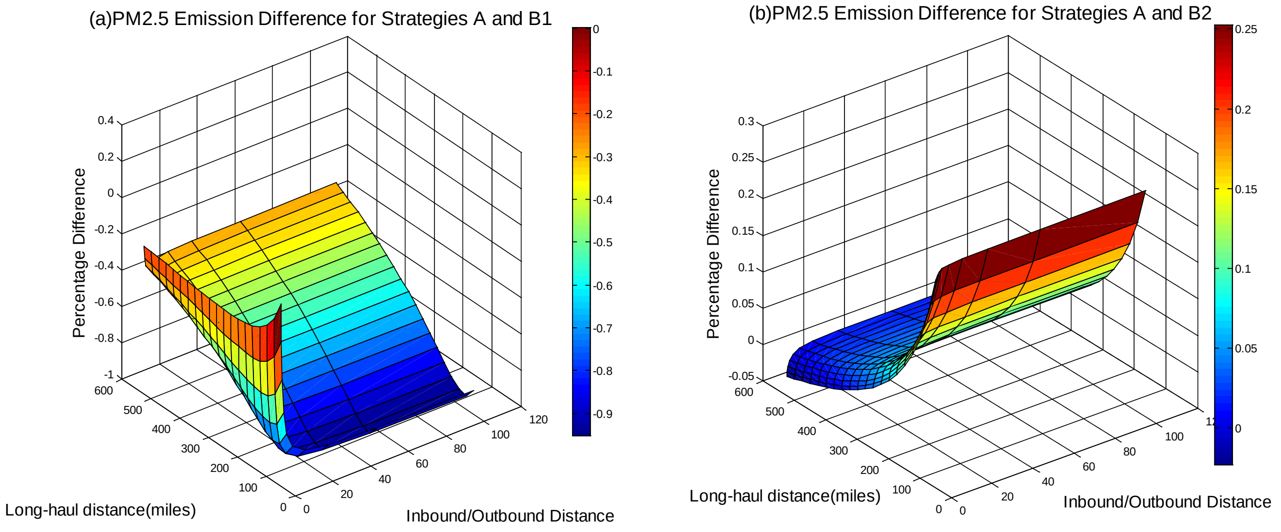
Figure 10 Cost as a Function of Long-haul Distance and UCC Location.

Figure 11 plots the %change in energy consumption with respect to long-haul distance and the distance ratio. Comparing Strategies A and B1, the difference increases with long-haul distance, showing that using Strategy B1 may bring more energy savings than Strategy A. On the other hand, the benefits drops quickly initially as the distance ratio increases and stay flat after the 20 value mark in the distance ratio. On the contrary, B2 energy savings become less and even negative as the long-haul distance increases. Similar trends are observed for PM2.5 in **Figure 12**.


(a)Energy Consumption Difference for Strategies A and B1

(b)Energy Consumption Difference for Strategies A and B2

Figure 11 Energy consumption as a Function of Long-haul Distance and UCC Location.


(a)PM2.5 Emission Difference for Strategies A and B1

(b)PM2.5 Emission Difference for Strategies A and B2

Figure 12 PM2.5 emissions as a Function of Long-haul Distance and UCC Location.

4.2 Effect of number of suppliers and number of customers on cost

4.2.1 Effect of Market Penetration

In this section, the cost sensitivity with respect to the number of suppliers is tested by fixing the number of customers at 500 and varying the number of suppliers from 1 to 20. As shown in

Figure 13, both motion and stationary costs increase as the number of suppliers increases. Furthermore, the total logistics cost increases at a higher rate in A than in B1 and B2, indicating that as the number of suppliers increases the benefit of using UCC becomes greater. This is because the customer demand is split into smaller drop sizes when the number of suppliers is large, and more delivery tours from suppliers are made, increasing the truck VMT in the city. By switching to the UCC strategy, some of the tours are combined into a larger drop size, reducing the truck VMT and lowering the total logistics cost.

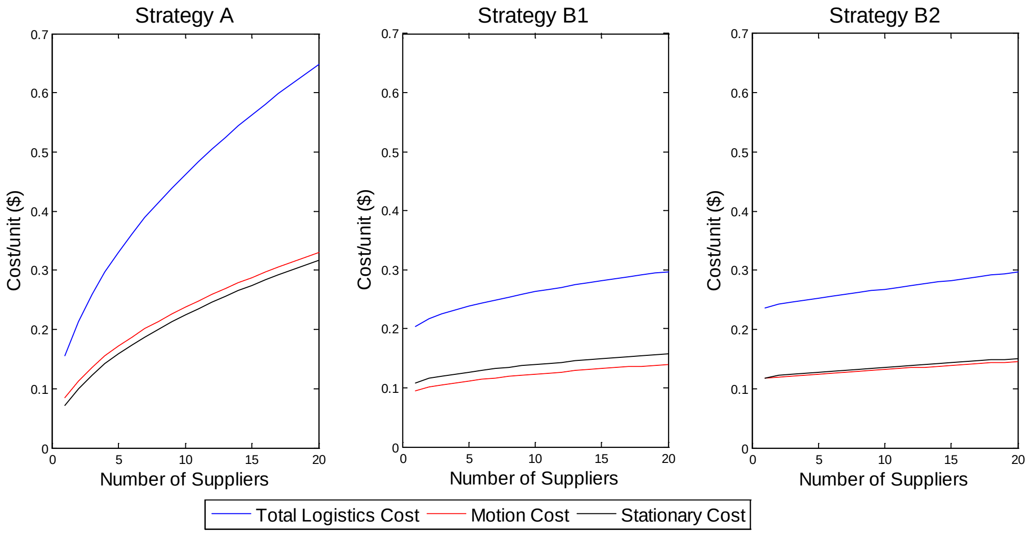
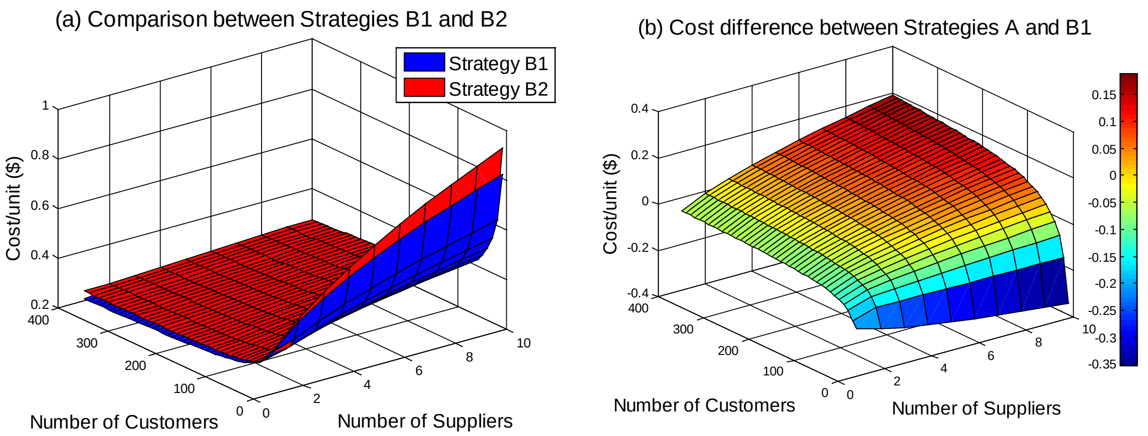


Figure 13 Cost as a Function of Number of Suppliers

4.2.2 Effect of Delivery Network Size

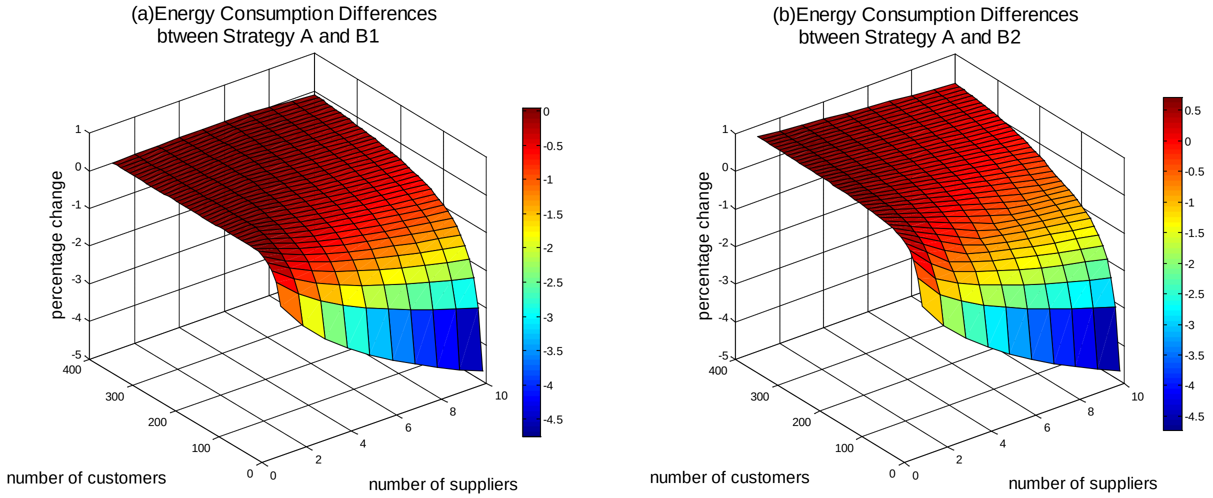
In the analysis result presented in **Figure 14**, the number of suppliers varies from 1 to 10 and the number of customers from 50 to 400. The total logistics cost for strategy A is not affected by the number of customers, while it decreases for both B1 and B2 as the number of customers increases as shown in **Figure 14**(a). The advantage of Strategy B1 over Strategy A, shown in **Figure 14**(b) is considerable when both the numbers of suppliers and customers are large, and decreases as both the numbers of suppliers and customers decrease, with the effect of the number of customers being more acute. The result also suggests that B1 is always the more economic one between the two UCC strategies.


(a) Comparison between Strategies B1 and B2

(b) Cost difference between Strategies A and B1

Figure 14 Cost as a Function of Number of Suppliers and Customers

Figure 15 shows that Strategy A saves more energy than Strategy B1 (or B2), and the saving increases as the number of customers decreases and as the number of suppliers increases. Similar findings for PM2.5 are shown in **Figure 16**.


(a)Energy Consumption Differences btween Strategy A and B1

(b)Energy Consumption Differences btween Strategy A and B2

Figure 15 Energy consumption as a Function of Number of Suppliers and Customers

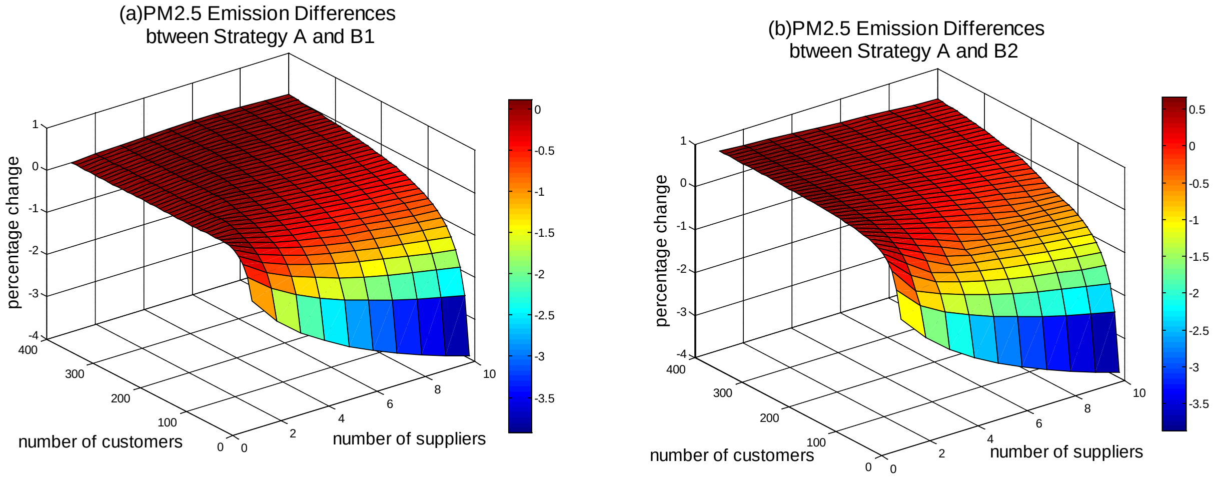


Figure 16 PM2.5 emissions as a Function of Number of Suppliers and Customers

4.3 Cost as function of customer density

This section tests the cost sensitivity to customer density per square mile (**Figure 17**). In Strategy A, both the motion cost and the stationary cost (and therefore the total logistics cost) go down, at a decreasing rate, as customer density increases. In Strategies B1 and B2, when the density is low, the total logistics cost increases initially as customer density increases mainly due to the increase in the stationary cost; after a certain break point around 0.8 customers per square mile, the total logistics cost decreases. So do stationary cost and motion cost. This indicate that UCC strategy may reduce the total logistics cost in urban areas with a high customer density.

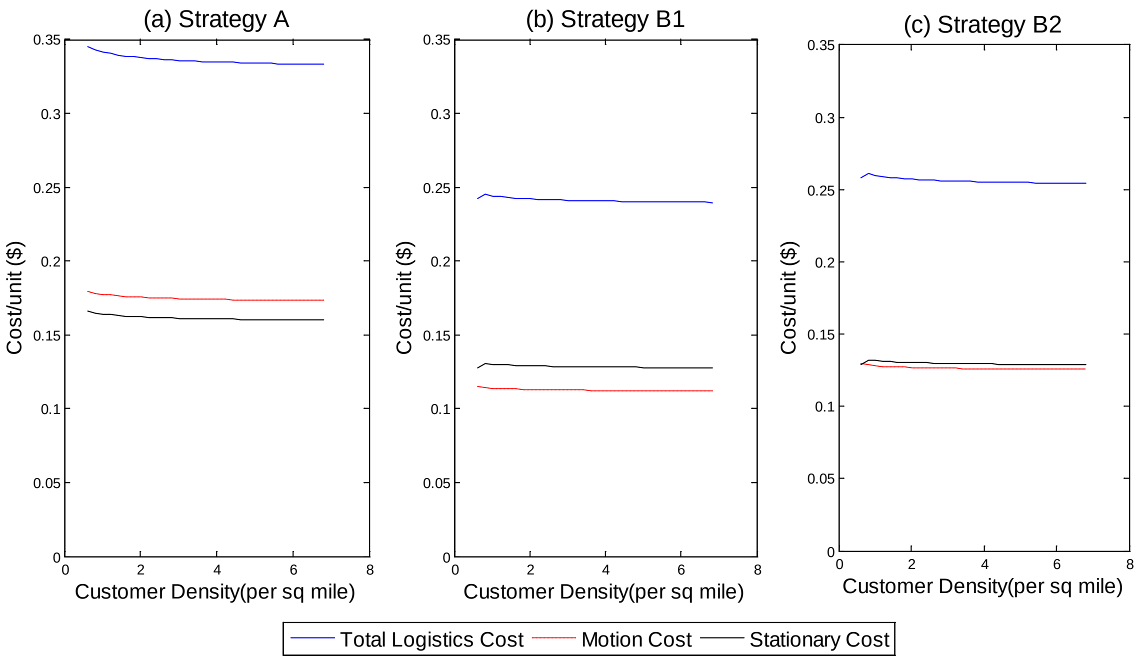


Figure 17 Cost as a Function of Customer Density

In terms of energy consumption and PM2.5 emissions, both B1 and B2 are lower than A (indicated by the positive values in **Figure 18**). However, the differences decrease, at a decreasing rate, as the customer density goes up.

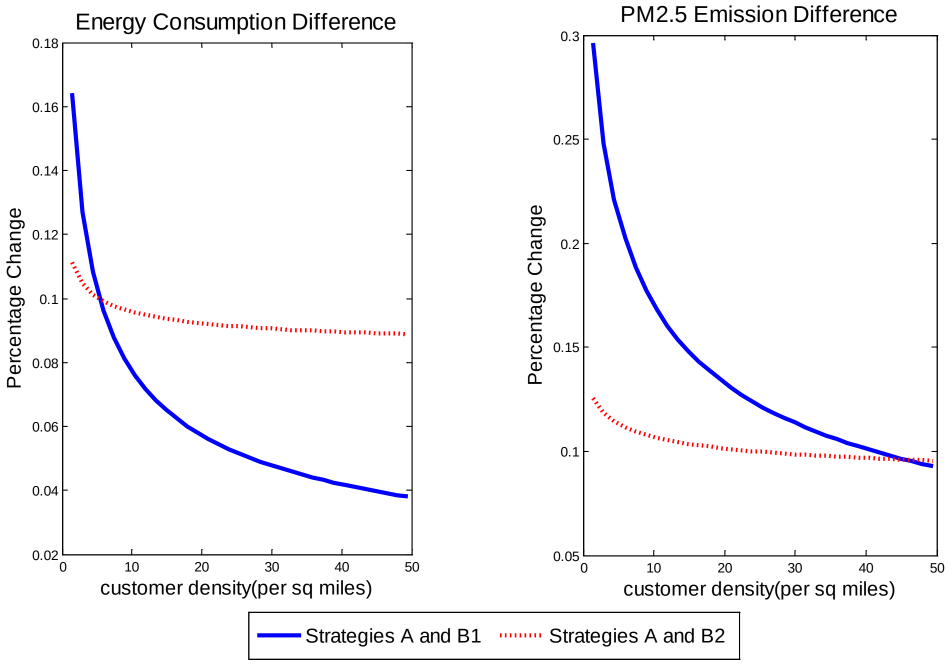


Figure 18 Energy consumption and PM2.5 emissions as a Function of Customer Density

4.4 Cost as function of customer demand rate

In the case of customer demand rate, the total logistics cost decreases in the order of magnitude of square root as customer demand rate increases, and the costs in Strategy A decrease faster than those in Strategies B1 and B2 (**Figure 19**), indicating the benefit of UCC diminishes as the demand goes up. Strategy B1 has higher energy consumption and PM2.5 emission than A at low customer demand rates (**Figure 20**). B2 almost always has lower energy consumption and PM2.5 emissions than A.

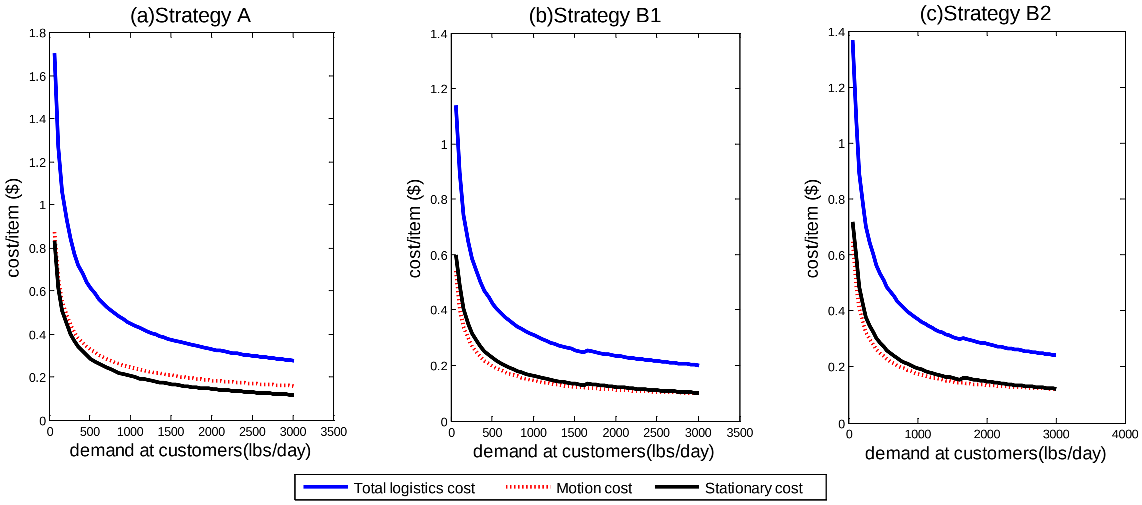


Figure 19 Cost as a Function of Customer Demand Rate

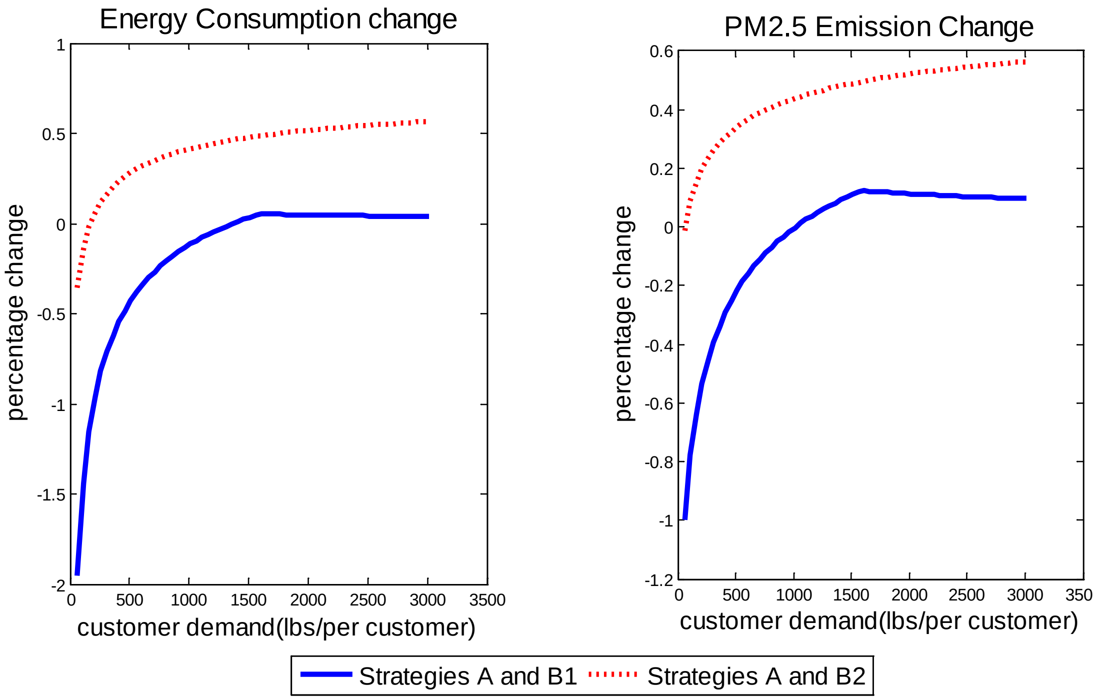
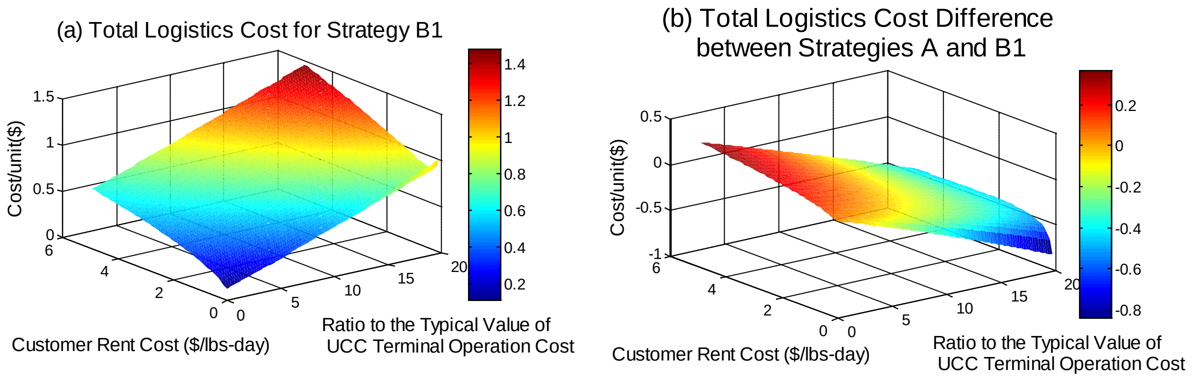


Figure 20 Energy consumption and PM2.5 emissions as a Function of Customer Demand Rate

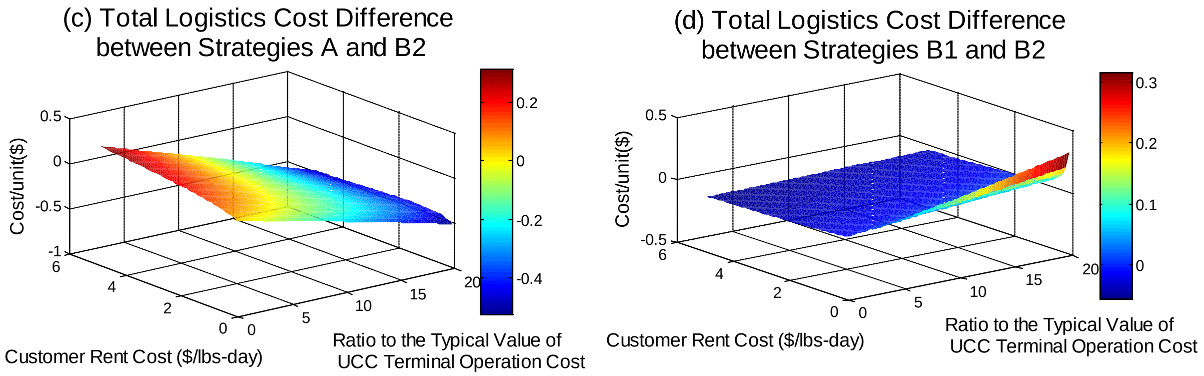
4.5 Cost sensitivity to customer rent cost and UCC terminal operation cost

As already discussed earlier in the report, the advantage of UCC over traditional delivery largely depends on the UCC terminal operation cost. UCC terminal operation cost may be influenced by the government policy towards UCC. For example, if the government subsidizes the UCC operation cost then the cost burden is shifted from the suppliers, the shippers and the receivers. UCC terminal operation cost may also depend on its location. For example, it is generally cheaper to have the UCC located outside of urban core areas where land is scarce. Additionally, the rent cost for the customers will play an important role by shifting the balance between motion cost and stationary cost.

When the customer rent cost varies from 0.4 to 4.5, representing the differences among urban regions like San Francisco and Manhattan, and the terminal operation cost varies from 0.2 to 20 times of typical base value, we find that the total logistics costs for UCC strategy increase with both the customer rent cost and the terminal operation cost (**Figure 21**a). Furthermore, when the rent cost is high and the terminal cost is low, the UCC strategies result in lower costs than Strategy A (**Figure 21**b,c). The reason is that by providing more frequent service to reduce the maximum accumulation in the customer facilities, the stationary cost components are lower in the UCC strategies. Otherwise, it may be more economical to choose Strategy A. **Figure 21**d shows that under low customer rent cost and high terminal operation cost, it is better to coordinate the shipments at UCC. Otherwise, the non coordinated delivery would be better off.


(a) Total Logistics Cost for Strategy B1

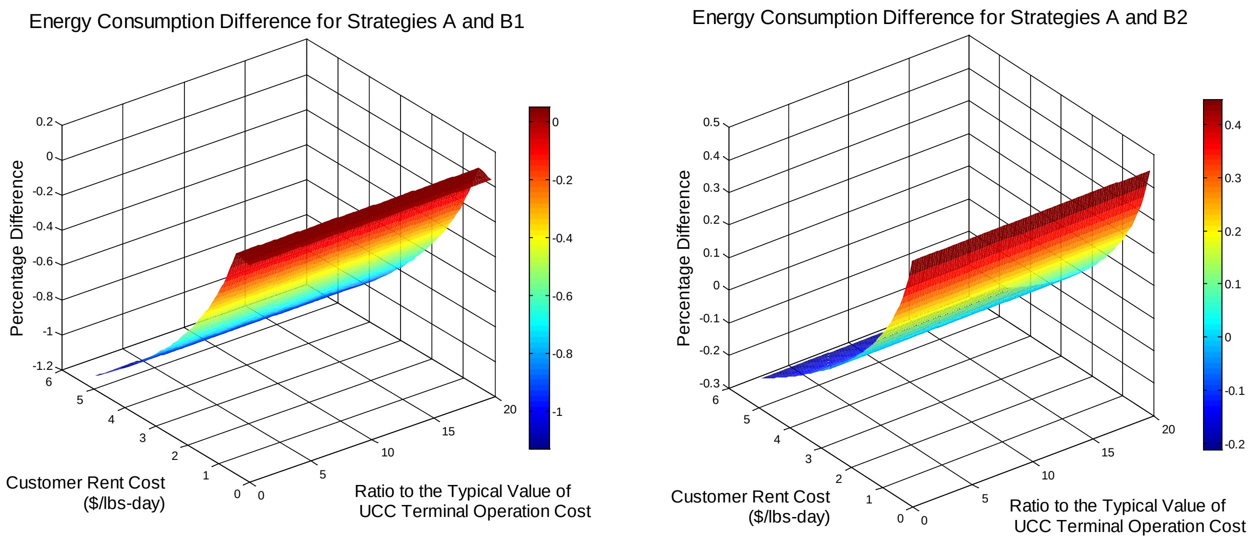
(b) Total Logistics Cost Difference between Strategies A and B1


(c) Total Logistics Cost Difference between Strategies A and B2

(d) Total Logistics Cost Difference between Strategies B1 and B2

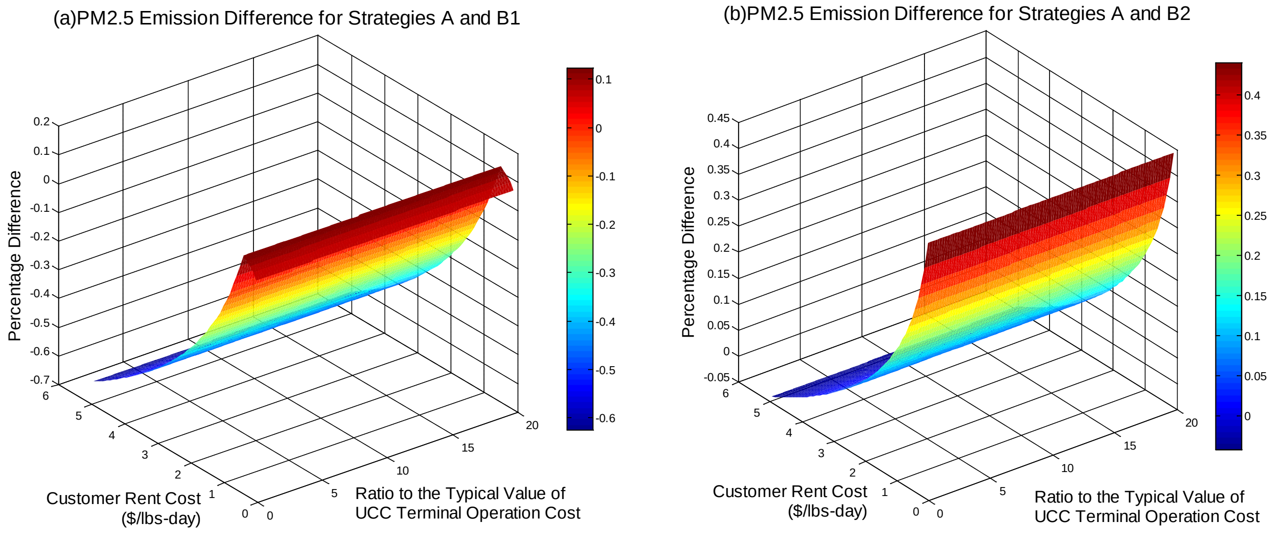
Figure 21 Effects of UCC Terminal Operation Cost and Customer Rent Cost

Interestingly, in terms of energy consumption and PM2.5 emissions, B1 seems to be almost always doing better than Strategy A, while B2 is better off than Strategy A only when high customer rent cost is achieved.


Energy Consumption Difference for Strategies A and B1

Energy Consumption Difference for Strategies A and B2

Figure 22 Energy consumption of UCC Terminal Operation Cost and Customer Rent Cost


(a)PM2.5 Emission Difference for Strategies A and B1

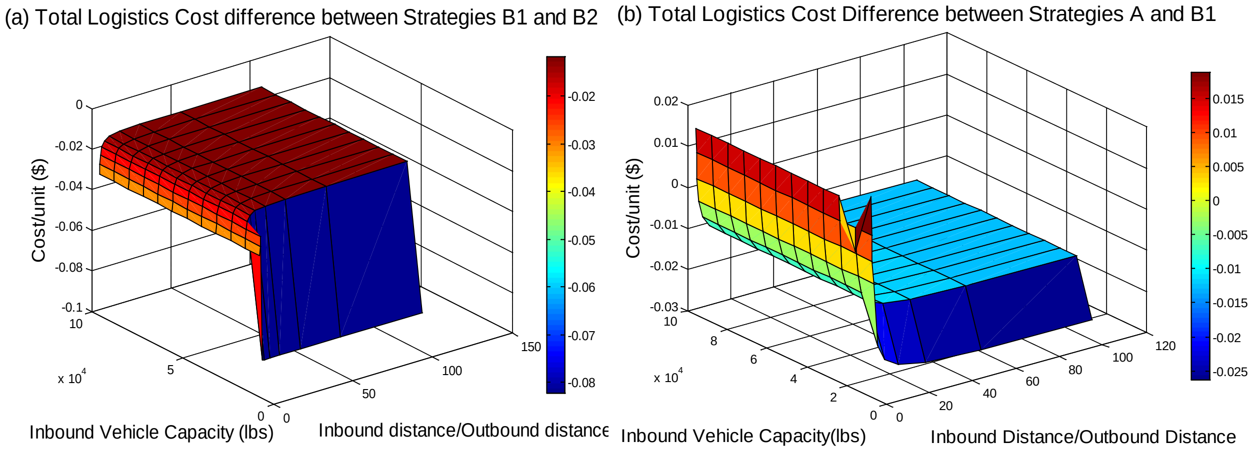
(b)PM2.5 Emission Difference for Strategies A and B2

Figure 23 PM2.5 emissions of UCC Terminal Operation Cost and Customer Rent Cost

4.5 Cost as a function of vehicle capacity

Consider the following scenario: suppose vehicles used for inbound and outbound shipments in the UCC strategies may be of different sizes. To simplify the problem without lost of generalization, we assume that one size vehicles are used for inbound shipments and the size vehicles are used for outbound shipments in the UCC strategies. Furthermore, vehicles in the direct delivery strategy are of the same size as the ones for outbound shipments in UCC. Let the ratio of inbound to outbound vehicle capacity vary from 0.2 to 2.4, representing vehicles from passenger car to big semi long-haul trucks. Further let the ratio of inbound distance to outbound distance vary from 0.2 to 100, which reflects the location of the UCC facility relative to the suppliers and the customers.

The result shows that B1 always seems to out-perform B2 in terms of total logistics cost regardless of the vehicle size or the UCC location, as illustrated in **Figure 24**(a). The difference becomes smaller when the inbound vehicle is larger, and is not affected by the UCC location. Additionally, the total logistics costs of strategies A and B1 are compared and shown in **Figure 7**(b). It shows that B1 is almost always cost less especially when the inbound distance is large, regardless of vehicle size.


(a) Total Logistics Cost difference between Strategies B1 and B2

(b) Total Logistics Cost Difference between Strategies A and B1

Figure 24 Cost as a Function of Inbound Vehicle Capacity and UCC Location

5. CONCLUSIONS

This research analytically examines the effectiveness of urban cooperative delivery (B1 and B2) in terms of monetary cost, energy consumption and PM2.5 emissions, compared with the direct delivery strategy (A).

In general, it is found that the total logistics cost of direct delivery increases more slowly with increase in long-haul distance than that of the UCC strategies, and the tipping point is at the long-haul distance of 200 miles. That means direct delivery strategy becomes more cost effective beyond that distance. Similarly, moving the UCC location closer to suppliers would reduce the total logistic cost. On the other hand, the study shows that UCC without coordination (B1) almost always generates higher energy consumption and PM2.5 emissions and the difference reaches the maximum point when the long-haul distance is around 150miles, whereas UCC with coordination (B2) seems to always provide energy and emission benefits over strategies without UCC (A).

Greater economic scale (i.e., higher numbers of customers and suppliers) also tends to cut the total logistics cost of UCC strategies. However, the benefit becomes less when the scale, especially the number of customers, is reduced. Interestingly, our analysis shows otherwise for energy consumption and PM2.5 emissions. That is, Strategy A saves more energy and emits less PM2.5 than Strategy B1 (or B2), and the saving increases as the number of customers decreases and as the number of suppliers increases.

Furthermore, the benefits of UCC strategies become significant when the customer rent cost is high and UCC terminal operation cost is low, which makes UCC strategies more attractive. It is also worth pointing out that when considering the UCC strategy, if the UCC terminal cost is high and the numbers of suppliers and customers are imbalanced (i.e., too many suppliers serving too few customers or vice visa), coordination among the inbound and outbound trips seems inevitable to cut down the cost. Interestingly, in terms of energy consumption and PM2.5 emissions, B1 seems to be almost always doing better than Strategy A, while B2 is better off than Strategy A only when high customer rent cost is achieved.

Cooperative delivery via UCC may also provide flexibility in vehicle size to meet city ordinance about truck size, curfew and environmental issues. For example, the inbound trips may be carried out by large trailer trucks without urban restriction on parking space and curfew. In the outbound portion, electrical vehicle may be a good vehicle choice because the serving radius limitation is of little problem and the UCC facility can be used for charging station as well as other value added service. And it reduces the vehicle emissions. Moreover, considering the policy option of congestion pricing and other truck restrictions in the urban areas, cooperative delivery may become an even more appealing option for its flexibility and reliability, which may bring significant savings especially to the receivers.

It must be pointed out that the above findings should be understood and interpreted within the study assumptions. In Kawamura and Lu (2007), they suggested that it would not be feasible to introduce UCC in the US context, by examining the shoe supply chain. Because of the different industry, different assumptions on market penetration and a wider range of variable values are incorporated to represent more types of urban areas compared to Kawamura and Lu (2007), our results reveal that under certain circumstances, it is possible to achieve the monetary benefits along with the social benefits by using cooperative delivery in the US.

Even though the analyses were conducted for the delivery of non-perishable grocery, the methodology can be applied to other commodities which share similar attributes to non-perishable grocery.

For future study, more complex consolidation schemes (e.g. schemes that do not require city terminal) and distribution channels (e.g. direct delivery from warehouse to home) under various urban freight policies and customer preferences will be incorporated in the model formulation, such as congestion pricing, night time delivery, alternative fuel vehicles in the UCC strategies and carbon cap and trade. Additionally, the case in which the customers are neither identical nor uniformly distributed spatially and temporally will be considered.

Furthermore, a total generalized cost will also be considered, which includes the logistics cost and the environmental costs (energy consumption and emissions) jointly to optimize the last mile delivery problems. And lastly, it is of our interest to implement the model framework to the real-world freight operation.

6. REFERENCES

Allen,J. and Browne,M.(2008), *Review of survey techniques used in urban freight studies-final report.* Transport Studies Group, University of Westminster, London.

Ademe, (2004) *Espaces Logistiques Urbains de Monaco et La Rochelle*. Analyse comparative des systemes logistiques rochelais et Monegasques.

American Association of State Highway and Transportation Officials (AASHTO) (2003) *Invest in America- Freight Rail Bottom Line Report.* American Association of State Highway and Transportation Officials, January 2003

Anand, N., Quak, H., Duin, R., Tavasszy, L. (2011) *City logistics modeling efforts: trends and gaps-a review*. Proceedings of the 7th International Conference on City Logistics. Mallorca, Spain.

BESTUFS (2006), *Quantification of urban freight transport effects I.* Available online at http://www.bestufs.net/results.html, last accessed in Sept, 2011.

BESTUFS (2007), *Good practice guide on urban freight.* Available online at http://www.bestufs.net/results.html, last accessed in Sept, 2011.

Boyer, K., Frohlich, M. and Hult, G.. (2005) *Extending the supply chain: how cutting- edge companies bridge the critical last mile into customers' homes*, AMACOM, New York, NY.

Boyer, K., Prud'homme,A. and Chung,W. (2009), *The last- mile challenge: evaluating the effects of customer density and delivery window patterns.* Journal of Business Logistics, 30 (1), pp185-201.

Browne, M., Sweet,M., Woodburn,A and Allen,J. (2005), *Urban freight consolidation centers-final report.* Transport Studies Group, University of Westminster, London.

Campbell, J. (1995) *Using Small Trucks to Circumvent Large Truck Restrictions: Impacts on Truck Emissions and Performance Measures.* Transportation Research Part A,Vol 29, pp445-458.

Chopra,S. (2001) *Designing the distribution network in a supply chain.* Transportation Research Part E.Vol39 ,pp123-140.

Chopra,S. and Meindl,P.(2003) *Supply Chain Management: Strategy, Planning and Operations*. 3rd Edition, Prentice Hall

Crainic, T. (2000). *Network Design in Freight Transportation.* European Journal of Operational Research, 122(2):pp272–288.

Crainic, T. (2003). *Long-Haul Freight Transportation.* In Hall, R.W., editor, Handbook of Transportation Science, pp 451–516. Kluwer Academic Publishers, Norwell, MA,second edition.

Crainic, T. and Gendreau, M.(2007) *Intelligent Freight Transportation Systems: Assessment and the contribution of operations research.* Transportation Research Part C: Emerging Technologies.

Civitas (2006) *Sustainable Urban Transport, Final report from the European project Trendsetter*. Published by the Environmental and Health Protection Agency, City of Stockholm.

Dablanc, L. and Rakotonarivo,D. (2009), *The impacts of logistic sprawl: how does the location of parcel transport terminals affect the energy efficiency of good' movements in Paris and what can we do about it?* Proceedings of the 6th International Conference on City Logistics. Puerto Vallarta, Mexico.

Dablanc,L. (2011) *City distribution, a key element of the urban economy: guidelines for practitioners.* City Distribution and Urban Freight Transport: Multiple Perspectives, Edward Elgar.

Daganzo,C.F. (1984a) The length of tours in zones of different shapes, Transportation Research, part B, Vol. 18(2), pp. 135-145.

Daganzo,C.F. (1984b) The distance traveled to visit N points with a maximum of C stops per vehicle: an analytic model and an application. Transportation Science, Vol. 18 (4), pp. 331-350.

Daganzo, C.F.(2005). *Logistics Systems Analysis.* 4rd ed. Springer. Verlag, New York.

Daganzo and Newell.(1986). *Physical distribution from a warehouse: vehicle coverage and inventory levels.* Transportation Research-Part B. Vol19:pp397-408.

Figliozzi, M.(2007), *Analysis of the efficiency of urban commercial vehicle tours: data collection, methodology, and policy implication.* Transportation Research Part B, Vol41, pp1014-1032.

Food environmental Altas http://www.ers.usda.gov/foodatlas/ last accessed in July 15th, 2011

Federal Highway Administration (FHWA, 2005) *Logistics Costs and U.S. Gross Domestic Product*, available online at http://ops.fhwa.dot.gov/freight/freight_analysis/econ_methods/lcdp_rep/index.htm, last accessed in Jan, 2012.

Gevaers,R., E. Van de Voorde and T.Vanelslander (2009) *Innovations in last-mile logistics: the relations with green logistics, reverse logistics and waste logistics.* Proceedings of International Symposium on Logisitcs. Istanbul, Turkey.

Gevaers,R., Van de Voorde,E.,Vanelslander,T. (2011) *Characteristics and typology of last-mile logistics from an innovation perspective in an urban context.* City Distribution and Urban Freight Transport: Multiple Perspectives, Edward Elgar.

Gray, R. (1992) *Accounting and environmentalism: An exploration of the challenge of gently accounting for accountability, transparency and sustainability*. Accounting, Organizations and Society, 17(5), 399-425.

Gray, R. (2002) *Of messiness, systems and sustainability: towards a more social and environmental finance and accounting*. The British accounting review, 34(4), 357-386.

Halldórsson, Á., Kotzab, H., & Skjøtt-Larsen, T. (2009). *Supply chain management on the crossroad to sustainability: a blessing or a curse?* Logistics Research, 1(2), 83-94

Hayashi,K., Ono,H. and Yano,Y.(2005). *Efforts to make distribution and transportation efficient through cooperation among Japanese companies.* City Logistics IV. Institute of City Logistics, Kyoto, Japan.

Holguin- Veras, J., Polimeni, J., Cruz, B., Xu, N., List, G., Nordstrom, J., Haddock, J. (2005), *Off-peak freight deliveries, challenges and stakeholders' perceptions.* Transportation Research Record, No1906, pp42-48.

Kawamura,K.(2000). *Perceived Value of Time for Truck Operators.* Transportation Research Record,No1725:pp31-36.

Kawamura,K.,Lu,Y.(2007).*Evaluation of Delivery Consolidation in US Urban Areas with Logistics Cost Analysis*. Transportation Research Record. No2008: pp34-42.

Langevin,A.,Mbaraga,P. and Campbell,J.(1996).*Continuous Approximation Models in Freight Distribution*. Transportation Research, Part B. Vol 30: pp163-188.

Marcucci,E (2008).*The potential demand for Urban consolidation center*. Transportation. No35:pp269-284.

Melo, S., Costa, A. (2011) *Definition of a set of indicators to evaluate the performance of urban goods distribution initiatives.* City Distribution and Urban Freight Transport: Multiple Perspectives, Edward Elgar.

Nepal, S.A., Farnsworth,S.P., and Pearson,D.F.. (2007). *2006 San Antonio Area Commercial Vehicle Survey Technical Summary*. Texas Transportation Institute.

Ogden, K.(1992)*Urban Goods Movement: A Guide to Policy and Planning,* Ashgate, Kent.

Patier,D. and Routhier, J.L.(2008) *How to improve the capture of urban goods movement data?,* 8th International Conference on Survey Methods In Transport. Annecy, France.

Panero, M., Shin, H, and Lopez, D (2011). *Urban distribution centers: a means to reducing freight vehicle miles traveled.* Final report prepared for New York State Energy Research and Development Authority and New York State Department of Transportation.

Quak,H.(2008) *Sustainability of urban freight transport retail distribution and local regulations in cities*. PhD thesis, Erasmus University Rotterdam.

Quak, H., De Koster,M. (2009), *Delivering in urban areas-how to deal with urban policy restrictions and the environment*, Transportation Science, Vol43 (2), pp211-227.

Quak H., Tavasszy,L. (2011), *Customized solutions for sustainable city logistics*. Transitions towards Sustainable Mobility, Berlin: Springer.

Quak,H. (2011) *Urban freight transport: the challenge of sustainability*. City Distribution and Urban Freight Transport: Multiple Perspectives, Edward Elgar.

Regan, A.C., Golob, T.F.(2005).*Trucking industry demand for urban shared use freight terminals.* Transportation.Vol32:pp23-36.

Riopel,D.,Langevin,A., and Campbell, J. (2005). The Network of Logistics Decisions. In Logistics Systems: Design and Optimization. Springer.

Roca-Riu, M., Estrada, M. (2011) *An evaluation of urban consolidation through logistics systems analysis in circumstances where companies have equal market shares.* Proceedings of the 7th International Conference on City Logistics. Mallorca, Spain.

Ruan, M., Lin,J., Kawamura,K. (2011) *Modeling Commercial Vehicle Daily Tour Chaining, the 90th Transportation Research Board Annual Meeting*, National Research Council, Washington, D.C., 2011

Seattle Urban Mobility Plan (2008) Available at http://www.seattle.gov/transportation/ump.htm last accessed in Jan, 2012.

Section 1909 Commission Staff (2007) *Commission Briefing Paper 4B-05 Impacts of Just-in-Time Freight Logistics.* Available online at http://transportationfortomorrow.com/final_report/pdf/volume_3/technical_issue_papers/paper4b_05.pdf, last accessed in Jan, 2012.

Schoemaker, J., Allen, J., Huschebek, M., and Monigl, J. (2006). *Quantification of Urban Freight Transport Effects I.* BESTUFS Consortium, Avaiable at www.bestufs.net last accessed in Dec,2011.

Stephen and Anderson (2007) *An assessment of the potential for London wide use*. Final report for London Construction Consolidation Centres project, prepared by Peter Brett Associates.

Suksri,J., Raicu,R.(2011) *Developing a conceptual framework for the evaluation of urban freight distribution initiatives.* Proceedings of the 7th International Conference on City Logistics. Mallorca, Spain.
Taniguchi, E. and Thompson, R.(2002) *Modeling city logistics.* Transportation research record 1970. pp45-51.

Taniguchi, E. and Van der Heijden, R (2000), *An evaluation methodology for city logistics*. Transport Reviews, Vol20 (1), pp65-90.

Taniguchi,E. and Tamagawa,D.(2005) *Evaluating city logistics measures considering the behavior of several stakeholders.* Journal of the Eastern Asia society for Transportation Studies. Vol.6, pp3062-3076.

Taniguchi,E., Thompson,R.,Yamada,T.. (2011*) Emerging techniques for enhancing the practical application of city logistics models.* Proceedings of the 7th International Conference on City Logistics. Mallorca, Spain.

Toth P. and Vigo D. (2001)*The vehicle routing problem.* Monographs on Discrete Mathematics and Applications. SIAM

Transport for London (2007a), London Construction Consolidation Centre Interim Report.

Transport for London (2007b), *London Freight Plan −Sustainable Freight Distribution: A Plan for London*, Mayor of London, Transport for London,

U.S. Environmental Protection Agency (EPA) (2006). *Greenhouse Gas Emissions from the U.S. Transportation Sector, 1990-2003*. Report No. EPA 420-R-06-003.

U.S. Environmental Protection Agency (EPA) (2008) *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2006.*

US Environmental Protection Agency(EPA)(2010), "*Motor Vehicle Emission Simulator. MOVES 2010a User Guide,*" Office of Transportation and Air Quality.

Vachon, S., and Klassen, R.D. (2006) *Extending green practices across the supply chain: the impact of upstream and downstream integration*. International Journal of Operations & Production Management, 26(7), 795-821.

Vallamsundar, S., J. Lin (2011) MOVES versus MOBILE: A comparison of GHG and Criteria Pollutant Emissions, *Transportation Research Record: Journal of Transportation Research Board*, No. 2233: 27-35

Victoria, I. and Walton, C.M., (2004) *Freight Data Needs at the Metropolitan Level and the Suitability of Intelligent Transportation Systems in Supplying MPOs with the Needed Freight Data*, Center for Transportation Research, The University of Texas at Austin

Visser, J., van Binsbergen, A., and Nemoto, T., (1999). *Urban freight transport policy and planning.* Paper presented at the 1st International Symposium on City logistics, July 1999, Cairns, Australia.
Victoria, I. and Walton, C.M., (2004) *Freight data needs at the metropolitan level and the suitability of intelligent transportation systems in supplying MPOs with the needed freight data*. Center for Transportation Research, The University of Texas at Austin.

VIUS2002 data. Available online at http://www.census.gov/svsd/www/vius/products.html. last accessed in Sept, 2011.

Wisetjindawat, W. et al(2007) *Micro-Simulation Model for Modeling Freight Agents Interactions in Urban Freight Movement.* Proceeding of 86th Annual Meeting of the Transportation Research Board. Washington D.C.

Wisetjindawat,W.(2010)*Review of good practices in urban freight transportation.* As part of the project Eco-efficient and sustainable urban infrastructure development in Asia and Latin America. UNESCAP,Bangkok.

NATIONAL CENTER FOR FREIGHT & INFRASTRUCTURE RESEARCH & EDUCATION

CFIRE

University of Wisconsin-Madison
Department of Civil and Environmental Engineering
1410 Engineering Drive, Room 270
Madison, WI 53706
Phone: 608-263-3175
Fax: 608-263-2512
cfire.wistrans.org