Sustainable Last-mile Solutions:

Urban Freight Consolidation and Eco-routing Strategies

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THESIS
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<tr>
<td>CA</td>
<td>Continuous approximation</td>
</tr>
<tr>
<td>CBD</td>
<td>Central business district</td>
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<td>EASI</td>
<td>Easy Analytic Software Inc.</td>
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<tr>
<td>EPA</td>
<td>Environmental Protection Agency</td>
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<tr>
<td>D&amp;B</td>
<td>Dun &amp; Bradstreet</td>
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<tr>
<td>DOT</td>
<td>Department of Transportation</td>
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<tr>
<td>FHWA</td>
<td>Federal Highway Administration</td>
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<tr>
<td>HDT</td>
<td>Heavy duty trucks</td>
</tr>
<tr>
<td>LDT</td>
<td>Light duty trucks</td>
</tr>
<tr>
<td>LTL</td>
<td>Less-than-truck-load</td>
</tr>
<tr>
<td>MOVES</td>
<td>Motor Vehicle Emission Simulator</td>
</tr>
<tr>
<td>MRI</td>
<td>Mediamark Research Inc.</td>
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<tr>
<td>PM$_{2.5}$</td>
<td>Particulate matter with particle diameter no more than 2.5 micrometers</td>
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<tr>
<td>Abbreviation</td>
<td>Full Form</td>
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<td>--------------</td>
<td>-----------</td>
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<tr>
<td>UCC</td>
<td>Urban consolidation center</td>
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<tr>
<td>US EPA</td>
<td>U.S. Environmental Protection Agency</td>
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<tr>
<td>VRP</td>
<td>Vehicle routing program</td>
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<td>VMT</td>
<td>Vehicle mile travel</td>
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SUMMARY

Due to modern manufacturing practices, an increase in demand for goods consumption and for service quality improvements from the customers, most urban areas have witnessed higher frequency of deliveries and larger quantities of freight shipments coming from, bound to or transiting through the regions. Increase in urban freight traffic significantly contributes to congestion and environmental problems (e.g., emissions and noise). There is a strong need for studying and implementing viable strategies to minimize truck traffic in congested areas. Furthermore, strategies to reduce logistics cost, energy consumption and emission output are of great research interest. Therefore, the objective of this study is to examine the effectiveness of urban freight solutions jointly in terms of air pollutant emissions, energy use, and logistics costs at different planning stage. Specifically, two types of urban freight strategies are considered in this research, i.e. urban freight consolidation and vehicle routing. The former represents a tactical level investigation and the latter an operational level one.

With the commercial vehicle survey data collected in Texas during 2005-2006, a distribution tour evaluation study is performed to investigate the distribution tour efficiency by tour pattern and commodity. Efficiency indicators used include vehicle usage (i.e., vehicle age, vehicle class, annual mileage), vehicle utilization (i.e., empty trip rates, distance weighted load factors), stop activities (i.e., dwell time), and tour attributes (i.e., tour length/duration, departure time, number of stops in a tour, tour type). Results from this study provide the empirical basis for the modeling assumptions in the following logistics models at both tactical level and operational level:
At tactical level, an urban distribution network model is developed to find the optimal vehicle dispatching (in terms of shipment size and frequency) and routing (in terms of number of stops) plan and the optimal logistics cost under different Urban Consolidation Center strategies, by providing an analytical framework for quantifying the effects of conflicting factors on and trade-offs among various objectives such as emission and economics.

At operational level, a preliminary investigation in sustainable vehicle routing strategies, which considers the joint effect of vehicle load and speed on energy consumption, pollutant emissions or both, is presented. Idling energy consumption and emissions at stops (due to loading and unloading at the customer’s) are also incorporated in the optimal routing strategies.

In sum, this research 1) developed an analytical framework for quantifying the effects of conflicting factors on and trade-offs among various objectives (i.e., minimizing logistics cost, fuel consumption, and/or emissions) intended for in urban consolidation schemes, which is especially suited for analyses with limited data in freight and logistics studies; 2) provided an initial and good understanding of urban commercial vehicle tour patterns and efficiency performance across different industries and commodities; 3) contributed to the literature in the area of sustainable last-mile logistics by showcasing the importance of incorporating environmental costs (energy and emissions) into the total cost when implementing last-mile logistics strategies; 4) demonstrated that with careful design, last-mile logistics strategies (e.g., UCC) can achieve environmental benefits (e.g., reducing
energy consumption and emissions) while maintaining the level of monetary logistics cost.
1. INTRODUCTION

1.1 Background

During the last three decades, the efficiency of the supply chain 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 suggest that 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 trucks (each carrying only 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. According to the statistics from FHWA in 2010, in the U.S metropolitan areas, combination truck VMT increase at 3.2% annually; while single-unit truck VMT increased by an average of 1.9% and 4.6% annually on freeway and other urban roads (e.g. arterial, alley) from 2000 to 2008. The report also summarized that approximately half of trucks larger than pickups and vans operate locally (within 50 miles of home), which account for 30% truck VMT. 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. Furthermore, strategies to also reduce logistics cost, energy consumption and emission output are of great research interest.

In the urban freight literature, it is only recently that environmental cost was taken into account in the total logistics cost. Therefore, one of the objectives of this research is to examine urban freight strategies jointly in terms of logistics cost, energy consumption and emission output.

1.2 Research Objective and Questions

The objective of this study is to examine the effectiveness of urban freight solutions jointly in terms of air pollutant emissions, energy use, and logistics costs. Specifically, two types of urban freight strategies are considered in this research: urban freight consolidation and vehicle routing. The former represents a tactical level investigation and the latter an operational level one.

This research strives to answer the following research questions:

1) What is the current urban freight efficiency by commodity and distribution pattern?

Urban freight efficiency varies greatly across distribution tour patterns (i.e., direct and peddling) and commodity categories. Ideally, if data were available across the country,
we would be able to present a more complete picture of the urban freight efficiency. In reality, due to data limitation, the above research question is answered partially through an empirical study using the Texas commercial vehicle survey performed in San Antonio, Amarillo, Valley, Lubbock and Austin during 2005 and 2006. In this research, efficiency indicators considered are vehicle usage (i.e., vehicle age, vehicle class, annual mileage), vehicle utilization (i.e., empty trip rates, distance weighted load factors), tour activities (i.e., tour length/duration, departure time, number of stops in a tour), stop activities (i.e., dwell time, cargo weight handled at stop).

2) Is urban freight consolidation a viable strategy in reducing truck traffic, congestion, and environmental cost while maintaining economic competitiveness?

Specifically in this research, we focus on the viability of a centralized consolidation facility known as urban consolidation center (UCC) - more detailed definition of UCC will be provided in Chapter 5. To answer the above question, we investigate what operational factors may make urban delivery consolidation more attractive and how those factors affect the effectiveness of delivery consolidation in terms of monetary 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 and energy consumption as a result of reduced truck trips and congestion in urban areas, is important from a sustainable system perspective. It is worth mentioning that institutional factors are as important as, if not more than, operational factors in the implementation of UCC, which in itself is an area of research and is outside...
the scope of this study. However, suffice it to say that a scheme that is attractive to the businesses would be less contentious to implement and even have a greater likelihood of surviving without subsidy. Due to the data limitation and the mathematical elegance and simplicity of the Continuous Approximation (CA) method, i.e., less input data requirement, less computational burden and able to provide a close form solution, the CA method is applied to investigate the cost-effectiveness of UCC to key decision-making factors. The advantage of the CA method is its ability to provide analytical insights to the effectiveness of urban cooperative delivery strategies, which contrasts to the case-study based approach most commonly seen in the current literature. Furthermore, the method can be readily adapted to other logistics chains in different study settings by adjusting the model parameters to the specified study settings.

3) At the operational level, what are the trade-offs between a distance/travel-time based vehicle routing strategy and an eco-routing one?

In contrast to distance/travel time based routing strategies, an eco-routing strategy is one that takes into account not only the vehicle operational cost (due to travel time), but also the environmental cost including fuel cost and emission cost associated with a vehicle routing scheme. Travel speed, travel distance (travel time), and vehicle weight are among the many factors that affect the fuel consumption and vehicle emissions. Using a numerical example, this research demonstrates the noticeable (joint) effects of vehicle payload, vehicle speed, and dwell time on urban commercial vehicle PM2.5 emissions and energy consumption, as well as trade-offs among different routing strategies (i.e.,
distance-based, environment-based, and total cost-based). Thus vehicle payload and speed could affect the visiting order of a distribution tour in eco-routing.

1.3 Contributions

The main contributions of this research are summarized as follows:

Foremost, this research has developed an analytical framework for quantifying the effects of conflicting factors on and trade-offs among various objectives (i.e., minimizing logistics cost, fuel consumption, and/or emissions) intended for in urban consolidation schemes. The proposed framework is especially suited for analyses with limited data, which is almost always the case in freight and logistics studies.

Furthermore, this research has provided an initial and good understanding of urban commercial vehicle tour patterns and efficiency performance across different industries and commodities. It has also demonstrated the use of urban commercial vehicle survey data for the above purposes as well as limitations of such data.

This research has contributed to the literature in the area of sustainable last-mile logistics by showcasing the importance of incorporating environmental costs (energy and emissions) into the total cost when implementing last-mile logistics strategies. Decisions with and without incorporating the environmental costs will lead to very different strategies. For example, in the traditional VRP literature, the effects of vehicle load on fuel consumption and emissions have only recently started to gain attention, and this research has demonstrated how vehicle load may alter the visiting order so as to minimize not only labor cost (travel time related) but also fuel cost. Furthermore, this research has
also demonstrated that with careful design last-mile logistics strategies (e.g., UCC) can achieve environmental benefits (e.g., reducing energy consumption and emissions) while maintaining the level of monetary logistics cost.

1.4 Organization of the Dissertation

The rest of this thesis is organized as follows. Chapter 2 provides a brief literature review of the state-of-art of sustainable urban freight network modeling and the corresponding data issue and modeling techniques; Chapter 3 highlights the research framework and the data source; Chapter 4 explores the urban freight behavior in terms of efficiency with a commercial vehicle survey data collected in Texas. Chapter 5 presents an urban distribution network model at tactical level to evaluate the economic and environmental cost/benefit of urban consolidation center with CA method; in addition, Chapter 6 brings about an operational level sustainable freight vehicle routing model which consider the joint effect of commercial vehicle load and speed on energy consumption or pollutant emissions or both. Lastly, Chapter 7 summarizes the research work and points out the direction of future work.
2. LITERATURE REVIEW

The relevant literatures to this study can be categorized into the following five areas:

2.1 Concept of Last Mile Problem

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 cheap 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 old 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.
The last-mile problem is commonly known as triple-P problem: people (social), profit (economic) and planet (environmental) (Quak and Tavasszy, 2011). The social (people) problem refers to traffic accidents, noise nuisance, visual intrusion, and local pollutants such as NOx and PM on public health. The economic (profit) problem refers to delivery inefficiency with low utilization of resources. The environmental (planet) problem contributes to global warming and greenhouse gas emissions.

The challenge in the last-mile problem is to provide a robust, transparent and rigorous evaluation framework for varieties of last-mile solutions (Taniguchi and Van der Heijden, 2000; Taniguchi, et al, 2011). Robustness means that the methods are not likely to be upset by minor order changes within the reasonable range of information provided; transparency implies that the stakeholders can easily identify the cost and benefits; rigorous means any analysis methodology must ensure that the triple-P issues are considered in the light of all relevant objectives.

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 fee 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., for energy saving vehicles, GPS tracking system, and label tracking system, etc.

2.2 Logistics Decision Hierarchy in Last-mile Distribution

Logistics decisions can be categorized in a three-level hierarchy: strategic, tactical and operational decisions, based on its time frame, resource requirements and level of managerial responsibility. Riopel et al. (2005) has provided a comprehensive review on logistics decisions in the three levels throughout the entire supply chain. Figure 1 shows the three-level decision structure specific to the last mile problem.
At the strategic level, long-term decisions are usually made with a consideration of market uncertainties. Decisions at this level often require knowledge of the business strategy, financial resource availability, information technology, the logistics network, and forecasted demand. Customer service level is defined according to the company’s business strategy and reflects the inventory level, response time and delivery requirements including delivery time window, delivery frequency and waiting time between the item being ordered and received. For example, a company aiming at
improving responsiveness over lowering cost may choose a transportation mode of a higher cost and greater frequent delivery to lower waiting time (Chopra, 2001).

Other dimensions at the strategic level include: (i) vertical integration of the geographic and activity boundary of the logistics network, number of facilities (distribution centers and warehouses) and their locations, (ii) outsourcing, and (iii) facility design of the layout, the storage space, and the receiving and handling areas.

At the tactical level, medium-range decisions are made without detailed data. The degree of consolidation (i.e., distribution channel) is chosen to take an advantage of the economies of scale and to optimize costs. Decisions include the direction of goods flow (i.e., delivery activity from suppliers to customers, or collection activity from customers to suppliers) and type of facility to use. These decisions are contingent upon the decisions at the strategic level regarding the network topology, facility location, demand quantity, establishment type, and the product’s characteristics. With the consideration of distribution channel, transportation and inventory planning are determined jointly. The former includes transportation mode selection and fleet mix; the latter includes stock plan and long-term replenishment. And the “long-term” (as opposed to the day-to-day operation) scheduling and routing plans are designed by taking into consideration the service area partition and the replenishment frequency.

At the operational level, shorter time span (usually daily or in real time) and smaller scope decisions are made in transportation, inventory and distribution channel design. These decisions are based on the decisions at the tactical level, with the consideration of stochastic demand and unexpected condition change. For example, if large quantities of
urgent demand are requested by the customer, then the distribution channel might be changed to allow direct goods flow from the suppliers to the customer without intermediate stop. The short-term replenishment plan and the daily operational routing and scheduling plan are made to incorporate the demand variation and the customer’s schedule, while the path selection decision is made by considering traffic conditions.

Detailed operating data and real time information are required to construct quantitative models for operational level decisions. Many well established researches in the literature have focused on the operational level problems (Toth and Vigo, 2002). For example, various algorithms for Vehicle routing problem (VRP) provide answers to how to arrange the daily delivery schedule and routing plan, and many well defined algorithms are capable of solving stochastic inventory control problem efficiently. However, these types of algorithm often require detailed data inputs, which are often unavailable or scatter. We argue that analysis at the tactical level is more appropriate given the lack of daily operating data and the nature of the decisions made at that level without the need for everyday information.

Contrary to the relatively abundant literature in the strategic level design (e.g., Crainic, 2000, 2003; Taniguchi and Thompson, 2002) and operational modeling as mentioned in the previous paragraph, there are few studies on the tactical level design. Among the very few, Crainic and Gendreau (2007) was among the few that focus on the tactical planning, in which they developed a detailed Vehicle Routing Program with Time Window (VRPTW) model and heuristics to solve the long-term routing planning problem. However, the difficulty to obtain the large input data set and the model complexity make
it expensive to perform the analysis. Thus, simple method with less data requirement for tactical level analysis is desired.

This research work studies both the tactical and operation level decisions. Specifically, the first part of the research focuses on the distribution channel design and the corresponding routing and scheduling plan development at the tactical level, and the second part an operational level sustainable vehicle routing (eco-routing) strategy aiming at minimizing vehicle fuel consumption and emissions.

2.3 Delivery Consolidation

Among many last mile solutions, delivery consolidation is viewed as one of the effective 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 (BESTUFS 2007, Nemoto, 1997).

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). 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 (a German term 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; Chen et al, 2012; Lin et al, 2014) and UK (Browne et al 2005, 2007). In 2005, the definition and the use of UCC has evolved since Browne et al (2005), please see chapter 5.2 for further discussion.
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 UCC 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 among suppliers and carriers; 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, the general sense is that delivery responsibility should be contracted to a well organized 3rd party logistics (BESTUFS, 2007;Panero et al., 2011).

Lastly, 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).

### 2.4 Data Issues in Freight Transportation

In urban freight research, 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 the surveys cover urban areas, they are usually not very useful for gaining detailed and insightful understanding of urban logistics decisions and 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; 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 a number of urban areas for specific projects, mostly in UK, followed by the U.S., the Netherlands, Germany and Italy (Victoria and Walton, 2004; Allen and Browne, 2008; Patier and Routhier, 2008). The common problems in urban freight data are: 1) the data sets are relatively small compared to personal travel data and traffic counts data; 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) the majority of urban freight surveys are funded by the public sector and 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 missing.

In addition to the above data issues, 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). On the one hand, great efforts should be made in collecting urban freight data, such as pilot freight GPS projects in Washington DOT and Minnesota DOT. This provides not only the important freight origin and destination information, but also freight vehicle operation and activities.

Reconciling with the freight data limitation in reality, this research proposes an alternative last-mile freight modeling approach by applying the continuous approximation method which has the mathematical advantage of working with limited data. The concept and applicability of the continuous approximation method is described in the next session below.

2.5 Continuous Approximation Method

Mathematical programming is the most widely used method when planning or analyzing a logistics system. However, it usually requires detailed data and comprehensive solution
techniques. On the other hand, the continuous approximation (CA) method (also known as continuous model) is a useful tool to obtain reasonable approximate solutions with as little information as possible and to gain a clear understanding of the trade-offs among decisions (Newell 1973). Mathematically speaking, CA relies on the spatial and temporal densities and the average distribution of demand rather than on the precise attributes at every demand point (customer). In other words, discrete demand points are approximated closely by continuous demand density and distribution functions, especially when the number of discrete points is sufficiently large (Newell 1973). CA typically involves a single cost objective composed of various cost elements approximated by slowly varying curves, and finds nearly optimal solutions, which are often sufficient in real decision making at the strategic and tactical levels.

CA is useful in planning a new service or expanding an existing one where no or few existing data can be found. Hall (1986) illustrated various applications of discrete and continuous approximations, and demonstrated that CA is a useful analytical tool and is easy to comprehend. He also noted that CA should supplement mathematical programming models rather than replace them. In the literature of CA, it has been applied in location theory, geometrical probability and transportation research.

**Location Theory**

In location theory, demand is usually modeled as a continuous spatial distribution (e.g. Losch, 1954). CA has been used to analyze the location choice of service facilities, such as production suppliers, police stations and warehouses (Newell, 1973; Drezner, 1995). Wirasinghe and Waters (1983) used both the CA and a traditional location-allocation
model to determine the location and the number of solid waste transfer facilities in an urban area. Their approach illustrated many advantages of the analytical model form. A well studied area in continuous location modeling is the market area modeling, which determine the optimal market size for a facility. Erlenkotter (1989) provides the historical background and an extensive review of market area models. Essentially these models find the location choice that balances the trade-offs between economy of scale from larger facilities and the higher costs of transport to more distance markets, and thus provided a theoretical base for deriving the form of relationships used in empirical investigations of the costs associated with non-optimal capacities (Weiss, 1972).

**Geometrical probability**

Geometrical probability, which deals with finding approximate travel distances between a single origins to continuously distributed points in an area, is another fundamental application area of CA (See Larson and Odoni, 1981 for details). It has the important application in transportation and location modeling, as well as emergency response time models for urban police, fire and ambulance service system (Larson and Odoni, 1981; Langevin et al 1996)

**Passenger Transportation Research**

The growth of CA application in transportation began in the 1960s, when Smeed(1961) used CA approach to approximate passenger travel distances or times for a variety of
roadway system and Black (1962) applied CA on zone scheduling a suburban rail transit system. In the 1970s this type of model became increasingly popular in transit planning, when Newell (1971) proposed that CA is both amenable to optimization methods of calculus and facilitates closed form solutions (Szplett, 1984). Typical applications of CA in transit planning are: 1) determining the service areas and locations for park and ride facilities (Szplett, 1984) ; and 2) determining the optimal bus stop location (Wiransinghe, 1980). Szplett (1984) and Hurdle & Wirasinghe (1980) provided detail reviews about the CA application in transit planning.

Freight and logistics Transportation Research

Daganzo and Newell have, separately and jointly, applied the CA method to delivery problems to analyze different logistics costs and trade-offs between cost components since the 1980s. 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

In chapter 5, we apply the CA method to evaluate the costs and benefits of Urban Consolidation Center. The proposed distribution network model is an extension of Daganzo’s work on Logistics Cost Functions.

2.6 Emission Models

Emission models provide estimates of emission factor/energy consumption rate in freight activities. In the U.S., emission models can be categorized as macroscopic and microscopic models. Macroscopic models (e.g. MOBILE from US EPA, California Air Resources Board’s EMFAC model) use average aggregate network parameters to estimate network wide energy consumption and emission factors. More recently, microscopic emission model (e.g. Virginia Polytechnical Institute's microscopic energy and emission models, US EPA MOVES model) is developed to represent real driving conditions by incorporating the effects of different instantaneous speed and acceleration profiles on vehicle emissions. MOVES has already replaced MOBILE model as its capability to 1) estimate emissions with modal-based approach, rather than applying correction factors to baseline emission factor; 2) the ability to model emissions at three levels of analysis for both on-road/off-road; 3) finer characterization of advanced technology vehicles and fuel technology. Vallamsundar and Lin (2011) provides more detail in comparison between MOBILE and MOVES model.

Demir et al(2011) provides an extensive review on a number of models on fuel consumption and greenhouse gas emissions associated with road freight transportation.
For example, a micro scale level instantaneous fuel consumption model developed by Bowyer et al (1985) estimated the fuel consumption rate per unit time as a function of vehicle mass, drag force, rolling resistance, etc. Then the same group of researchers extended it to several variant of models to estimate fuel consumption for idle, cruise, acceleration and deceleration activities separately (four-mode elemental fuel consumption model) and jointly (running speed fuel consumption model).

Alternatively, a comprehensive emission model for heavy-duty vehicle which consisted three modules: engine power, engine speed ad fuel rate, is developed by Barth et al (2000, 2008). It requires more accurate vehicle-specific parameters to estimate the engine friction coefficient and engine speed compares to the instantaneous fuel consumption model. Based on on-road measurements and experiments, Hickman et al (1999) developed the MEET model to calculate road emission and energy consumption for heavy-duty vehicles in a given weight class (less than 3.5 tonnes, 2.5 to 32 tonnes, and 32 tonnes up). Similarly, the COPER model (Ntziachristos and Samaras, 2000) estimates the emission by vehicle categories (i.e. passenger cars, light duty vehicles, heavy duty vehicles, mopeds and motorcycles) and weight.

Demir et al (2011) compared the above models by varying the vehicle related factors (weight, engine size and type), environmental related factors (roadway geometric, pavement type, weather) and traffic related factors(speed and accelerations); the simulation results showed that although the models are slightly different in terms of approach, modeling structure and assumptions, overall they are consistent with
expectations; e.g. fuel consumption varies with size of vehicle, the gradient of the road track, and speed.
3. RESEARCH FRAMEWORK AND DATA SOURCES

3.1 Research Framework

Figure 2 illustrates the research framework to address the research questions in section 1.2. First, a distribution tour\(^2\) evaluation study is performed and presented in Chapter 4 using the commercial vehicle survey data collected in Texas during 2005-2006. In this study, distribution tour efficiency by tour pattern and commodity is investigated. Efficiency indicators used include vehicle usage (i.e., vehicle age, vehicle class, annual mileage), vehicle utilization (i.e., empty trip rates, distance weighted load factors), stop activities (i.e., dwell time), and tour attributes (i.e., tour length/duration, departure time, number of stops in a tour, tour type). Results from this study provide the empirical basis for the modeling assumptions in the logistics models described in Chapters 5 and 6.

In Chapter 5, an urban distribution network model is developed to find the optimal vehicle dispatching (in terms of shipment size and frequency) and routing (in terms of number of stops) plan and the optimal logistics cost under different UCC strategies. The distribution network model is based on the CA method at the tactical level (as opposed to the operational level with detailed stop-by-stop routing).

\(^2\) A trip is the vehicle movements between two consecutive stops, while a tour consists of multiple trips and starts and ends both at a home location.
Assumptions

Distribution channel selection (Tactical level)
- Emission estimation model
- Shipment size/Frequency (Schedule plan)
- Tour pattern (Routing plan)
- Evaluation indicator selection
- Evaluation

Distribution tour evaluation
- Tour efficiency
  - by tour pattern
  - by commodity

Sustainable routing (Operational level)
- Vehicle routing model
- Objective selection
- Evaluation

Evaluation indicator selection
- Economic
  - Logistics cost
  - Inventory cost
  - Transportation cost
  - Emission cost
- Social
  - VMT
  - Number of trucks
  - Traffic accidents
- Environmental
  - Energy consumption
  - GHG emission
  - Local pollutants (i.e., NOx and PM)

Figure 2. Research Framework.
Chapter 6 presents a preliminary investigation in operational level sustainable vehicle routing strategies, which considers the joint effect of vehicle load and speed on energy consumption, pollutant emissions or both. In addition, idling energy consumption and emissions at stops (due to loading and unloading at the customer’s) are also incorporated in the optimal routing strategies.

In both Chapters 5 and 6, the environmental impact (energy consumption and emissions) of studied strategies is estimated using the Motor Vehicle Emission Simulator (MOVES) developed by the U.S. Environmental Protection Agency (US EPA). Section 5.3.3 and Section 6.2.3 provides a detailed description of the setup and input parameters of MOVES.

3.2 Data Sources

Due to the limited data availability, this research has relied on the following data sources to infer urban distribution channels, freight vehicle activities and establishment attributes in different metropolitan regions.

Vehicle inventory and usage survey (VIUS)

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. This survey was conducted every 5 years till 2002, as part of the economic census.” (North Carolina
Department of Transportation). In this research work, VIUS 2002 is used to obtain the vehicle information at the state level for this research.

**Food Environment Atlas**

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 2006-2008. Table I lists the key parameters recorded in this data set.

<table>
<thead>
<tr>
<th>County level Indicators</th>
<th>Description</th>
</tr>
</thead>
</table>
| 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 |
| **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/refined grain, 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 |

**SimplyMap and Bizcost.com**

SimplyMap is a web mapping application that allows users to create map and reports of demographic, business and marketing data between 2010 and 2013 in the U.S.

Bizcost.com provides reports on business operating cost for specific industries (e.g., food processing) and distinctive corporate function (i.e. headquarters, distribution warehousing) in different geographic locations. Section 5.3.2.4 provides more details about both data sources.
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. Ruan et al(2012) provided a detail description about this dataset:

"Surveyed commercial vehicles were random samples selected from a combined database of field observations of privately operated certified commercial vehicles in the study areas, the vehicle registration database, and the motor carriers’ database, as well as the employer database maintained by Texas DOT. Drivers or operators of the selected vehicles completed both a vehicle information form and a daily travel log on an assigned day. The vehicle information form contains basic vehicle data like vehicle type, fuel type, gross weight, odometers, etc., and the travel log records all trips the commercial vehicles made and all locations they visited during the study day." As shown in Table II, the surveys record the trip information such as departure time, arrival time, location, commodity, quantities of drop-off size; and the vehicle information like vehicle type, fuel type, gross weight, odometers, etc. Key variables included in the travel logs are summarized in Table II.
<table>
<thead>
<tr>
<th>Stop-level attributes</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitude and latitude</td>
<td>Stop coordinates</td>
</tr>
<tr>
<td>Departure time</td>
<td>Departure time at stop</td>
</tr>
<tr>
<td>Arrival time</td>
<td>Arrival time at stop</td>
</tr>
<tr>
<td>Loading/unloading cargo weight</td>
<td>Total loading or unloading cargo weight</td>
</tr>
<tr>
<td>Activity type</td>
<td>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</td>
</tr>
<tr>
<td>Land use type of stop</td>
<td>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</td>
</tr>
</tbody>
</table>
4. EMPIRICAL STUDY OF COMMERCIAL VEHICLE TOUR PATTERNS

4.1 Introduction

Commercial vehicle travel carries less than one-third of the total freight shipment weight, but contributes to over 80% of the total freight energy consumption (Komar, 1995). As commercial vehicle travel continues to grow in the U.S., traffic congestion and emissions conditions are exacerbated. While shifting from the energy intensive modes (e.g., truck) to the energy efficient ones is a common option to reducing energy uses for long-haul movements, improving logistic efficiency is essential to sustainable urban and short-haul freight transportation. In logistics, many decisions influence commercial vehicle movement efficiency, but the underlining causalities are not well understood. Identifying how and what aspects of these logistic decisions have an impact on commercial vehicle efficiency is a crucial research endeavor. Thus, this chapter analyzes the distribution tour efficiency as a result of two distinctive logistic decisions: direct and peddling tours.

Please note that a tour consists of multiple trips and starts and ends both at a home location (depot) and a trip is the movement between two consecutive stops.

Urban commercial vehicle movements have drawn much attention in both the research communities and the practice because of its significant influence on both urban transportation and the economy. Commercial vehicle movements include all vehicle travels that are not for personal uses but for the distribution of goods or service. Accordingly, they are critical components of the economy, and any disruption in commercial vehicle movements will interrupt the regular economic activities. Improvements in the efficiency and reliability of urban commercial vehicle movements
would greatly mitigate urban traffic congestion, reduce air pollutions, alleviate infrastructure damages, and facilitate smoother trade flows.

Urban commercial vehicle movements are distinctively different from urban passenger travel and long haul commercial vehicle movements. Unlike urban passenger travel, which typically concerns only the individuals, urban commercial vehicle activities involve collaborative decisions among multiple actors (i.e., shippers, carriers and receivers). Each actor involved in freight logistics and supply chain has its own business agenda to follow, which adds to the degree of difficulty for the freight modelers to fully understand the decision process. Unlike long haul commercial vehicles, which primarily ship goods, urban commercial vehicles deliver both service (i.e. utility trucks) and goods. Another noticeable attribute of urban commercial vehicle movements is that they tend to make frequent stops in a trip chain.

Using the Texas Commercial Vehicle Survey data, this empirical study aims at 1) comparing efficiency between direct and peddling patterns defined by the number of stops within a tour; and 2) comparing efficiency between three most observed commodity types, i.e., Food, Health, and Beauty Products; Clay, Concrete, Glass, or Stone; Manufactured Goods/Equipment. The rest of the chapter is organized as follow: Section 4.2 briefly reviews current research on commercial vehicle efficiency; Section 4.3 presents the data sources in detail; Section 4.4 introduces the efficiency indicators and Section 4.5 compares the efficiency between tour patterns. Section 4.6 further examines efficiency difference between the three chosen commodity groups. Finally, section 4.7 concludes the study and gives suggestions for future development.
4.2 Literature Review

Logistics efficiency means something different for different actors: for private sectors, efficiency translates to maximizing net profit; for public agencies, efficiency is measured in terms of mitigating traffic congestion and transportation emissions. These two aspects are synergistic in that both the mitigation of traffic congestions and emissions and maximization of profits point to increasing vehicle utilization given the same amount of service demand. Efficiency measures from the point of view of logistic companies have been widely studied (Lai, Ngai & Cheng, 2004). On the other hand, as pointed out by the Victoria Transport Policy Institute (2008), while logistics put emphasize on minimizing shipper costs, little considerations have been paid to social costs, e.g., congestions, emissions. With available disaggregate commercial vehicle movement data, this study examines commercial vehicle efficiency from the public sectors’ point of view.

Based on 200 interview results in UK by Department of Environment, Transport and Regions, Leonardi and Baumgartner (2004) summarized the efficiency in four categories: logistic efficiency, vehicle efficiency, driver efficiency and route efficiency. Logistic efficiency includes the consideration of increasing truck load factor, choosing the optimum vehicle category or optimizing the entire transportation chain from origins to final delivery. Route efficiency measures the route performance under certain itinerary requirements and road or traffic conditions (Haughton, 2002). Vehicle and driver efficiencies concern fuel consumption either through different vehicle design and technology or driver training.
Efficiency measures vary according to the scope of study. For example, Figliozzi (2007) considered VMT as an efficiency indicator, and modeled its changes under four different logistics constraints (i.e., number of stops per tour, tour duration, and time window). It was found that multi-stop tours generally produced more VKT than direct deliveries under equal payloads. Léonardi and Baumgartner (2004) examined CO2 emission efficiency using tonne-km (tkm) per emitted kg of CO2, based on a survey in 50 German haulage companies during 2003. In the same study, vehicle use efficiency was evaluated with indicators such as vehicle travel distance, mean payload, empty trip percentage in distance, and vehicle age. Fernie and McKinnon (2003) assessed the grocery supply chain efficiency with the following performance indicators: vehicle fill, empty running, time utilization, deviation from schedule, and fuel efficiency. Similarly, a study by the University of St. Gallen (2000) explored ways to improve truck travel efficiency by increasing vehicle load factor, reducing empty running and maximizing the amount of productive time in vehicle scheduling, and concluded that it would be possible “either to reduce vehicle movements by up to 30% or to absorb up to 30% growth in business freight tonnage-kilometers without any increase in current levels of goods vehicle movements” if appropriate regulations were in place.

Based on literature reviews and data availability, commercial vehicle efficiency in this study will be measured by vehicle usage (i.e., vehicle age, vehicle class, annual mileage), vehicle utilization (i.e., empty trip rates, distance weighted load factors), stop activities (i.e., dwell time), and tour attributes (i.e., tour length/duration, departure time, number of stops in a tour).
4.3 Data Sources

The data used for the efficiency analyses comes from the Texas Commercial Vehicle Surveys (Nepal et al, 2007, Ruan et al, 2012). It accounted for a total of 13,802 trips made by 1,711 commercial vehicles in counties of San Antonio, Amarillo, Valley, Lubbock and Austin during 2005 and 2006 (See Table II in Section 3.2). In addition, travel distance of a vehicle tour is estimated as the sum of the shortest distance between stops in the Texas highway traffic network using commercial vehicle routing packages such as TransCAD.

4.4 Efficiency Indicators

Table III presents the efficiency indicators used in this study.

<table>
<thead>
<tr>
<th>Efficiency Indicators</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>(1) Vehicle Usage</strong></td>
<td></td>
</tr>
<tr>
<td>Vehicle Age</td>
<td>Calculated as the year survey was conducted (2006) minus the vehicle year</td>
</tr>
<tr>
<td>Vehicle Class</td>
<td>5 vehicle classes are identified as in the survey: Single Unit 2-axle (6 wheels), Single Unit 3-axle (10 wheels), Single Unit 4-axle (14 wheels), Semi (all Tractor-Trailer Combinations), Other</td>
</tr>
<tr>
<td>Annual Mileage</td>
<td>Calculated as the vehicle odometer reading divided by vehicle age</td>
</tr>
<tr>
<td><strong>(2) Vehicle Utilization</strong></td>
<td></td>
</tr>
<tr>
<td>Distance weighted Load Factor</td>
<td>The sum of load factor multiple by trip dist then divided by tour length</td>
</tr>
<tr>
<td>Empty Trips Rate</td>
<td>The ratio of number of empty trips and total number of trips within a tour</td>
</tr>
<tr>
<td><strong>(3) Stop Activities</strong></td>
<td></td>
</tr>
<tr>
<td>Dwell Time (mins)</td>
<td>Average dwell time in a tour</td>
</tr>
<tr>
<td><strong>(4) Tour Attributes</strong></td>
<td></td>
</tr>
<tr>
<td>Tour Length/Duration (miles)</td>
<td>Total travel distance in the tour</td>
</tr>
<tr>
<td>Departure Time</td>
<td>Starting time of the first trip in the tour</td>
</tr>
<tr>
<td>Number of Stops</td>
<td>Total number of stops in the tour including the base locations</td>
</tr>
<tr>
<td>Tour Pattern</td>
<td>Direct if the tour has only one non-base stop, and peddling if more than one non-base stop.</td>
</tr>
</tbody>
</table>
**Vehicle Usage**

Older vehicles are usually less energy efficient and tend to produce more emissions (Zachariadis et al, 2001). By comparing vehicle age in different commercial vehicle groups, we can identify what older vehicles are mostly used for so that the policy makers can provide targeted incentives for replacing them. In terms of vehicle size five vehicle classes (see Table III) are defined representing five different vehicle sizes in the Texas commercial survey. According to US EPA, the annual average mileage for commercial vehicles ranges from 12,000 to 14,000 miles, which will be used as a reference point for the average vehicle annual mileage.

**Vehicle Utilization**

*Load factor* is the ratio of the average load to total vehicle freight capacity, in tons or volume (European Environment Agency, 2010). For each vehicle type in Texas (Texas Department of Transportation, 2009), the load factor is first calculated for each trip. Those trip specific load factors are then weighted by trip distance and aggregated into a tour average, i.e., distance weighted load factor (see Table IV for formulation). Another indicator for vehicle utilization is *empty trip rate* per tour, which is the ratio between the number of empty trips per tour to the total number of trips per tour. Distance weighted load factor and empty trip rate are two common efficiency indicators for vehicle utilization. A distance weighted load factor value closer to 1 indicates that the vehicle is close to being fully loaded during the entire tour; and an empty trip rate value closer to 0 means that all trips in a tour are at least partially loaded.
Table IV  PERMISSIBLE TRUCK LOAD WEIGHTS USED
(Source: Texas DOT, 2009)

<table>
<thead>
<tr>
<th>Commercial Vehicle Class</th>
<th>Permissible Weights (lbs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Unit 2-Axle</td>
<td>40,000</td>
</tr>
<tr>
<td>Single Unit 3-Axle</td>
<td>60,000</td>
</tr>
<tr>
<td>Single Unit 4-Axle</td>
<td>76,000</td>
</tr>
<tr>
<td>Semi (all Tractor-Trailer Combinations)</td>
<td>80,000</td>
</tr>
</tbody>
</table>

Stop Activities

Dwell time measures the effective use of time and cargo handling efficiency at stops. In general, shippers/carriers work to reduce dwell time for better efficiency.

Tour Attributes

Three key tour attributes are considered: departure time at the beginning of the tour, total number of stops and tour length.

Following Burns et al. (1985), two types of tours are considered in this analysis based on the number of customers (stops) visited in a tour: direct (Figure 3A) and peddling (Figure 3B) tours. Direct shipping serves only one customer per vehicle load. Peddling shipping serves more than one customer per vehicle load. Furthermore, the peddling tour in this study may consist of both delivery and pick-up shipments.

Figure 3. Examples of Tour Patterns.
Source: Ruan et al (2010)
4.5 Efficiency by Tour Type

There are a total of 2537 tours identified in the data source with 1456 direct tour and 1081 peddling tour. The efficiency indicators by tour type are shown below in Table V. The key findings are summarized as follows:

1) The average distance weighted load factor of a direct tour (0.21) is almost twice of that of a peddling tour (0.12), while empty trip rates are about the same (0.32 versus 0.29). This suggests that direct tours are on average packed with higher loads than peddling tours.

2) As expected, the average tour length and duration of a peddling tour is more than double of those of a direct tour. As such, the annual mileage for vehicles operating in the peddling pattern (37,768 miles) is 20% higher than that of the direct pattern.

3) A peddling tour makes four times the number of stops on average than a direct tour. On the other hand, a direct tour has twice as long the average dwell time at stops as that of a peddling tour, which is consistent with the much higher load observed in direct tours.

4) Peddling tours generally depart (8:56AM) earlier than direct tours (9:58AM) as they require longer travel time and farther distance.

5) Vehicle age does not show a distinctive difference between vehicles running in a direct or a peddling pattern.

---

3 Due to missing values in some indicators, the total number of observation for both direct and peddling may not be equal to 2537.
### Table V  SUMMARY OF EFFICIENCY INDICATORS FOR DIRECT AND PEDDLING PATTERNS

<table>
<thead>
<tr>
<th></th>
<th>Tour Pattern</th>
<th>Mean</th>
<th>Number of Observations</th>
<th>Std. Deviation</th>
<th>Median</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Vehicle Usage</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vehicle Age</td>
<td>Direct</td>
<td>7.77</td>
<td>1,293</td>
<td>5.14</td>
<td>7.00</td>
<td>1</td>
<td>34</td>
</tr>
<tr>
<td></td>
<td>Peddling</td>
<td>7.54</td>
<td>933</td>
<td>4.92</td>
<td>7.00</td>
<td>1</td>
<td>28</td>
</tr>
<tr>
<td><strong>Annual Mileage</strong></td>
<td>Direct</td>
<td>31,402</td>
<td>1,052</td>
<td>39,996</td>
<td>20,548</td>
<td>34</td>
<td>663,288</td>
</tr>
<tr>
<td></td>
<td>Peddling</td>
<td>37,768</td>
<td>735</td>
<td>70,272</td>
<td>20,299</td>
<td>34</td>
<td>1,164,461</td>
</tr>
<tr>
<td><strong>Distance weighted Load Factor</strong></td>
<td>Direct</td>
<td>0.21</td>
<td>663</td>
<td>0.15</td>
<td>0.20</td>
<td>0</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>Peddling</td>
<td>0.12</td>
<td>480</td>
<td>0.13</td>
<td>0.06</td>
<td>0</td>
<td>0.65</td>
</tr>
</tbody>
</table>

| **Vehicle Utilization**  |              |      |                         |                |        |     |     |
| Empty Trip Rate          | Direct       | 0.32 | 1,456                   | 0.30           | 0.33   | 0   | 1   |
|                          | Peddling     | 0.29 | 1,081                   | 0.29           | 0.20   | 0   | 1   |

| **Stop Activities**      |              |      |                         |                |        |     |     |
| Dwell Time (mins)        | Direct       | 284  | 815                     | 411            | 60     | 15  | 999 |
|                          | Peddling     | 147  | 300                     | 291            | 30     | 15  | 999 |

| **Tour Attributes**      |              |      |                         |                |        |     |     |
| Tour Length (miles)      | Direct       | 30   | 1,456                   | 61             | 14     | 0   | 653.48 |
|                          | Peddling     | 74   | 1,081                   | 93             | 42     | 1.24 | 656.36 |
| Tour Duration (mins)     | Direct       | 69   | 1,319                   | 102            | 45     | 0   | 1,080.00 |
|                          | Peddling     | 189  | 1,078                   | 251            | 139    | 0   | 4,685.00 |
| Departure Time (hour)    | Direct       | 9.58 | 1264                    | 3.37           | 9      | 0   | 22  |
|                          | Peddling     | 8.56 | 928                     | 2.94           | 8      | 0   | 21  |
| Number of Stops          | Direct       | 2.47 | 1456                    | 0.51           | 2      | 2   | 3   |
|                          | Peddling     | 8.17 | 1081                    | 4.43           | 7      | 3   | 25  |

In addition, vehicle size distribution by tour pattern is depicted in Figure 4. Over 50% of the peddling tours use single unit 2-axle vehicles, followed by semi trucks (26.1%) and single unit 3-axle. Vehicle size distribution for the direct tours is more even in that there is no one single dominant size: 37.8% single unit 3-axle, 35.0% single unit 2-axle and 25.1% semi trucks. Single unit 4-axle vehicles are rarely used in either tour pattern.
4.6 Efficiency by Commodity Type

In this section, the efficiency measures are compared among the top three commodity groups: food, health and beauty products, manufactured goods and equipment and clay, concrete and stone. The findings are presented in sections 4.6.1 through 4.6.4 as follows.

4.6.1 Vehicle Usage

Vehicle Age Distribution

Figure 5 below shows the vehicle age distribution by commodity type. For all three commodity types, majority of the vehicles (over 80%) are within 10 years old. Furthermore, all three commodity types follow a similar distribution with a long right tail indicating some small percentage of very old vehicles (>16 years).
Figure 5. Vehicle Age Distribution by Commodity Type.

Vehicle Class Distribution

The most noticeable difference is between Clay, Concrete, Glass or Stone and the other two commodities types which share a similar distribution (Figure 6). That is, over 70% of the tours shipping Clay, Concrete, Glass or Stone used the single-unit 3-axle vehicles, compared to 60% of the tours shipping the other two respectively with smaller vehicles (single-unit 2-axle). It is also seen that majority of the urban shipments used smaller (2- or 3-axle) single unit trucks possibly due to the shipment size and/or vehicle size restriction on urban streets. Nonetheless, about 20% of the shipments among all three commodity types were made by semi (all tractor- and trailer combination trucks).
Annual Mileage

According to US EPA, average annual vehicle mileage for commercial vehicle is 12,000 to 14,000 miles in the year 2006. Figure 7 shows that the percentages of annual vehicle mileage less than 12,000 miles are 54%, 27%, and 39% for the three commodities respectively. The vehicles used for food commodity generally have lower annual mileages, while the vehicles for construction materials are intensively used with high annual mileages. Combining the fact that older vehicle with larger size tends to have larger emission rate (Zachariadis et al, 2001, US EPA 2010, and the analysis in Chapter 6.2.3), vehicles used in construction commodities would generate more emissions (calculated as the product of VMT and emission factor) than the vehicles for other commodities.
4.6.2 Vehicle Utilization

Distance weighted Load Factor

As shown in Figure 8, for food, health and beauty products and manufactured goods and equipment, about 90% of the tours have a load factor of 0.2 and less. Clay, concrete or stone have a slightly higher load factor with about 50% of the tours 0.2 and less and 45% between 0.2 and 0.4. In any case, the load factor is low. This finding is consistent with other survey results. For example, trucks in Japan operated with an average load factor around 30%-40%, and more importantly the load factor was downward between 1970-1997 (Taniguchi, 2003).
Figure 8. Distance Weighted Load Factor Distribution by Commodity Type

Empty Trip Rate

Empty trip rate distribution is shown below in Figure 9. Among the three commodities, food commodity have the lowest empty trip rate (75% of the tours has less than 0.2 empty trip rate), followed by the construction commodities. The food commodity have the lowest empty trip rate mainly because they need to perform both pick-up and delivery activities among depots and customers.
4.6.3 Stop Activities

Dwell Time

Average dwell times during a tour have been aggregated into less than 15min, 15-30min, 30-60min, 60+ min bins in Figure 10 by commodity group. About 55% of the food commodity tends to have tours with average dwell time less than 30 minutes, among which 22% are less than 15 minutes; while the percentage for manufactured equipment commodity is 15% and 7% less respectively. Most food products have longer dwell time than manufacture products because the units are hard to handle and special requirements are needed. The clays require longer dwell time and over 50% dwell times are over half hour, because of the difficulty and the safety issue of handling such commodity.
4.6.4 Tour Attributes

Tour Length/Duration

In terms of the tour distance (Figure 11a), 60% of the equipment commodity tours and 80% of food commodity tours are less than 50 miles. This indicates the customer density of food commodity is higher, or transportation cost per distance is higher. As shown in Figure 11b, the food commodity also have shorter tour duration (less than 30 min); while the equipment commodity tours are usually around 1 hour.
Figure 11. Tour Length/Duration Distribution by Commodity Type.

**Departure Time**

*Figure 12* clearly shows that food, health and beauty products are typically shipped out early in the morning between 4 and 7 am before most of the restaurants and supermarkets
open their doors. The construction materials are shipped out to the sites during the beginning of the working hours because, for example, concrete should not be mixed too far in advance than the actual construction work begins. The manufactured goods and equipment have a much flattened departure time distribution throughout the morning hours, which may be explained by the reason that such commodities are generally speaking less time sensitive or constrained by delivery time than the other two commodity types.

![Figure 12. Departure Time Distribution by Commodity Type.](image)

Tour Pattern and Number of Stops

As seen in **Figure 13**, the three commodity types display very different tour patterns. For food, health and beauty products, 72.4% of the tours are the peddling type, and it is the opposite for clay, concrete or stone, where over 80% of the tours are direct shipping. For
manufactured goods and equipment, there is a slight preference in peddling (about 52%) over direct shipping. These findings conform to the common knowledge.

Figlozzi (2007) pointed out that time reduction per customer can have a significant impact on the efficiency of the tour for those tours with more stops. Figure 14 shows the cumulative distribution of number of stops. Again, the tours that ship food, health and beauty products make significantly more stops than the other two, which indicated that food tour efficiency can be greatly enhanced if we can optimize the handling activity at the customers. Considering the fact that construction products have more direct tours (with 2 stops), we can see that the vehicle tours with construction products have large variance in terms of number of stops.

Figure 13. Tour Type Distribution by Commodity Type.
Figure 14. Cumulative Number of Stops Distribution by Commodity Type.

4.7 Summary and Limitations

This chapter has presented an empirical study of urban commercial vehicle movement efficiency based on the observations of the Texas Commercial Vehicle Survey performed in Counties of San Antonio, Amarillo, Valley, Lubbock and Austin during 2005 and 2006. Efficiency was measured by vehicle usage (i.e., vehicle age, vehicle class, annual mileage), vehicle utilization (i.e., empty trip rates, distance weighted load factors), tour attributes (i.e., tour length/duration, departure time, number of stops in a tour), and stop activities (i.e., dwell time, cargo weight handled at stop).

Efficiency study between direct and peddling pattern suggests that direct tours: 1) have higher possibility to generate empty trips, 2) better utilize vehicle capacity when loaded with goods, 3) operate in shorter duration and length but longer dwell time at stops, 4) start the tour later than the peddling tours. By comparing the three commodities, the
study also has the following findings: 1) Construction materials tend to have lower efficiency in terms of the vehicle usage: older and larger vehicles (thus higher emission rate) with high annual mileages implies that more emissions will be generated from this type of commodity tours; 2) In terms of the tour activities, significantly different patterns are discovered: vehicle tour with construction materials either have higher load or no load at all, while food commodity tends to have much lower empty trip rate but very low amount of goods on each trip during the tour. This indicated that food commodity has the potential to enhancing the efficiency by increasing the vehicle load factor. 3) It is found that the food products have longer dwell time than equipment because the units are hard to handle and special requirements like refrigerators are needed; The construction materials commodity have the longest dwell time and over one third dwell times are over one hour because of the handling difficulty and safety issue; 4) the food commodity tends to have higher stop density therefore the tour length and duration are shorter than the other two; 5) the equipment commodity is more flexible in terms of departure time and less time sensitive, while food commodity is usually departed early to ensure delivery before the merchandise open the door. It is interested to note that there are two peak hours for construction materials to be shipped out around 10am and 2pm because they are trying to avoid the morning and evening peak hours and the construction materials should not be mixed too far in advance than the actual construction work begins; 6) Food commodity is likely to use peddling tour pattern with more stops and smaller vehicles for the small drop-off size, while the construction material commodity prefers direct tour for the large quantities and the handling difficulty. For tours with equipment commodity, the tour patterns are equally split between direct and peddling, and the peddling tour usually
has less stops than food commodity and construction material commodity, which reflects the flexibility of imperishable goods with medium size.
5. COST AND BENEFIT ANALYSIS OF URBAN CONSOLIDATION CENTER: A TACTICAL LEVEL ANALYSIS

5.1 Introduction

Due to the modern manufacturing practice, the increased 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. 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 27.2% of total highway transportation energy consumption and 66.4% of total highway vehicle PM2.5 emissions (U.S. Department of Energy 2012). These problems arising in the final stage of the supply chain are referred to as the last-mile problem.

In some European and Asian countries, urban delivery consolidation has been deployed by establishing cooperation among suppliers, carriers and customers to better utilize the shipping resources, e.g., shipping capacity, storage space (Kohler 2001, Taniguchi and Nemoto 2003). In addition to improving efficiency, Taniguchi and Thompson (2002) pointed out that delivery consolidation could significantly reduce urban congestion and vehicle emissions if set up properly. A recent successful case is Binnenstadservice.nl (BSS), a consolidation center in the City of Nijmegen, one of the oldest cities in the Netherlands. The consolidation center has successfully eliminated unnecessary truck trips entering the city centre and hence reduced the truck VMT (Rooijen and Quak 2010, Quak and Tavasszy 2011). Another example is La Petite Reine, a French intra-urban freight terminal, which partners with companies to deliver goods in
local neighborhoods within the city center by using the so-called cargo cycle, a manual tricycle (source: La Petite Reine website).

However, not all of the delivery consolidation projects survived beyond the initial government subsidy period; the reasons behind are multi-fold. Panero et al. (2011) explored the various factors involved in the implementation of the so-called Urban Consolidation Center (UCC) projects and found that the key factors for the success of UCC include the institutional ones such as leadership, operational agreement, financial support, obligation of stakeholders and interaction with the logistics network, and the operational ones including nature of the service industry, spatial coverage, location and the fleet management. For example, the UCC project in Leidin, the Netherlands is no longer in operation because it became financially unsustainable with increased monetary cost after 3 years of operation, although it reportedly had reduced the truck trips and vehicle emissions by 40% (Browne et al. 2005, BESTUFS 2007).

This study is designed to investigate what operational factors may make urban delivery consolidation more attractive and how those factors affect the effectiveness of delivery consolidation in terms of monetary 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 and energy consumption as a result of reduced truck trips and congestion in urban areas, is important from a sustainable system perspective. It is worth mentioning that institutional factors are as important as, if not more than, operational factors in the implementation of UCC, which in itself is an area of research and is outside the scope of this study. However,
suffice it to say that a scheme that is attractive to businesses would be less contentious to implement and even have a greater likelihood of surviving without subsidy.

The objective of this study is to investigate UCC by examining the effectiveness of urban delivery consolidation on reducing vehicle emissions, energy use, and costs to businesses from a strategic point of view. Specifically, the effects of a number of factors (i.e., facility rent cost, truck load factor, customer density and demand, and vehicle type) on the logistics cost, the vehicle miles traveled (VMT), the energy consumption and PM$_{2.5}$ emissions of different delivery strategies (UCC and non UCC) will be presented in this paper. The main contribution of this study is to demonstrate the urban freight policy analysis capability of Continuous Approximation (CA), an alternative modeling method, especially when detailed real-world data is hard or too expensive to obtain.

The rest of the chapter is organized as follows. Section 2 reviews the literature in the evolution of urban consolidation center schemes and mathematical modeling methods of urban freight problems. Section 3 presents the methodology to quantify UCC cost, vehicle energy consumption, and emissions. The model results under a selected set of urban freight policies and operational factors are presented and discussed in Section 4. Lastly, study conclusions are presented in Section 5.

5.2 Literature Review

The last mile delivery concerns the delivery process from the warehouse or distribution center to the recipient, either at the recipient’s home or a collective point (e.g., a retail store). The last mile is considered the least efficient in the entire supply chain. In practice, there are policy- and non-policy-related obstacles to improving the last mile
efficiency in terms of logistics cost, energy consumption and emissions. To name a few, just-in-demand delivery, time window constraints, delivery curfew hours, and truck size restriction in many cities. For example, Quak and Koster (2009) found that time window restrictions greatly impacted the retailers' costs to consolidate deliveries into one vehicle delivery tour. Vehicle size restriction seems to be the biggest factor for cost increase to retailers in that the delivery tour length is restricted by the vehicle capacity. Holguin-Veras et al. (2013) pointed out that banning large trucks into the city would force the carriers to split a shipment or a larger truck load into several smaller ones, and thus increase small truck trips (delivery frequency) and VMT. There are trade-offs in switching from large size to small size trucks. On the one hand, increased truck trips, delivery frequency and VMT may introduce additional logistics cost, energy consumption and emissions. On the other hand, switching to smaller trucks and/or decreasing truck load may reduce individual vehicle emissions and energy consumption. The key question here is whether there are conditions under which both logistics cost and emissions (and fuel) are reduced, and if the answer is “yes”, then it is of particular interest in knowing what are the determinants of such conditions and the tipping point where UCC becomes more attractive than direct delivery.

5.2.1 Urban Consolidation Center Studies

Urban Consolidation Center (UCC) is one urban freight strategy intended to reduce truck trips into urban centers and therefore truck VMT, energy consumption and emissions. It is particularly attractive in European and Japanese cities, where urban centers are highly
dense with congestion, and rental space is very limited. In one of the most cited early UCC studies, Browne et al. (2005) provided an extensive literature review on UCC initiatives primarily in the United Kingdom and other European countries. In their study, they defined UCC as "a logistics facility that is situated in relatively close proximity to the geographic area that it serves be that a city centre, an entire town or a specific site (e.g. shopping centre), from which consolidated deliveries are carried out within that area". Shippers/carriers with deliveries scheduled for the urban area or site transport their shipments to the UCC and the UCC is responsible for the last leg of the delivery. The UCC sorts and consolidates the shipments from the shippers/carriers and delivers them, often by an environmentally friendly vehicle, with a minimum required frequency and the shortest routing distance. Browne et al. (2005) provided the London Heathrow Airport Consolidation Centre as an example, which consolidates and performs security-check on deliveries, through a third party logistics company, for 40 retailers throughout London. It reportedly resulted in 66% reduction in delivery trips, 1.35kg less carbon dioxide (CO2) emissions per week and time saving equivalent to 370,000 Euros per year, while maintaining a 95% on-time delivery rate (Allen 2002). What's more, UCC may provide optional value-added logistics and retail services, such as off-site stockholding, consignment unpacking, preparation of products for display and price labeling. (Browne et al. 2011). Such value-added services can benefit receivers (e.g., retailers) in the serviced area by reducing their on-site space requirements and enhancing productivity and sales in their core business activities.

Since Browne et al. (2005), the definition of UCC has evolved and the recent applications/studies of UCC specifically refer to a UCC located within the city limit and
in close proximity to the serviced area which is typically the city center or a congested area within the city. One such example is the Binnenstadservice.nl (BSS) mentioned above (Rooijen and Quak 2010), Quak and Tavasszy 2011). Unlike the Heathrow Airport Consolidation Centre, BSS is located inside the Dutch city of Nijmegen right outside the serviced area. Such a shift is also reflective of a significant change in the UCC business model resulting from lessons learned from a few decades of field experiments, both successful and failed. That is, the earlier business model of UCC was targeting shippers/carriers as clients by providing them a central consolidation point. However, this model lacks incentives to attract shipper/carriers who already have established delivery clients and networks and are used to running their businesses without a UCC; at the same time UCC represents little additional value but potential high additional cost (if without substantial government subsidies) to shippers/carriers it tries to court. In addition, the receivers/customers in the city are not involved in the UCC scheme nor are they aware of potentially more sustainable options in receiving their goods.

In the most recently emerging UCC applications, the business model is shifted to targeting small and independent receivers/customers, e.g., small and independent retailers (Rooijen and Quak, 2009) within the serviced area. That is, UCC becomes the only gateway to those small and independent receivers/customers who join the UCC scheme and functions like a customer coalition. UCC provides basic free last-mile delivery service and optional paid value-added services (e.g., storage rental, home delivery) to the member receivers/customers. The optional paid value-added services may be subsidized by the government resulting in a reduced fee on the member receivers/customers and thus
provide even stronger incentives for small and independent receivers/customers to join. On the other hand, all shippers/carriers who wish to do business with those receivers/customers under the UCC coalition must go through the UCC and agree to share the cost of last-mile deliveries with UCC. Or else they will risk losing business. This is obviously a much more sustainable business model and an example of it is the Binnenstadservice.nl (BSS) in Nijmegen, the Netherlands that has been in operation without government financial support since 2009 (Rooijen and Quak 2010, Quak and Tavasszy2011).

UCC strategies tend to work better for certain types of industries than others. For example, based on a survey in New York City, Holguin-Veras et al. (2008) found that small and mid-size companies were more likely to use consolidation service and that food carriers were more likely to participate in the cooperative delivery than other industry sectors, followed by chemical and household goods carriers. Marcucci and Danielis(2008) conducted a stated-preference survey on how transportation decisions were made by customers or carriers in response to the potential demand for UCC in the city of Fano, Italy. The survey found that certain types of commodity such as food and grocery items and certain types of business such as stores/shops with limited storage space would more likely use consolidation service.

5.2.2 Mathematical Modeling Methods to Urban Logistics Problems

In transportation-related urban logistics problems, the so-called vehicle routing problem (known as VRP) in the literature is probably the most studied problem. Mathematical
programming is the most commonly used modeling tool in the VRP literature (e.g., Quak2008, Figliozzi2007). The beauty of the mathematical programming models is their elegant mathematical forms and their ability of associating a set of factors with the variable of interest quantitatively. Within the VRP family, the two-echelon VRP can be a particularly useful tool in addressing the distribution problem via UCC through minimizing the total transportation cost incurred in two levels: base depot to intermediate depots (i.e. UCC) and intermediate depots to customers. Constraints on maximum vehicle capacity and intermediate depots can be considered (Perboli et al. 2011). There have been a number of city logistics applications of the two-echelon VRP in recent years. For example, Crainic et al. (2009) applied a two-echelon VRP model to make a coordinated routing and scheduling decision in an urban distribution network composed of multiple trips, multiple depots, multiple products and heterogeneous vehicles with soft time windows at customers and hard time windows at Urban Distribution Center. VRP models tackle detailed operational issues concerning scheduling and routing of vehicle deliveries. The main concern of implementing these models is the model requirement of detailed discrete input data at every customer point and the considerable amount of computing time. In actuality, detailed discrete input data is often unavailable or hard to acquire or too expensive to afford.

As mentioned in Section 2.5, Continuous Approximation (CA) provides an alternative to the above-mentioned mathematical programming as a useful tool especially when planning a new service or an expansion of an existing one at the strategic/tactical level above the day-to-day operation (Langevin et al. 1996). 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.

First introduced by Beardwood et al. (1959), the CA method has been extended to a number of logistics problems particularly by Daganzo since 1984. A summary of such applications are documented in Daganzo (2005). The applications include, for example, finding a near optimal routing strategy of a traveling salesman problem in different shapes of the service area, partitioning the service region into clusters with different shapes and approximating the route length in each subarea, analyzing logistics cost components and their trade-offs, and solving for VRP and facility location problems. Some recent CA applications in urban delivery problems include Figliozzi (2009, 2010 and 2011), Kawamura and Lu (2007), and Chen et al. (2012). In Chen et al. (2012), we applied CA in comparing a UCC strategy with direct delivery with respect to a selected number of factors and found that UCC could be cost saving if set up correctly.

5.3 Methodology

5.3.1 Framework

Figure 15 depicts the comprehensive framework of this study. The core of the framework consists of two models: 1) a distribution network model to find the optimal vehicle scheduling and routing (in terms of number of stops) plan and the optimal logistics cost, and 2) an environmental impact model to estimate the vehicle energy consumption and emissions (PM$_{2.5}$) from the corresponding delivery plan. The distribution network model
is modeled at the tactical level (as opposed to the operational level) by employing the 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 environmental impact model, the Motor Vehicle Emission Simulator (MOVES) developed by the U.S. Environmental Protection Agency (US EPA) is used to calculate the PM$_{2.5}$ emission factors and the energy consumption rate.

![Study Framework](image.png)

**Figure 15. 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 objective function is to minimize the total logistics cost, which includes the transportation cost occur on the links and the storage/handling costs occur at the nodes. 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-today 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.

In this research, we classify the key factors influencing the decision-making into four categories as follows:

**Public policy**

Public regulations and policies towards freight transportation have direct impact on distribution channel choice. For example, with the low emission zone policy, only certain
types of vehicle that meet the desired emission level can enter the restricted areas. This may lead to the use of smaller delivery trucks and thus higher cost on the long-haul transportation portion and the total logistics cost without cooperation. Cooperative delivery can allow better utilization of small trucks in the last mile delivery. In this research study, we will consider the vehicle size regulation policy.

**Supplier/Customer/Commodity Characteristics**

The logistics decision is highly dependent on the type of logistics chain captured by commodity characteristics and establishment characteristics. On the one hand, different commodities have different requirements on transportation and handling. For example, perishable goods cannot be delayed during transportation, which represents a high pipeline inventory cost (the depreciation value of the goods). On the other hand, logistics decisions are also affected by the supplier/customer characteristics as follows:

1) Facility location, which refers to the origin and destination location of a delivery trip;

2) Demand quantities;

3) Market share, which determines the good flow quantity between each origin-destination pair.

**Network topology**

Delivery process depends on regional culture (i.e. narrow street caused by street vendors) availability of infrastructure (existing road network, UCC location), and geographical
topology (e.g., distribution of supplier/customer points), which are inputs to the
distribution channel model.

**Economics indicator**

Regional economy has great impact on logistics decision-making, such as labor cost, unit
transportation cost and unit storage cost. For example, storage cost in Manhattan is much
higher than in Queens, and labor cost in Europe is generally much higher than in Asia.

By varying the above four input parameters to the distribution channel model, we may
construct a number of scenarios to represent different delivery processes in different
logistics chains. In this research, we propose a number of scenarios for detailed
investigation.

In all strategies considered, suppose there are M suppliers S_i (i=1,2,..,M) located outside
of an urban area – a supplier can be a producer, a distribution center or a warehouse –
that supply the same commodity to N customers C_{uj} (j=1,2,..,N) in the study area
located in the city center. In this study, we consider retail stores as the customers that
receive replenishments of non perishable prepared food items whose values depreciate
only very gradually over time and do not require special containers when shipped. 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 C_{uj} for all suppliers is D’_j.

In the direct delivery strategy (Figure 16A), because each shipper makes decisions
independently, it can be formulated as M parallel one-to-many distribution problems. In
the UCC strategies (Strategies B1 and B2), the total logistics cost has an additional component: the UCC terminal-specific cost, e.g., operating and rent cost at the terminal.

The total logistics cost can be formulated as the sum of a one-to-one distribution problem in the inbound portion and a one-to-many distribution problem in the outbound portion, plus the UCC terminal-specific cost. The detailed explanation of the cost components involved in the study is provided in the next section.

![Delivery Strategies](image)

**Figure 16. Delivery Strategies.**

5.3.2 Distribution Network Model

The distribution network model is an extension, with necessary modifications, to Daganzo’s work on Logistics Cost Functions (Daganzo and Newell 1985, Daganzo 2005).

It should be noted that some of cost terms defined in the CA literature (e.g., Daganzo...
2005) are inconsistent with those used in business management and logistics literature (e.g., Mas-Colell et al. 1995). To help readers understand the differences in cost definitions between CA and the business and logistics literature, we have compared them side by side in Table VI. In this paper we follow the cost terminology in the business and logistics literature (Column 1 in Table VI) and further define the fixed and variable portions of the stop and operating costs at UCC in ways similar to Daganzo (2005).

The logistics cost in this study consists of costs incurred during transport (transportation cost and stop cost) and during storage (rent/storage cost, inventory cost, and terminal operating cost). All the costs incurred are counted regardless of who pays them, and are measured in terms of cost per shipping unit of goods, e.g., lbs, gallon, and pallet. In CA modeling, the UCC stop and operating cost items are further split into the so-called fixed cost, which is invariant to the shipped volume, and the variable cost, which varies according to shipped volume.

In the business and logistics literature, transportation cost includes the cost of moving items from one point to another, while stop cost accounts for loading and unloading cost at the stops. Rent cost (or storage cost) captures the rent for space, machinery needed to store the items in place, and any maintenance cost (i.e. security and utilities) directly related to the provision of storage space. It is proportional to the maximum accumulation of items, the item size, and the storage requirements. Inventory cost, also known as waiting cost, is associated with the delay incurred to the items, including the capital opportunity cost locked in storage, and the item value lost while waiting.
### Table VI  COST TERMINOLOGY

<table>
<thead>
<tr>
<th>Cost terminology in business and logistics literature</th>
<th>Cost elements in Daganzo(2005)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transportation cost</td>
<td>Line-haul transportation cost</td>
<td>Truck operation cost</td>
</tr>
<tr>
<td></td>
<td>Detour (or local) transportation cost</td>
<td></td>
</tr>
<tr>
<td>Stop cost</td>
<td>Fixed stop cost</td>
<td>Loading/ unloading cost at the stop</td>
</tr>
<tr>
<td></td>
<td>Variable stop cost</td>
<td></td>
</tr>
<tr>
<td>Operating cost (UCC)</td>
<td>Fixed terminal handling cost</td>
<td>Warehouse related cost (not including rent cost)</td>
</tr>
<tr>
<td></td>
<td>Variable terminal handling cost</td>
<td></td>
</tr>
<tr>
<td>Rent cost(UCC)</td>
<td>Terminal rent cost</td>
<td>Rent for space and machinery as well as maintenance cost directly related to the provision of storage space</td>
</tr>
<tr>
<td>Storage cost (customer)</td>
<td>Customer rent cost</td>
<td></td>
</tr>
<tr>
<td>Pipeline inventory cost</td>
<td>Inventory cost (or Waiting cost )</td>
<td>Cost of delay on the items</td>
</tr>
</tbody>
</table>


Here is an example of how to account for the logistics cost components in the CA model:

**Transportation cost** can be counted in the following way:

The 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)

The variable cost per shipment = \( C_v \times v \),

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

The handling cost per shipment = \( C_s \times v \)

Where \( C_s \) is the added handling cost of carrying an extra item ($/item);

Then, the costs incurred during transport per shipment = \( C_f + C_v \times v + C_s \times v \)

We use \( \bar{H} \) to represent the average dispatch headway, and use \( D' \) to capture the customer demand rate. With the fact that \( v = D' \times \bar{H} \), the costs incurred during transport can be expressed as a function of the average headway.

**The costs incurred during transportation per item** = \( \frac{C_f}{D' \times \bar{H}} + (C_v + C_s') \)
**Rent cost (or storage 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 = \( C_r \times \text{(max accumulation)} / D' = C_r \times H_{\text{max}} \)

Where \( C_r \) is the rent cost per item per unite time ($/item-time) and \( H_{\text{max}} \) 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 = \( C_i \times \text{(average wait / item)} = C_i \times (H_{\text{max}} + t_m) \)

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 costs incurred during storage per item** = \( (C_r + C_i) \times H_{\text{max}} + C_i \times t_m \)

To minimize the storage related cost, it is better to dispatch regularly, and the lower bound for \( H_{\text{max}} \) is \( H' \).

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 transportation related and
storage related costs. 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).

The total logistics cost/item = \( C_f / D \tilde{H} + (C_v + C_s) + (C_r + C_i) * \tilde{H} + C_i * t_m \)

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

\[ \tilde{H} = \sqrt{C_f / D (C_i + C_r)} \]

5.3.2.1 Model Assumptions

A number of assumptions are made to simplify the model formulation:

1. The UCC facility location is outside of the urban center, fixed and known;
2. Each customer is served by all suppliers, and each supplier serves all customers in the study area;
3. The customers are homogeneous and uniformly distributed in the study area, and have the same demand rate for each supplier. That is, \( D_{ij} = D' \), and \( \sum_i D_{ij} = D_j' \);
4. The demand rate \( D_{ij}' \) is constant over time;
5. The study area can be partitioned into rectangles or circles.
6. The number of customers (N) in the study area is large (N>>Square of the number of stops per tour). In other words, multiple delivery tours are needed to serve all of the customers. Each tour has the base-customer(s)-base structure. The base is either the supplier's (in Strategy A) or the UCC (in Strategies B1 and B2);
7. Shipped goods have negligible inventory costs;
8. Vehicles have a maximum load of \( V_{max} \). Combining assumption 7 it implies that vehicles always set out with a maximum load in this study since that is obviously more economical.
9. The truck fleet information is known
10. There is no reverse flow, which means the vehicle does not collect items during the tour and bring them back to the base.

The mathematical formulations of the direct and cooperative delivery strategies are presented in the following sections. The parameter notations with the adopted values are given in Table VIII through Table X, with detailed explanation on parameter value estimation presented in Section.

5.3.2.2 Direct Delivery (Strategy A)

Strategy A is treated as an M-parallel one-supplier-to-many-customer distribution problem (Figure 16A). It is assumed that 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 and the number of stops is equal in every delivery tour. Furthermore, each customer $C_{uj}$ ($j=1,\ldots,N$) 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 represent the line-haul transportation/stop cost ($\alpha_{1A}$), the detour transportation/stop cost ($\alpha_{2A}$) and the storage cost at the customer's ($\alpha_{4A}$):

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

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

and

$$\alpha_{4A} = C_iM / D.$$
Divide by the shipment size per tour, the total logistics cost per item in direct delivery can be formulated as follows:

\[ Z_A = C_s + \alpha_{1A} / n_s v + \alpha_{2A} / v + \alpha_{4A} v \]  

\text{(5.3)}

\begin{align*}
\text{St.} & \quad n_s v \leq V_{\text{max}} \quad \text{(5.4)} \\
& \quad n_s \geq 1 \quad \text{(5.5)} \\
& \quad 2r_1 / \text{speed}_1 + n_s k \delta d^{-0.5} / \text{speed}_2 + n_s \omega \leq L \quad \text{(5.6)}
\end{align*}

Constraint (5.4) guarantees that the shipment size per tour cannot exceed the vehicle capacity and constraint (5.5) ensures at least one customer is served in the tour. Constraint (5.6) enforces the labor rule such that the delivery time does not violate the work hour limit, L. Notations \( \omega, \text{speed}_1 \) and \( \text{speed}_2 \) represent the stop dwell time, average speed for line-haul and average speed for detour transportation respectively. It is a simple quadratic program which can be solved either by hand or commercial software.

\textbf{5.3.2.3 UCC Strategy (B1 and B2)}

In strategy B, we consider the UCC is located inside the city limit and in close proximity to the serviced area where the customers are located. We denote the average distance from a supplier to UCC as \( r_1 \), and the average distance from UCC to a customer as \( r_2 \). The values of \( r_1 \) and \( r_2 \) are explained in section 5.3.2.4.

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

\[ Z_B = Z_{Bi} + Z_{Bo} + Z_{Bl} \]  

\text{(5.7)}

Where, \( Z_{Bi} = C_s' + \alpha_{1Bi} / v_i \)  

\text{(5.8)}
\[ Z_{Bo} = C_s + \alpha_{1Bo} / n_v + \alpha_{2Bo} / v_o + \alpha_{4Bo} v_o \]  \hspace{1cm} (5.9)

\[ Z_{Bi} = C_i (\max[H_i, H_o]) + H_i + \alpha_3 / ND + \alpha_6 \]  \hspace{1cm} (5.10)

St. \hspace{0.5cm} v_i \leq V_{max} \hspace{1cm} (5.11)

\[ v_o n_s \leq V_{max} \]  \hspace{1cm} (5.12)

\[ n_s \geq 1 \]  \hspace{1cm} (5.13)

\[ 2r_2 / \text{speed}_1 + n_s k \delta_d^{-0.5} / \text{speed}_2 + n_s \omega \leq L \]  \hspace{1cm} (5.14)

Equations (5.8), (5.9) and (5.10) represent the inbound cost, the outbound cost and the UCC terminal cost respectively, where the inbound transportation/stop cost \( \alpha_{1Bi} = 2r_1 C_{d1} + C_s \), the outbound line-haul transportation/stop cost \( \alpha_{2Bo} = 2r_2 C_{d1} + C_s \), the outbound detour transportation/stop cost \( \alpha_{2Bo} = C_{d2} k \delta_d^{-0.5} + C_s \), the customer storage cost \( \alpha_4Bo = \alpha_s / D \), UCC terminal operating cost \( \alpha_5 \) (fixed portion) and \( \alpha_6 \) (variable portion), as well as the UCC rent cost as a function of the terminal processing time \( H_i \) and the storage time \( \max[H_i, H_o] \), which is equal to the largest time gap between the inbound shipment and the next outbound shipment. If one supplier provides frequent service while others operate 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 considered here:

**No coordination between inbound and outbound trips at UCC (Strategy B1):** Inbound trips to UCC and outbound trips from UCC are assumed to be not 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 defined respectively by (5.15) (5.11) and (5.9)(5.12)(5.13)(5.14) separately, and the objective function is the sum of (5.8)(5.9)(5.10).

To construct an EOQ form for inbound shipments, we use the following auxiliary formulation to get the inbound solution,

\[ Z_{Bi} = C_{i} + \alpha_{4Bi} / v_{i} + \alpha_{4Bi} v_{i} \]  

(5.15)

where \( \alpha_{4Bi} = C' M / ND \) represents the rent cost corresponding to the inbound headway at the UCC.

**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, one single quadratic problem (5.8)-(5.14) is solved.

### 5.3.2.4 Parameter Estimation

In this chapter, the different 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. In order to demonstrate the policy analysis capability of the proposed CA model,
the model parameter values must be set as representative of the real-world as possible. To accomplish that, we have assembled and consulted a number of sources, which are described as follows. It is worth mentioning that an ideal data source would be a shipper-carrier-receiver survey (or surveys) specifically designed for the study purposes in the study area. However, given the reality that (1) such data does not exist currently; and (2) surveys are often too expensive and often suffer from small sample size and poor response rate and hence poor data quality, we have to rely on other existing and generally credible data sources in the area of freight research for this study. That is an important data limitation to note and points to the future data collection effort.

*SimplyMap* is a web mapping application that allows users to create map and reports of demographic, business and marketing data between 2010 and 2013 at various geographic scales, i.e., national, state, county, ZIP code, census tract, and business establishment (point). It serves as a data portal with data providers such as Dun & Bradstreet (D&B), Mediamark Research Inc. (MRI), The Nielsen Company, Easy Analytic Software Inc. (EASI) and Experian. It contains information about grocery (retailer) stores such as store location, number of employees, sales volume, which are used in this study.

*Bizcost.com* provides reports on business operating cost for specific industries (e.g., food processing) and distinctive corporate function (i.e. headquarters, distribution warehousing) in different geographic locations. The reports provide such detailed costs as labor cost, lease cost and utilities by location. Such information is used to estimate the UCC facility related parameters in this study.
**Food Environment Atlas** is a program administrated by the Economic Research Service of the U.S. Department of Agriculture. 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. The data is used to generate customer related parameter values (e.g., customer demand rate) in this study.

**Other data sources** include a study by McCormack et al. (2010) based on a telephone survey/interview in grocery delivery in the Seattle area, a freight survey in NYC area by Holguin-Veras et al. (2008), the research findings from Kawamura and Lu (2007), the American Transportation Research Institute 2010 truck operating cost report (Trego and Murray 2010), and the online Commercial Real Estate reports (Loopnet.com).

(1) Customer related parameters (density, demand, and distance to suppliers)

According to a freight survey in NYC (Holguin-Veras et al. 2008), small and mid-size companies are more likely than large chain companies to use consolidation service. Hence, we selected the convenience stores as the customers in this study. Data based on the City of Chicago are used to estimate the customer related parameter values.

**Table VII** lists the data sources at the zip code level used to calculate customer density and demand rate. There are 55 zip codes in the City of Chicago limit. Customer density and demand rate are calculated for each zip code.
### Table VII  SUMMARY OF CUSTOMER RELATED DATA RESOURCE AT THE ZIP CODE LEVEL

<table>
<thead>
<tr>
<th>Data Source</th>
<th>Data field</th>
<th>Data year</th>
<th>Variable estimated</th>
<th>Adopted value (lower/upper bound)²</th>
</tr>
</thead>
<tbody>
<tr>
<td>D&amp;B survey</td>
<td>Number of convenient stores per zip code</td>
<td>2010</td>
<td>Customer density $\delta_j$ (# conv. stores/sq mi)</td>
<td>1.93 (0.44/24.85)</td>
</tr>
<tr>
<td>(via SimplyMap)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D&amp;B survey</td>
<td>Prepared food sales volume by store type (supermarket and convenient) ($/year)</td>
<td>2010</td>
<td>Convenient store market share = (total convenient store sales volume) / (total convenient store &amp; supermarket sales volume)</td>
<td>0.14 (0.01/0.65)</td>
</tr>
<tr>
<td>(via SimplyMap)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Census 2010</td>
<td>Zip code area (sq miles)</td>
<td>2010</td>
<td></td>
<td>956.43 (31/3518)</td>
</tr>
<tr>
<td>(via SimplyMap)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Census2010</td>
<td>Population per zip code</td>
<td>2010</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(via SimplyMap)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Food Environmental Altas¹</td>
<td>Prepared food demand rate (lbs/capita-year)</td>
<td>2006</td>
<td>Customer demand rate $D$(lbs/store-day) = (prepare food demand rate)(Population per zip code)(Convenient store market share)/number of conv. stores per zip code/365</td>
<td>956.43 (31/3518)</td>
</tr>
</tbody>
</table>

¹Food Environment Altas data is only available at the county level
²The 5th percentile point is used as the lower bound; the 50th percentile point is used as the typical value; and the 95th percentile point is used as the upper bound
Although the UCC location choice is beyond the scope of this paper, it is worth noting that in practice the location of UCC must be carefully chosen to maximize the benefits it brings. Generally speaking, UCC should be situated in close proximity to its service area. Chen et al. (2012) showed that the closer the distance, the bigger cost saving the UCC brings. Olsson and Woxenius (2012) concluded that UCC location depends on the city characteristics, both its density (activities and population) and the spatial scope; and that UCC should be located close to intermodal nodes and distribution terminals where the incoming transport assignments are generated, therefore to minimize the VMT.

Following the literature findings, the UCC location relative to its customers and suppliers is determined as follows. Within the city limit of Chicago, the warehousing/distribution district serving downtown Chicago is Goose Island, which is within 5 miles from the Chicago city center and about 20 miles from the O'Hare airport, and is right off the major interstate highway I-90/94 (see Figure 17). Hence, the average distance of line-haul 1 in Figure 16B between suppliers and UCC \( (r_1) \) is set to be 20 miles and the average distance of line-haul 2 between UCC and the serviced area \( (r_2) \) is set to be 5 miles.
Figure 17. Goose Island Warehousing/Distribution District in Chicago.

(2) Vehicle related parameters (capacity, transportation cost, and stop cost)

In a telephone survey/interview of the grocery deliveries in the Seattle area (McCormack et al. 2010), deliveries were observed at the loading docks and through the grocery store’s front door. Front door deliveries were generally made by the smaller “FHWA (Federal Highway Administration) Class 1” trucks (2-axle single-unit), whereas "FHWA Class 3”(4-5 axle tractor trailer) trucks delivered to loading docks. According to FHWA, the maximum payloads for Classes 1 and 3 trucks for the prepared food commodities are 9895lbs and 37097 lbs respectively (FHWA 2007). Those values are used to define vehicle capacity in the study.
Vehicle line-haul and detour transportation costs are estimated based on the findings in Trego and Murray (2010), in which the average hourly truck operating cost at large firms was found to be $61.91 in 2010. This figure is assumed to represent the hourly operating cost for heavy-duty trucks. According to the U.S. Bureau of Labor Statistics (2010), the national average hourly wages in 2010 were $18.16 and $13.00 for heavy- and light-duty truck drivers respectively. By assuming a similar ratio of the operating costs between the heavy- and light-duty trucks to that of the hourly wages, the hourly operating cost for light-duty trucks would be about $40.

According to a commercial vehicle survey in six metropolitan areas of Texas (Nepalet al. 2007), the arterial average speed for commercial vehicle is 19.36 mph; the highway average speed, after adjusted for the congestion effect, is estimated to be 44 mph. Using those speeds and the above operating costs, we estimated the line-haul and detour transportation costs as shown in Table VIII.

<table>
<thead>
<tr>
<th>Truck type$^1$</th>
<th>FHWA truck classification</th>
<th>Truck payload $V_{max}$ (lbs)</th>
<th>Line-haul transportation cost $C_{d1}$ ($/mile)</th>
<th>Detour transportation cost $C_{d2}$ ($/mile)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LDT</td>
<td>Class 1</td>
<td>9895</td>
<td>0.91</td>
<td>2.07</td>
</tr>
<tr>
<td>HDT</td>
<td>Class 3</td>
<td>37097</td>
<td>1.41</td>
<td>3.20</td>
</tr>
</tbody>
</table>

$^1$ LDT stands for light duty trucks; HDT stands for heavy duty trucks.
McCormack et al. (2010) found that the minimum dwell time for grocery delivery was 10 to 15 minutes and the average was 25 to 30 minutes for a fully loaded Class 1 truck. Using the minimum dwell time to estimate the fixed stop cost, it comes out to be $10.32/stop for a 10 minute dwell time (= $61.91*(10/60)= $10.32/stop), and the variable stop cost =\$61.91*[(30-10)/60]/9895=\$0.002/lbs.

According to a freight movement survey in NYC (Morris et al. 1999), the average duration of a dispatched round-trip in and out of the central business district ranged between five and eight hours. Hence, we set the work hour limit at 8 hours in this study.

(3) Facility related parameters (rent/storage/operating cost)

There are two cost categories related to the UCC facility and storage at the customer end: operating cost and rent/storage cost\(^4\). The UCC operating cost was estimated using Bizcost report 2010 (http://Bizcost.com). Bizcost provides warehouse operating cost from 72 comparative sites in the U.S. We obtained the labor cost ($17.75/labor-hr) and annual power cost ($1,263,216/year) for a hypothetical 450,000 sqft warehouse with 150 employees in a major US metropolitan area like Chicago. The warehouse size represents an average across the country suggested by Bizcost.com. The labor cost is used to determine the variable terminal operating cost, which depends on the volume and hence the labor involved. The electricity and power cost for operating and maintaining the

\(^4\) These costs vary greatly across metropolitan areas in the U.S. In particular, New York City (esp. Manhattan) represents an outlier in that regard and is not comparable to many other metropolitan cities such as Chicago. In addition, a port city (e.g., NYC) and an inland city (e.g., Chicago) have distinctively different characteristics in supply chain and logistics. That is another contributing factor to the differences in many of the parameter values.
facility is used to determine the fixed terminal operating cost, which is independent of the volume of goods processed at the terminal.

Rent/storage cost was obtained from the Online Commercial Real Estate (http://Loopnet.com), i.e., $6.4/sq.ft.-year for a 450,000 sq.ft warehouse on the city center boundary (UCC terminal) and $18/sq.ft.-year within the city center (customer). On the customer side, a convenient store size can be anywhere between 13,000 and 25,000 sq. ft, with 10% of the space is used for storage. (The Community Development Financial Institution Fund 2011). Note that the UCC rent cost is about a third of the customer storage cost. In actuality, the UCC rent cost may be even higher. While that ratio may still be debatable, what is clear is that the UCC rent cost must be kept relatively low, either due to the less centralized location and/or an artificial outcome of government subsidy or other cost sharing mechanisms, in order for UCC to even be an option on the table. Table IX summarizes the operating cost and rent cost at UCC and storage cost at customers'.

<table>
<thead>
<tr>
<th>Cost category</th>
<th>Cost elements</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating cost (UCC)</td>
<td>Fixed terminal operating cost $\alpha_5$</td>
<td>$/day$</td>
<td>3460.87</td>
</tr>
<tr>
<td></td>
<td>Variable terminal operating cost $\alpha_6$</td>
<td>$/lbs$</td>
<td>0.059</td>
</tr>
<tr>
<td>Rent cost(UCC)</td>
<td>Terminal rent cost $C_r^t$</td>
<td>$/lbs\cdot day$</td>
<td>0.022</td>
</tr>
<tr>
<td>Storage cost (customer)</td>
<td>Customer storage cost $C_r$</td>
<td>$/\text{lbs-day}$</td>
<td>0.067</td>
</tr>
<tr>
<td>-------------------------</td>
<td>-------------------------------</td>
<td>-----------------</td>
<td>-------</td>
</tr>
</tbody>
</table>

Other CA model parameters are summarized in **Table X**.

### Table X  OTHER CA MODEL PARAMETERS

<table>
<thead>
<tr>
<th>Notation</th>
<th>Explanation</th>
<th>Unit</th>
<th>Adopted Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r$</td>
<td>Line-haul distance in direct delivery</td>
<td>Miles</td>
<td>25.00</td>
</tr>
<tr>
<td>$r_1$</td>
<td>Supplier-UCC line-haul distance</td>
<td>Miles</td>
<td>20.00</td>
</tr>
<tr>
<td>$r_2$</td>
<td>UCC-customer line-haul distance</td>
<td>Miles</td>
<td>5.00</td>
</tr>
<tr>
<td>$K$</td>
<td>Dimension less parameter$^1$</td>
<td></td>
<td>0.82</td>
</tr>
<tr>
<td>$M$</td>
<td>Number of suppliers</td>
<td>/</td>
<td>5.00</td>
</tr>
<tr>
<td>$N$</td>
<td>Number of customers</td>
<td>/</td>
<td>375.00</td>
</tr>
<tr>
<td>$C_s$</td>
<td>Fixed stop cost (invariant to shipped volume)</td>
<td>$/\text{stop}$</td>
<td>10.32</td>
</tr>
<tr>
<td>$C_s'$</td>
<td>Variable stop cost (depending on shipped volume)</td>
<td>$/\text{lbs}$</td>
<td>0.002</td>
</tr>
<tr>
<td>$H'$</td>
<td>Fixed terminal process time</td>
<td>Days</td>
<td>0.083</td>
</tr>
<tr>
<td>$n_s$</td>
<td>Number of stops in a delivery tour</td>
<td>(decision variable)</td>
<td></td>
</tr>
<tr>
<td>$v$</td>
<td>Delivery lot size from one supplier to one customer</td>
<td>(decision variable)</td>
<td></td>
</tr>
</tbody>
</table>

$^1$K is a dimensionless parameter, which only depends on the metric to reflect the detour distance. It is an approximation to the VRP distance without the precise location of each customer. $K=0.82$ in the L1 Metric, see Daganzo (2005) Appendix 1 for the proof.
5.3.3 Emission Estimation Model

To evaluate the environmental impacts on delivery consolidation, US EPA's vehicular emission model MOVES is used to generate the emission factors of various vehicle types and road types at different speeds. MOVES classifies the vehicle activities into different activity bins by 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) and estimates the emission rates associated with those bins (US EPA 2010). For more details about how emission rates are generated at various speeds in MOVES, please refer to Vallamsundar and Lin (2011).

In this study, energy consumption and PM$_{2.5}$ emissions of diesel trucks are considered. To estimate the PM$_{2.5}$ emission rates and the energy consumption rates in MOVES, a number of input parameters must be specified. Table XI summarizes the key inputs to MOVES for the study. Note that emissions are typically regionally specific and hard to generalize. Many of the input parameters shown in Table XI are Chicago (Cook County) specific. But the estimation procedure is common to any geographical area in the U.S. Again two types of truck are considered for urban delivery: single unit short-haul truck in MOVES which is equivalent to the light-duty FHWA Class 1 truck, and combination short-haul truck in MOVES which is equivalent to the heavy-duty FHWA Class 3 truck. Winter season is considered because it is associated with higher emission and energy consumption rates.
Table XI  KEY INPUT PARAMETERS TO MOVES

<table>
<thead>
<tr>
<th>Input</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Season</td>
<td>Winter</td>
</tr>
<tr>
<td>Time of day/Day of Week</td>
<td>Mid-day, weekday</td>
</tr>
<tr>
<td>Analysis year</td>
<td>2011</td>
</tr>
<tr>
<td>Road type</td>
<td>- Urban Unrestricted Access (arterials)</td>
</tr>
<tr>
<td></td>
<td>- Urban Restricted Access (highways)</td>
</tr>
<tr>
<td>Pollutants</td>
<td>PM$_{2.5}$, Energy consumption</td>
</tr>
<tr>
<td>Emission Processes</td>
<td>Running exhaust, crankcase running exhaust, brake and tire wear and tear</td>
</tr>
<tr>
<td>Vehicle type</td>
<td>Single Unit Short-haul Truck, Combination short-haul Truck</td>
</tr>
<tr>
<td>Vehicle speed</td>
<td>0-70 mph</td>
</tr>
<tr>
<td>Fuel type</td>
<td>Diesel (Cook county specific)</td>
</tr>
<tr>
<td>Temperature</td>
<td>Cook county specific</td>
</tr>
</tbody>
</table>

With the emission rates and energy consumption rates for diesel trucks for calendar year 2011 from Table XII, and the total vehicle miles traveled from the model described in 7.3.2, we can calculate the total emissions with the following equation:

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

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 \( road \).

### Table XII  PM\(_{2.5}\) EMISSION RATES AND ENERGY CONSUMPTION RATES

<table>
<thead>
<tr>
<th>Truck type</th>
<th>Energy consumption rate ((10^6\text{ joules/mile}))</th>
<th>PM(_{2.5}) emission rate ((\text{grams/mile}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Speed=19.36mph</td>
<td>Speed=44mph</td>
</tr>
<tr>
<td>LDT</td>
<td>24.4</td>
<td>15.5</td>
</tr>
<tr>
<td>HDT</td>
<td>34.3</td>
<td>25.0</td>
</tr>
</tbody>
</table>

### 5.4 Results

This section presents the investigation results of the effects of vehicle size restrictions (Section 7.4.1), rent/storage cost (Section 7.4.2), customer demand (Section 7.4.3), customer density (Section 7.4.4), UCC location (Section 7.4.5) and network size (Section 7.4.6) on three metrics: logistics cost, energy consumption and PM\(_{2.5}\) emissions among Strategies A, B1 and B2.

#### 5.4.1 Effect of Vehicle Size Restrictions

As described earlier, two types of delivery trucks are considered in the study: Class 1(light-duty) and Class 3 (heavy-duty) truck. If there is no vehicle size restriction
imposed by a city, from the pure economic point of view, shippers or carriers will opt for
the larger trucks and pack up the trucks as much as possible - recall the assumption of
very low waiting cost. In other words, the truck load factor would be very close to one.

If there is a vehicle size restriction such that the city prohibits larger vehicles entering the
city streets, then in the case of direct delivery (Strategy A), only LDTs are used, and in
the case of UCC (Strategy B) outbound shipping can only use LDTs. When LDTs are
used, it is likely to ship less-than-truck-load (LTL) in direct shipping (Holguin-Veras et al.
2011). Therefore, Scenario S4 considers an extreme case of LTL in narrow cities like
Tokyo. Table XIII summarizes the four possible scenarios of vehicle size considered in
this analysis.

Table XIII  VEHICLE SIZE SCENARIOS

<table>
<thead>
<tr>
<th>Scenarios ID</th>
<th>Strategy A</th>
<th>Strategy B</th>
<th>Vehicle load factor in Strategy A</th>
<th>Size restriction applied?</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Inbound</td>
<td>Outbound</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S1</td>
<td>HDT</td>
<td>HDT</td>
<td>1.00</td>
<td>N</td>
</tr>
<tr>
<td>S2</td>
<td>LDT</td>
<td>HDT</td>
<td>1.00</td>
<td>Y</td>
</tr>
<tr>
<td>S3</td>
<td>LDT</td>
<td>LDT</td>
<td>1.00</td>
<td>Y</td>
</tr>
<tr>
<td>S4</td>
<td>LDT</td>
<td>LDT</td>
<td>0.40</td>
<td>Y</td>
</tr>
</tbody>
</table>

For each of the four scenarios, we estimated the optimal logistics cost, and the
corresponding energy consumption, PM$_{2.5}$ emissions, and total truck VMT under
Strategies A, B1 and B2. Table XIV summarizes the percentage changes between B1
and A as well as B2 and A. A negative value means Strategy B (with UCC) has a lower
value than Strategy A (without UCC) in a given metric, indicating a potential benefit of
using UCC.
Table XIV  PERCENTAGE CHANGE FROM STRATEGY A FOR SCENARIOS S1-S4

<table>
<thead>
<tr>
<th>Scenario ID</th>
<th>Logistics cost (%)</th>
<th>Truck VMT (%)</th>
<th>Energy consumption (%)</th>
<th>PM$_{2.5}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>-17.36</td>
<td>-17.36</td>
<td>21.12</td>
<td>21.38</td>
</tr>
<tr>
<td>S2</td>
<td>-9.13</td>
<td>-9.08</td>
<td>-19.76</td>
<td>-17.74</td>
</tr>
<tr>
<td>S3</td>
<td>-10.61</td>
<td>-10.52</td>
<td>2.38</td>
<td>3.78</td>
</tr>
<tr>
<td>S4</td>
<td>-18.76</td>
<td>-18.86</td>
<td>-48.85</td>
<td>-43.1</td>
</tr>
</tbody>
</table>

In Scenario S1, the UCC strategies bring significant cost savings compared to direct delivery. The possible reason is that UCC serves to shift from the expensive customer storage cost to the cheaper UCC rent cost, by providing cheaper storage space and more flexible shipping frequencies for the outbound shipments (from UCC to customer) in the UCC strategies to allow minimum or even no stocking necessary at the customer end. That is what has happened in the BSS case (Rooijen and Quak 2010, Quak and Tavasszy2011). However, the downside of that flexibility is a greater level of truck VMT, which also results in higher energy consumption and PM$_{2.5}$ emissions than Strategy A. That is a confirmation to Holguin-Veras et al. (2013)'s conclusion that UCC may have negative impact in energy consumption and emissions.

In Scenario S2, when considering truck size restriction in the city center, only LDTs are used in Strategy A. In strategy B, it is possible to split a larger truck load into several smaller trucks at the UCC, known as "break-bulk": In other words, it is possible to use HDTs for the inbound shipments and LDTs for the outbound shipments. As a result, both
cost and VMT are saved. So is the energy consumption. However, PM$_{2.5}$ is higher for the UCC strategy. The reason is two-fold: (1) HDT used in the inbound shipping produces much higher PM$_{2.5}$ emissions than LDT (see Table 7); and (2) using smaller trucks for the outbound shipping results in a higher level of truck VMT on city streets although the overall VMT is reduced from direct delivery. Since PM$_{2.5}$ emission rate on arterial streets is much higher than that of highways, the UCC strategies under S2 resulted in higher overall PM$_{2.5}$ emissions.

The results in Scenario S3 are similar to those in S1. However, the increases in energy consumption, PM$_{2.5}$ emissions, and truck VMT are to a much lesser degree in S3 than in S1 due to the switch to LDT from HDT, a much higher emitter of PM$_{2.5}$. Moreover, the results suggest that B2 performs better than B1 in terms of energy consumption and emissions, primarily because B2 requires coordination between inbound and outbound shipments, resulting in reduced inbound shipment frequency and thus inbound VMT and emissions.

Between S3 and S4, the only difference is that in S4 Strategy A ships less-than-truck-load (LTL). And that has resulted in a very different saving profile than S3. Because now Strategy A is less efficient, the UCC strategies display large savings in all four metrics as expected.

As mentioned earlier, the issue with LTL is that there is a trade-off between more shipping trips required (and consequently more VMT and congestion) and less energy consumption and emissions per vehicle, when compared to fully loaded shipping. In this study, we are interested in determining the tipping point for UCC to become more
attractive. Thus, we carried out the following sensitivity test: using only LDTs and letting the load factor in Strategy A vary from 0.4 to 1 while keeping everything else the same between A and B, we calculated the optimal shipment plans for Strategy B and compared the differences between A and B in all four metrics. Figure 18 shows the results.

As expected, the benefits of UCC decrease as the load factor in Strategy A increases. When Strategy A load factor is above 0.82, which is practically close to a full load, then UCC strategies do not provide fuel or emission saving since in that case direct delivery is most efficient in all respects - cost, energy consumption, and emissions. Though in reality truck load factors almost never reach that level. For example, trucks in Japan operated with an average load factor around 30%-40%, and more importantly the load factor was downward between 1970-1997 (Taniguchi, 2003). Similarly in thirteen European countries (Austria, Czech Republic, Denmark, Germany, Hungary, Latvia, Netherlands, Poland, Portugal, Slovenia, Spain, Sweden and the UK) where data were available, truck load factors were found generally under 50 % (by weight) and declined between 1997 and 2008 (European Environment Agency 2010). A commercial vehicle survey in Texas (Nepal et al. 2007) showed that the empty-loaded trips by commercial vehicles in six Texas metropolitan regions accounted for over 60% of all goods trips on a given day and 95% of the trips have load factor less than 0.4 during 2005-2006 survey period. It should be noted that the assumption of a perfect load factor in the UCC strategies is a direct derivation of assumption 7 in Section 5.3.2, i.e., shipped goods have negligible inventory (waiting) cost. That obviously does not always apply, e.g., in just-in-time demand. However, by design we can still expect a higher load factor to be achieved
by UCC. This indicates UCC may reduce logistics cost, energy consumption, and emissions.

In summary, UCC strategies could become a more attractive alternative, monetary cost alone, to direct delivery by shifting the rent/storage cost from the more expensive customer end to the cheaper UCC end and/or better utilizing the vehicle capacity. However, by doing so UCC may not always bring energy and emission savings.

In the rest of the analyses presented in Section 5.4.2 through 5.4.6, vehicle choice follows S2 - 'break-bulk' at UCC with vehicle size restriction inside the city limit.

Figure 18. Effect of Load Factor.
5.4.2 Effect of Rent/Storage Cost

In Section 5.4.1, we have seen the effect of rent cost on the efficiency of UCC. UCC terminal rent cost may be influenced by the government policy towards UCC. For example, if the government subsidizes the UCC rent cost then the cost burden is reduced for suppliers (shippers), carriers, and customers (receivers). UCC terminal rent cost also depends on its location. For example, it is generally cheaper to have the UCC located outside the city center. Moreover, the recent UCC applications seem to suggest that cheap storage space may be another incentive for city customers to participate in UCC. As such, city customers especially in large (more expensive) cities may be able to further reduce in-house storage space.

In this analysis, we varied the UCC terminal cost from $2.5 to $10.8/sq.ft. to reflect the geographic variation (cost gradient) from cheaper urban areas like Little Rock, AR to more expensive urban areas like San Francisco, CA and Chicago, IL, and the rent cost ratio between customer storage cost and UCC terminal rent cost from 1 to 6. Results are shown in Figure 19.

As expected, when the rent cost ratio is high (meaning the customer storage cost is proportionally high), then the UCC strategies (B1 and B2) are better off than direct delivery (A) in terms of logistics cost. Interestingly, the results also show that when the UCC terminal rent cost is high, UCC strategies may also bring more cost savings. That may seem counter-intuitive at first, but what this analysis suggests is that UCC would work better for more expensive cities like Chicago and San Francisco than the less expensive ones. At the customer end, because of high rent cost in the expensive city
center, further reducing the in-house storage space (and thus the storage cost) means more sales space - the total floor space is generally fixed under a mid- or long-term contract. More sales space generally means more product variants the store can carry and better atmosphere the store can provide (Browne et al. 2005). So space is much better utilized where the rent is high. In fact, that was one of the reasons cited by the UCC participants (i.e., the city receivers) in the Nijmegen BSS case.

On the hand, the energy consumption and PM$_{2.5}$ emissions show the opposite trend. However, there seems to be a rent cost range in which UCC may bring both monetary and environmental benefits. In other words, under certain conditions, UCC could be an attractive strategy for the businesses, and at the same time, provide social benefits.
Figure 19. Effect of Rent Cost.

5.4.3 Effect of Customer Demand

As shown in Figure 20, the UCC logistics cost saving decreases as customer demand increases (Figure 20a), whereas the savings in energy consumption and emissions are of the opposite trend. The tipping points are noted in the figures. Recall that in this analysis LDTs are used in A and a combination of HDTs and LDTs are used in Strategy B (i.e.,
S2 in Table XIII). Higher customer demand means much more delivery trips required in Strategy A, and therefore higher energy consumption and emissions. In comparison, Strategies B1 and B2 become more environmentally friendly. On the other hand, the facility related cost (i.e., operating, rent, storage, and inventory cost items) is dominating the transportation cost especially in Strategy A - the former accounts for 79.9%, 73.1% and 65.7% of the total logistics cost, for A, B1 and B2 respectively in this particular scenario. With increased delivery trips (and thus the transportation cost) Strategy A may still be more cost efficient when customer demand is high because LTL may be effectively avoided. That may also explain why large chain stores are not likely to use UCC, as concluded in Holguin-Veras et al. (2008).

Figure 20. Effect of Customer Demand.
5.4.4 Effect of Customer Density

Figure 21. Effect of Customer Density.

Figure 21 shows the cost/energy consumption/PM$_{2.5}$ emission sensitivity to customer density in number of convenient stores per square mile. As the customer density increases, the cost/energy consumption/PM$_{2.5}$ percentage change decreases, suggesting higher benefit of UCC. This may be due to the economy of scale as higher customer density implies more potential users of UCC. Recently, some new type of UCCs in Japan seem to serve small and high density area near the UCC, i.e. a shopping mall with vertical layout (Tokyo midtown) or stores within a walking distance (Soramachi) (Taniguchi and Qureshii, 2014). These UCCs, which can be seen as extreme cases of high customer density, are still operating without government’s subsidy.

5.4.5 Effect of Market Penetration

In this section, the sensitivity with respect to the number of suppliers is tested by fixing the number of customers at 375 and varying the number of suppliers from 1 to 20. As
shown in Figure 22, the amount of percent decrease in cost/energy consumption/PM2.5 compared against Scenario A increases as more suppliers participated the UCC scheme, indicating that as the number of suppliers increases the benefit of using UCC becomes greater. This is because the demand at customers is split into smaller order size when the number of suppliers is large, and more traditional 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 with a larger drop-off size, reducing the truck VMT and lowering the total logistics cost. This is another example of economic of scale benefit brought by using UCC.

Figure 22. Effect of Market Penetration.

5.4.6 Effect of Distance

In this analysis, the average distance between supplier and customer is varied from 10 to 50 miles, and the ratio of inbound trip distance \( r_1 \) to outbound trip distance \( r_2 \) varies from 0.2 to 10. Larger ratio indicates the UCC is closer to the customer. As shown in Figure 23(a)(b), when UCC is relatively closed to the suppliers (small ratio), the cost
benefit of using UCC decrease as the line-haul distance increases; at this point, UCC functions as a consolidation point at the supplier side, and the small saving (if there is any) is offset by the UCC operation cost, making it less attractive. When UCC is more closed to the customer ends, the cost benefit of using UCC increase as the line-haul distance increases; this confirm the assumption that UCC should be locate relatively close to the customer in order to make profit.
However, the percentage change of energy consumption/ PM2.5 emissions is monotonously increase at a decreasing rate as UCC is closer to the customer ends, which means the benefit of UCC in terms of energy consumption/PM2.5 emission is decreasing. This is because the higher energy consumption/ emission rate with inbound heavy-duty trucks offsets the VMT saving. And the line-haul distance doesn't make much difference in terms of the energy consumption/PM2.5 emission saving.

### 5.5 Conclusions

This chapter demonstrates an alternative modeling framework with the Continuous Approximation method and the US EPA's MOVES model to examine the effectiveness of urban delivery consolidation in terms of monetary logistics cost, energy consumption and PM$_{2.5}$ emissions with respect to a number of operational (e.g., rent cost, customer demand) and policy factors (e.g., commercial vehicle size restriction in city centers). The major
finding of the study is that the potential benefit of UCC could come from either maximizing the utilization of the vehicle capacity by consolidation, or providing cheaper storage space at the UCC for its customers. It is also found that the logistics cost and the environmental impact (energy consumption and PM$_{2.5}$ emission) of UCC do not always trend in the same direction. In other words, the general belief that consolidating urban goods deliveries reduces truck trips and therefore truck VMT, congestion, and emissions does not always apply. The good news is that with proper settings and favorable conditions, UCC could achieve both monetary and environmental benefits compared to non-consolidation strategy. For example, our study suggests that UCC could work well when there is an economy of scale or high customer density. Certain value-added service at the UCC, e.g., cheap storage space for its customers, may also make UCC more attractive.

Another added benefit of UCC noted in the study is its relative flexibility in using various combination of vehicle sizes to meet the city ordinance of commercial vehicle size restriction, because UCC can perform the "break-bulk" function at the terminal so that the outbound shipments can be carried out by smaller and cleaner commercial vehicles (e.g., electrical trucks). In Europe and Japan, street designs in urban core areas require break-bulk operations before shipments enter the city, and that may explain the greater level of interest in UCC in those places. UCC could provide other value added services such as electrical vehicle charging stations for its own and even outside electrical vehicles.

It is important to keep in mind the following limitations of the analyses presented in the paper. Firstly, the paper studied the logistics cost and environmental sustainability of
UCCs, but those by no means are the only determining factors for using UCC. Many other factors are also important but beyond the scope of this study, for example, the role of government, the UCC ownership, the cultural perception of sharing resources, customer visibility, freight liability etc. Secondly, all the findings presented in the paper should be understood and interpreted within the problem settings and premises. While the trends in the findings and the conclusions should generally hold, some specific results (e.g., the tipping points) are subject to how the problem is set up and the values of the model parameters use. As noted earlier in the paper, ideally, one should carry out field observations and even surveys and/or interviews of the shippers, carriers, and customers to obtain accurate data and also assimilate real-world knowledge of the supply chain and logistics to better understand how urban freight consolidation works and to better calibrate and validate the model. For example, the rent/storage cost might be proportion to customer density, land value and the UCC-customer area distance. It would be interest to investigate additional scenarios in which rent cost varies in proportion to customer density, land value and UCC location if such data is available for parameter calibration. In reality, such luxury is rare due to financial reasons (surveys are expensive) and the proprietary nature of freight data.

For next steps, the environmental costs (energy consumption and emissions), will be considered jointly in the objective function to optimize the last mile delivery problems according to sustainability measures. We can also consider the scenario with alternative fuel vehicles in the UCC strategies. Furthermore, we can incorporate broader sets of urban freight policies and customer preferences will be incorporated in the model formulation, such as congestion pricing, delivery time window, night time delivery and
carbon cap and trade. And lastly, it is of our great interest to carry out first hand data collection in the field if all possible.
6. ECO-ROUTING PROBLEM: AN OPERATIONAL LEVEL ANALYSIS

6.1 Introduction & Literature Review

In urban areas in the U.S., good movements account for 24% of total transportation energy consumption, 30% of the total vehicle miles traveled (VMT) and 20-50% of total transportation emissions (Consulting.ICF 2005). Fuel cost contributes 39% of the operating cost for the trucking industry (The truckers report). All these factors have led to increasing effort in the trucking industry to come up with innovative energy-saving (and even emission-saving) vehicle routing strategies in recent years. They have also motivated research interests in sustainable vehicle routing problems.

Eguia et al. (2013) provided a detailed review on sustainable vehicle routing literature, in which the objective is usually to minimize the CO₂ emissions or energy consumption, typically as a function of speed. They also showed that the solutions for minimizing the CO₂ emissions might be the same as that for the shortest path problem under many circumstances. Figliozzi (2010) developed a vehicle routing with time window (VRPTW) algorithm for reducing CO₂ emissions and found that the proposed algorithm might provide significant emission savings for commercial vehicles especially in congested areas where vehicle speed was very low. However, the emission savings were not uniform because the route characteristics (e.g., speed) and other routing constraints (e.g., time window) affected CO₂ emissions differently.

There are other factors that affect vehicle emissions and energy consumption in a goods distribution tour. Arvidsson(2013) presented a load factor paradox in the urban distribution network and showed that if the truck load enforcement (i.e., minimum load
mandate) was in place in an urban area then factor restriction is in enforcement, which in

effect works as a minimum load factor threshold, then drivers had the tendency to have

the heaviest goods delivered at the last stop, which had an unintended consequence of

increasing the energy consumption and emissions compared to the same route with the

reversed visiting order. This is because energy consumption generally increases with the

vehicle load, especially for heavier trucks. Gaines et al. (2006) found that the total

energy consumed by idling trucks was more than two billion gallons per year, among

which the workday idling at customer stops dominated the energy usage. Therefore, the

idling energy consumption and emissions should not be neglected in sustainable vehicle

routing problems (VRPs).

As mentioned in Bektas and Laporte (2011), Energy based VRP model which considered

the effect of vehicle load (or in many instances the same as visiting order) and the joint

effect of vehicle load and speed is rare. Suzuki (2011) developed a VRPTW algorithm

with the objective of minimizing the distance but also considering the energy

consumption as a function of vehicle load both on the road links and at the customer sites.

The study found that the heavier items should be unloaded first and the lighter items

should be unloaded later while all at the same time minimizing the distance. By changing

the visiting order the study showed that the new routing strategy produced up to 6.9%


(CumVRP), in which the cost function is the multiple of length of the arc traveled and

the flow on this arc. An illustrative example showed that CumVRP can be used to model

the energy-minimizing VRP with a weighted load function (load multiplied by distance).

With the objective of minimizing energy consumption, Xiao et al. (2012) added the
vehicle load dependent energy consumption rate to the classical capacitated vehicle routing problem (CVRP) and solved it with the simulated annealing algorithm. They concluded that considering vehicle load in the CVRP model can reduce energy consumption by 5%.

All the studies mentioned above considered only the effect of vehicle load on energy consumption in vehicle routing. This research attempts to fill the literature gap by investigating the more realistic sustainable vehicle routing strategies by considering the joint effect of commercial vehicle load and speed on energy consumption (or CO₂ emissions) or pollutant emissions or both. Moreover, idling energy consumption and emissions at stops (due to loading and unloading at the customer’s) will also be incorporated in the optimal routing strategies.

Specifically, this chapter presents the preliminary investigation towards filling that gap. Using a numerical example we will demonstrate the complexity of optimal commercial vehicle routing based on energy consumption and/or emissions many factors (e.g., link speed, vehicle load, dwell time) often times do not work in the same direction for energy consumption and/or emissions. In addition, loading/unloading cargo weight at a customer stop will affect the vehicle load and thus the energy consumption and emissions in the rest of the route, which means the visiting order of a commercial vehicle to customers matters and makes the vehicle routing problem more complicated than the traditional shortest-path based routing. And new optimization algorithms to solving such routing problems may be in order.
This chapter is organized as follows. Section 6.2 describes the problem and the study approach followed by discussions of data source and parameter estimation. Section 6.3 presents the numerical example results followed by sensitivity analyses of a set of key factors in Section 6.4. Lastly, study conclusions are provided in Section 6.5.

6.2 Study Approach and Scenarios Setting

6.2.1 Problem Setting

Consider the following graph: suppose there are \( n \) customers with demand \( D_i (i=1,...,n) \) served by one vehicle departing and returning to the same depot \( 0 \). The customer location (coordinates) and the distance of the arc connecting from node \( i \) to node \( j \), \( L_{ij} \), \((i=0,...,n, j=0,...,n, i\neq j)\) are known. Assume that the total customer demand does not exceed the vehicle capacity – in other words, the vehicle is able to visit all the customers in one vehicle load. There are different routing options (or visiting orders) to serve the customers depending on the selected objective (i.e. distance, energy consumption, emissions, or any combination of the three). That is, for a selected route option,

(a) Total pollutant emissions are the sum of all traveled arc emissions and node idling emissions defined as follows:

\[
Emissions = \sum_{i=0}^{n} \sum_{j=0}^{n} EFL_{ij} \cdot L_{ij} \cdot x_{ij} + \sum_{i=1}^{n} EFN_i \cdot DW_i \tag{6.1}
\]

where, \( EFL_{ij} \) is the emission factor (in grams/mile) on arc \( ij \) \((i=0,...,n, j=0,...,n, i\neq j)\),

\( L_{ij} \) is the length (miles) of arc \( ij \)

\( x_{ij} = 1 \) if arc \( ij \) is visited, otherwise, \( x_{ij} = 0 \);
\[ EFN_i \] is the emission factor (grams/hr) at node \( i = 1, ..., n \);

\[ DW_i \] is the dwell time (hrs) at node \( i = 1, ..., n \)

(b) Total energy consumption is calculated in the similar fashion to the total emissions, by substituting the emission factor (in grams/mile) with energy consumption rate (in Joules/mile).

(c) Total travel distance is the sum of all visited arc lengths (in miles):

\[
distance = \sum_{i=0}^{n} \sum_{j=0}^{n} L_{ij} \cdot x_{ij}
\] (6.2)

6.2.2 Study Approach

In this preliminary investigation, the distance-based, emission-based and energy-based routing options are compared and illustrated through a numerical example, and a number of sensitivity analyses are performed on vehicle weight (a surrogate for vehicle payload), arc average speed, cargo type and network topology to examine the effects of those factors on the routing decisions.

The numerical example is adopted from Suzuki (2011) with modification. In the example, there are three customers (n=3) served by a fully loaded single-unit truck departing and returning to the same depot (D). The truck has a gross vehicle weight (GVW) of 30,000 lbs, with a curb weight of 8,000 lbs. Assume that the vehicle has 20 units of payload (the unit demand is 1,100 lbs = (30000-8000)/20). The customer demand (in units) and location (coordinates) are summarized in Table XV. The arc distance is Euclidean.
distance, and further assume the arcs are representing urban arterials with a speed of 30mph. Dwell time at each customer stop is also showed in Table XV. Detailed explanation is provided in Section 6.2.3 on how dwell time is estimated at stops.

<table>
<thead>
<tr>
<th>Place</th>
<th>ID</th>
<th>Coordinate</th>
<th>Demand(units)</th>
<th>Dwell time (hrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depot (D)</td>
<td>0</td>
<td>(1,1)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Customer1(C1)</td>
<td>1</td>
<td>(2,3)</td>
<td>8</td>
<td>2.0</td>
</tr>
<tr>
<td>Customer2(C2)</td>
<td>2</td>
<td>(4,2)</td>
<td>10</td>
<td>2.4</td>
</tr>
<tr>
<td>Customer3(C3)</td>
<td>3</td>
<td>(10,10)</td>
<td>2</td>
<td>0.6</td>
</tr>
</tbody>
</table>

The U.S. Environmental Protection Agency’s Motor Vehicle Emission Simulator (MOVES) is used to estimate the emission factors – PM$_{2.5}$ is chosen to be the pollutant in this investigation – as well as energy consumption rate as a function of both speed and vehicle weight (US EPA). There are two sets of PM$_{2.5}$ emission factors:

1) Arc emission factor, $EFL_{ij}$(grams/mile), is a function of both vehicle weight (Arcweight$_{ij}$) and arc speed($V_{ij}$), where $\text{Arcweight}_{ij} = \text{GrossVehicleWeight} - \sum_{p} \text{D}_p$, and $p$ are the nodes which have been visited before enter arc $ij$, and $\text{D}_p$ is the demand at node $p$. GrossVehicleWeight is the total vehicle weight at the start of the vehicle journey.

2) Node idling emissions, $EFN_i$ (grams/hr), is a function of the average vehicle weight at node $j$ (Nodeweight$_{i}$), where $\text{Nodeweight}_j = \text{Arcweight}_{ij} - 0.5 * \text{D}_j$. 
6.2.3 Parameter Estimation

To obtain realistic values of commercial vehicle weight/payload and speed in urban areas, we use Texas Commercial Vehicle Surveys data (Nepal et al 2007) to generate the inputs to the MOVES model summarized in Table XVI. The surveys were conducted in several counties in Texas including San Antonio, Amarillo, Valley, Lubbock and Austin during 2005 and 2006 through a vehicle information form and a daily travel log completed by the drivers or operators on an assigned day. The data set includes the trip information such as departure load factor, departure time, arrival time, location, cargo type, cargo drop-off/pick-up weight; and the vehicle information such as vehicle type, fuel type, gross weight, and odometer readings, etc. More detailed data descriptions are provided in Ruan et al (2011). This data set provides the real-world information to estimate the ranges of vehicle weight and dwell time, as well as common commercial vehicle type (single-unit truck) and commercial vehicle travel speeds on arterial streets. Two key parameters, vehicle weight and dwell time, are described in detailed next.

<table>
<thead>
<tr>
<th>Input</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analysis year</td>
<td>2013</td>
</tr>
<tr>
<td>Road type</td>
<td>Urban Unrestricted Access (arterials)</td>
</tr>
<tr>
<td>Pollutants</td>
<td>PM2.5, Energy consumption</td>
</tr>
<tr>
<td>Emission Processes</td>
<td>Running exhaust, crankcase running exhaust, brake and tire wear and tear</td>
</tr>
</tbody>
</table>
Vehicle type | Single Unit Short-haul Truck
---|---
Vehicle speed | 2.5-75 mph
Vehicle weight (source mass) | 4,000-50,000 lbs
Fuel type | Diesel

**GVW and payload**

To estimate the emission factors as a function of vehicle weight in MOVES, it is necessary to know the vehicle curb weight and payload. *Vehicle curb weight* is the total weight of a vehicle with standard equipment, all necessary operating consumables, a fuel tank of fuel, while not loaded with cargo. Gross Vehicle Weight (GVW) is the maximum vehicle operating weight specified by the manufacturer, including cargo weight. In other words, a fully loaded vehicle has the following GVW:

\[
\text{GVW} = \text{curb weight} + \text{maximum payload} \quad (6.3)
\]

According to the Texas survey data, the range of GVW is between 4,000lbs and 50,000lbs and the ratio of maximum payload to curb weight is between 0.3 and 10 for a single-unit truck with 95% confidence of interval.

**Dwell time**

Dwell time by cargo type was estimated using a linear regression model with the Texas survey data. It was found that the dwell time was highly correlated with cargo drop-off/pick-up weight at the stop:
For food & beauty products,

dwell time (hr) = 0.203 * cargo weight (× 10³ lbs) + 0.192667, with \( R^2 = 0.53 \) \( (6.4) \)

For farm products,

dwell time (hr) = 0.01 * cargo weight (× 10³ lbs) + 0.527017 with \( R^2 = 0.38 \) \( (6.5) \)

For manufacture equipment products,

dwell time (hr) = 0.103 * cargo weight (× 10³ lbs) + 0.582283 with \( R^2 = 0.42 \) \( (6.6) \)

For parcel products,

dwell time (hr) = 0.36 * cargo weight (× 10³ lbs) + 0.121537 with \( R^2 = 0.37 \) \( (6.7) \)

The numerical results to be shown in Section 6.3 are based on the dwell time estimates using Eq 6.4. A sensitivity analysis of cargo type on emissions and energy consumption is presented later in Section 6.4.3.

Finally, after all the parameters were estimated and entered into MOVES, PM\(_{2.5}\) emission factors and energy consumption rates are displayed in

**Figure 24** and **Figure 25** for the arcs and nodes respectively.

It is found that the arc energy consumption rates and PM\(_{2.5}\) emission factors are decreasing functions of vehicle speed till about 65 mph. On the other hand, they are
decreasing at first and then increasing with respect to GVW. For example, the energy consumption rate reaches the lowest around 4,000 lbs of GVW at speed of 25mph and 8,000 lbs at higher speed >30mph. The PM$_{2.5}$ emission factor reaches its minimum point at the GVW of 4,000lbs with a speed <20mph and at 8,000lbs with a speed >25mph. These findings indicate that the optimal route for energy consumption might not be optimal for PM$_{2.5}$ emissions.

The node idling energy consumption rates and PM$_{2.5}$ emission factors are convex functions of GVW; the minimum values occur at the GVW of 20,000lbs and 8,000lbs for energy consumption rate and PM$_{2.5}$ emission factor, respectively. Note that the idling emissions and energy consumption are orders of magnitude lower than those of arcs – for example, for a 8,000lbs truck, PM$_{2.5}$ emissions for an hour dwell time is 0.016 grams while the on-road PM$_{2.5}$ emissions is 10.3grams for an hour at a speed of 20mph. However, idling emissions and energy consumption may add up to an un-negligible amount especially in a congested urban area where customer density is high with large drop-off/ pick-up cargo weights and power-on (idling) is required, e.g., for perishable grocery items.
Figure 24. Arc Energy Consumptions (Joules/mile) and PM$_{2.5}$ Emission Factors (grams/mile) as a Function of GVW and Speed.
Figure 25. Node Idling Energy Consumptions (Joules/hr) and PM$_{2.5}$ Emission Factors (grams/hr) as a Function of Vehicle Weight and Speed.
6.3 Numerical Example Results

Three different visiting orders were considered in the numerical example defined in Table XV: (A) depot (0) → 1 → 3 → 2 → 0, (B) 0 → 2 → 3 → 1 → 0, and (C) 0 → 1 → 2 → 3 → 0. Route B is a reverse order of Route A, and C represents a third alternative routing strategy. Table XVII summarizes the resulting travel distance, energy consumption and PM$_{2.5}$ emissions for the three routing strategies, A, B and C.

Among all the possible routes, it is easy to see that the shortest-path visiting order should be 0-1-3-2-0 (Route A), or 0-2-3-1-0 (Route B), and the total distance is 26.03 miles. However, Route B saves 1.54% of energy consumption and 1.43% of PM$_{2.5}$ emissions from Route A. If the objective is to minimize the energy consumption, then the optimal visiting order should be 0-1-2-3-0 (Route C), with an optimal energy consumption of 5.07x10$^8$ joules. Coincidentally, Route C also represents the minimal PM$_{2.5}$ emission routing strategy of 11.87 grams. What is interesting here is that Route C has a 4.5% longer travel distance and yet it brings 5.2% of energy savings and 6.6% less PM$_{2.5}$ emissions compared to Route A. This can be explained by the different vehicle weight distribution during the route in A, B, and C.
Table XVII  NUMERICAL EXAMPLE RESULTS

<table>
<thead>
<tr>
<th>Route</th>
<th>(i,j)</th>
<th>Arc distance (miles)</th>
<th>Total route distance (miles)</th>
<th>Energy consumption ($\times 10^8$ Joules)</th>
<th>PM$_{2.5}$ (grams)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Route A</td>
<td>(0,1)</td>
<td>2.2</td>
<td><strong>26.03</strong></td>
<td>Arcs:5.32</td>
<td>Arcs:12.62</td>
</tr>
<tr>
<td></td>
<td>(1,3)</td>
<td>10.6</td>
<td></td>
<td>Nodes:0.0296</td>
<td>Nodes:0.0846</td>
</tr>
<tr>
<td></td>
<td>(3,2)</td>
<td>10.0</td>
<td></td>
<td>Total:5.35</td>
<td>Total:12.70</td>
</tr>
<tr>
<td></td>
<td>(2,0)</td>
<td>3.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Route B</td>
<td>(0,2)</td>
<td>3.2</td>
<td><strong>26.03</strong></td>
<td>Arcs:5.24</td>
<td>Arcs:12.44</td>
</tr>
<tr>
<td></td>
<td>(2,3)</td>
<td>10.0</td>
<td></td>
<td>Nodes:0.0297</td>
<td>Nodes:0.0845</td>
</tr>
<tr>
<td></td>
<td>(3,1)</td>
<td>10.6</td>
<td></td>
<td>Total:5.27</td>
<td>Total:12.52</td>
</tr>
<tr>
<td></td>
<td>(1,0)</td>
<td>2.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Route C</td>
<td>(0,1)</td>
<td>2.2</td>
<td><strong>27.2</strong></td>
<td>Arcs:5.04</td>
<td>Arcs:11.79</td>
</tr>
<tr>
<td></td>
<td>(1,2)</td>
<td>2.2</td>
<td></td>
<td>Nodes:0.0297</td>
<td>Nodes:0.0847</td>
</tr>
<tr>
<td></td>
<td>(2,3)</td>
<td>10.0</td>
<td></td>
<td>Total:5.07</td>
<td>Total:11.87</td>
</tr>
<tr>
<td></td>
<td>(3,0)</td>
<td>12.7</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
In Route C, the customer with the smallest demand (C3) is served last, which means the heavier goods are unloaded first and early so the vehicle is traveling lighter for the most part of the route than in Route A or B. Thus the arc emissions and energy consumption are lowered more than in Routes A and B – recall the increasing effect of GVW on emissions and energy consumption (at speed of 30 mph) shown in Figure 24. Note that Route C has slightly higher idling emissions because serving larger demand customers first while GVW is higher increases the idling emissions slightly than that with a lower GVW. Overall from a sustainable routing stand point of view, Route C represents the most economical (in terms of energy consumption) and environmental friendly (in terms of PM$_{2.5}$ emissions) routing strategy. The flip side is that Route C incurs longer travel distance (or time). In reality, if there is a time window constraint, the energy savings and environmental benefits may be dampened and even become negative.

### 6.4 Sensitivity Analyses

The numeric example results have demonstrated that considering vehicle weight and speed in routing can bring savings on energy consumption and/or PM$_{2.5}$ emissions. This section examines to what extent different factors may contribute to the savings by a series of sensitivity analyses defined in Table XVIII. Using Route A as a base, each analysis calculates the percent changes of distance, energy consumption and PM$_{2.5}$ for Routes B and C, respectively, from Route A. A positive value indicates that route A is preferable and a negative value demonstrates Route B or Route C brings savings.
### Table XVIII  SUMMARY OF THE SCENARIOS IN SENSITIVITY ANALYSIS

<table>
<thead>
<tr>
<th>Factors</th>
<th>Test value</th>
<th>Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gvw (lbs)</td>
<td>8k, 16k, 30k, 45k</td>
<td>4.1</td>
</tr>
<tr>
<td>Weight ratio (payload/curb weight)</td>
<td>0.5, 1, 2.75, 5</td>
<td></td>
</tr>
<tr>
<td>Constant speed across arcs (mph)</td>
<td>5, 10, 20, 30, 40, 55, 70</td>
<td>4.2.1</td>
</tr>
<tr>
<td>Variant speed across arcs (mph)</td>
<td>Various speed profiles representing various traffic conditions</td>
<td>4.2.2</td>
</tr>
<tr>
<td>Cargo type (or dwell time)</td>
<td>Farm, manufacturing, food, parcel</td>
<td>4.3</td>
</tr>
<tr>
<td>Gvw (lbs)</td>
<td>16k, 30k, 45k</td>
<td></td>
</tr>
</tbody>
</table>

#### 6.4.1 Effect of Gvw and Weight Ratio

This section tests the percentage changes of energy consumption and PM$_{2.5}$ emissions for Routes B and C, respectively, from Route A by Gvw and weight ratio (defined as payload/curb weight). For the same Gvw, a larger weight ratio means a larger payload.

**Table XIX** and **Table XX** summarize the percentage changes. As expected, Route C generally has higher energy and emissions savings from Route A than Route B. For a given weight ratio, more savings are resulted for heavier Gvw for both B and C. For Gvw greater than 16,000 lbs, larger weight ratios render more energy and emissions savings on both B and C; less than 16,000 lbs, both B and C actually have worse energy and emissions performance than A. Such a pattern can be explained by the similar
pattern in the idling energy consumption and emissions shown in Figure 25. In general, heavier vehicles with larger initial payloads can benefit more from the sustainable routing strategies which incorporate the effect of vehicle weight.

Table XIX  EFFECT OF GVW AND WEIGHT RATIO: PERCENTAGE CHANGE FROM ROUTE A TO B

<table>
<thead>
<tr>
<th>Percentage change (B-A)%</th>
<th>GVW (lbs)/Weight ratio</th>
<th>8,000</th>
<th>16,000</th>
<th>30,000</th>
<th>45,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy consumption</td>
<td>0.5</td>
<td>0.17%</td>
<td>-0.39%</td>
<td>-0.54%</td>
<td>-0.84%</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>0.25%</td>
<td>-0.30%</td>
<td>-0.81%</td>
<td>-1.35%</td>
</tr>
<tr>
<td></td>
<td>2.75</td>
<td></td>
<td>-0.19%</td>
<td>-1.60%</td>
<td>-1.74%</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td></td>
<td>-2.10%</td>
<td>-2.03%</td>
<td></td>
</tr>
<tr>
<td>PM₂.₅</td>
<td>0.5</td>
<td>0.02%</td>
<td>-0.51%</td>
<td>-0.51%</td>
<td>-0.75%</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>0.04%</td>
<td>-0.52%</td>
<td>-0.71%</td>
<td>-1.16%</td>
</tr>
<tr>
<td></td>
<td>2.75</td>
<td></td>
<td>-0.49%</td>
<td>-1.61%</td>
<td>-1.53%</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td></td>
<td>-2.29%</td>
<td>-1.80%</td>
<td></td>
</tr>
</tbody>
</table>
Table XX  EFFECT OF GVW AND WEIGHT RATIO: PERCENTAGE CHANGE 
FROM ROUTE A TO C

<table>
<thead>
<tr>
<th>Percentage change (C-A)%</th>
<th>GVW (lbs)/ Weight ratio</th>
<th>8,000</th>
<th>16,000</th>
<th>30,000</th>
<th>45,000</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Energy consumption</strong></td>
<td>0.5</td>
<td>5.83%</td>
<td>2.68%</td>
<td>0.14%</td>
<td>-2.12%</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>6.48%</td>
<td>3.41%</td>
<td>-2.64%</td>
<td>-4.95%</td>
</tr>
<tr>
<td></td>
<td>2.75</td>
<td>7.10%</td>
<td>-3.90%</td>
<td>-9.67%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>-1.25%</td>
<td>-9.69%</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>PM2.5</strong></td>
<td>0.5</td>
<td>4.69%</td>
<td>1.55%</td>
<td>0.41%</td>
<td>-1.25%</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>4.78%</td>
<td>1.52%</td>
<td>-3.00%</td>
<td>-4.09%</td>
</tr>
<tr>
<td></td>
<td>2.75</td>
<td>3.06%</td>
<td>-6.85%</td>
<td>-10.26%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>-6.05%</td>
<td>-12.10%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

6.4.2 Effect of Speed

6.4.2.1 Constant Speed across Arcs

In this section, vehicle speed is assumed constant across all arcs in the graph and its value varies from 5mph to 70 mph. The percentage changes (B from A and C from A respectively) are shown in Figure 26. The trends are similar in both cases. That is, increasing energy consumption savings are gained when speed goes up from 5 mph till around 20 to 30 mph; then the savings drop slightly until around 40mph and go up again afterwards. This seems to indicate that, road traffic being equally good or bad, more
Energy savings can be expected on congested urban roadways as well as on highways with the new sustainable routing strategies. PM$_{2.5}$ emissions savings display the similar trend to that of energy consumption at lower speed (between 5 and 30mph) but then continuously decrease at higher speeds. These findings suggest that the optimal routing speeds for minimizing PM$_{2.5}$ emissions and energy consumption may be different.

![Figure 26. Sensitivity on Speed Bin.](image-url)
6.4.2.2 Variant Speed Across Arcs

Table XXI defines three speed profiles where different traffic conditions (congested versus uncongested, highways versus urban arterials) could be encountered during the vehicle's journey. Table XXII summarizes the percentage change results between Routes B and A and Routes C and A.

In Profile 1, Routes A and B have the exact same arc speeds but in the reverse directions - recall that Route B is in the reverse visiting order of Route A; and Route C has a very low speed arc (3,0), which has the longest travel distance than any other arcs in Route A, B, or C. As a result, Route C actually has higher energy consumption and PM$_{2.5}$ emissions compared to Route A.

In Profile 2, three of the four arcs in Route A have very low speeds (congested); Route B has considerably much higher speeds (highway speeds) than those in Route A and the heaviest arc in Route B (0,2) has the highest speed among all arcs; Route C also has better speed performance than Route A albeit not as high speeds as Route B. What we see now is that both Routes B and C display significant savings in energy and PM$_{2.5}$ emissions over Route A.

In Profile 3, now Route A has much higher speeds than Route B and arc speeds on Route C are comparable to those on Route A. As a result, Route B has the worst energy and emissions performance among the three routes and Route C also has higher energy consumption and emissions than Route A likely due to the low speed on the longest arc (3,0).
To summarize, the one thing that is clear in this analysis is that speed greatly impacts energy consumption and emissions and low speeds seem to have the greater impact, causing higher energy consumption and emissions.

Table XXI  VARIANT SPEED PROFILES

<table>
<thead>
<tr>
<th>Route</th>
<th>link</th>
<th>Speed profile (mph)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Profile 1</td>
</tr>
<tr>
<td>A</td>
<td>(0,1)</td>
<td>32</td>
</tr>
<tr>
<td>A</td>
<td>(1,3)</td>
<td>14</td>
</tr>
<tr>
<td>A</td>
<td>(3,2)</td>
<td>68</td>
</tr>
<tr>
<td>A</td>
<td>(2,0)</td>
<td>73</td>
</tr>
<tr>
<td>B</td>
<td>(0,2)</td>
<td>73</td>
</tr>
<tr>
<td>B</td>
<td>(2,3)</td>
<td>68</td>
</tr>
<tr>
<td>B</td>
<td>(3,1)</td>
<td>14</td>
</tr>
<tr>
<td>B</td>
<td>(1,0)</td>
<td>32</td>
</tr>
<tr>
<td>C</td>
<td>(0,1)</td>
<td>32</td>
</tr>
<tr>
<td>C</td>
<td>(1,2)</td>
<td>33</td>
</tr>
<tr>
<td>C</td>
<td>(2,3)</td>
<td>68</td>
</tr>
<tr>
<td>C</td>
<td>(3,0)</td>
<td>8</td>
</tr>
</tbody>
</table>
Table XXII  SENSITIVITY OF SPEED

<table>
<thead>
<tr>
<th>Speed profile</th>
<th>Percentage change B-A</th>
<th>Percentage change C-A</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Energy</td>
<td>PM$_{2.5}$</td>
</tr>
<tr>
<td>Profile 1</td>
<td>-2.35%</td>
<td>-4.71%</td>
</tr>
<tr>
<td>Profile 2</td>
<td>-65.82%</td>
<td>-71.52%</td>
</tr>
<tr>
<td>Profile 3</td>
<td>116.24%</td>
<td>157.49%</td>
</tr>
</tbody>
</table>

6.4.3 Effect of Cargo Type (or Dwell Time)

As described in section 6.2.3, dwell time is a linear function of the drop-off/pickup cargo weight at the customer locations for different cargo types. The cargo unit service times ($\times 10^3$lbs/hr), i.e., the coefficients in the linear models Eq. 4-7, vary between from 0.01 (farm products) to 0.36 (parcels). Using the cargo unit service time for food and beauty products as the baseline, a term called cargo service ratio is introduced to measure the cargo unit service time ratio between a specified type of cargo and the baseline cargo type. Cargo service ratio reflects the relative loading/unloading speed, which is affected by the cargo characteristics such as packaging method and value-to-weight ratio. As such, farm products have a cargo service ratio of 0.05, manufactured goods 0.51, and parcels 1.77. In other words, parcels have the longest unit service time among the four cargo types considered and farm products have the least unit service time.

Table XXIII shows the following results for Route C: percent idling emissions of the total PM$_{2.5}$ emissions, and the percentage changes of energy consumption and PM$_{2.5}$ emissions from route A. By varying the GVW from 16000 to 45000 lbs while keeping
the weight ratio (Payload-to-curb-weight ratio) constant at 2.75, it represents the different demand levels are served.

As expected, the higher the cargo service time the higher the idling emissions in percentage share. Both the energy and PM$_{2.5}$ emissions savings on Route C go down very slightly from farm products to parcels in an ascending order of cargo service ratio. But overall because both the idling emissions and energy consumptions account for a very small portion of the total quantities as already discussed earlier, the effect of cargo type (or dwell time) is very small (to the second decimal point in the percentage changes).

<table>
<thead>
<tr>
<th>Cargo type</th>
<th>GVV</th>
<th>Weight ratio</th>
<th>Cargo service ratio</th>
<th>% node idling emissions</th>
<th>percentage change from A: C-A</th>
<th>Energy</th>
<th>PM$_{2.5}$</th>
<th>energy</th>
<th>PM$_{2.5}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Farm</td>
<td>16000</td>
<td>2.75</td>
<td>0.05</td>
<td>0.17%</td>
<td>0.19%</td>
<td>7.11%</td>
<td>3.07%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Farm</td>
<td>30000</td>
<td>2.75</td>
<td>0.05</td>
<td>0.18%</td>
<td>0.20%</td>
<td>-3.92%</td>
<td>-6.88%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Farm</td>
<td>45000</td>
<td>2.75</td>
<td>0.05</td>
<td>0.18%</td>
<td>0.21%</td>
<td>-9.72%</td>
<td>-10.32%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manufactured</td>
<td>16000</td>
<td>2.75</td>
<td>0.51</td>
<td>0.29%</td>
<td>0.34%</td>
<td>7.10%</td>
<td>3.06%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manufactured</td>
<td>30000</td>
<td>2.75</td>
<td>0.51</td>
<td>0.39%</td>
<td>0.45%</td>
<td>-3.91%</td>
<td>-6.86%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manufactured</td>
<td>45000</td>
<td>2.75</td>
<td>0.51</td>
<td>0.49%</td>
<td>0.56%</td>
<td>-9.69%</td>
<td>-10.29%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Food</td>
<td>16000</td>
<td>2.75</td>
<td>1</td>
<td>0.29%</td>
<td>0.34%</td>
<td>7.10%</td>
<td>3.06%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Food</td>
<td>30000</td>
<td>2.75</td>
<td>1</td>
<td>0.49%</td>
<td>0.57%</td>
<td>-3.92%</td>
<td>-6.85%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Food</td>
<td>45000</td>
<td>2.75</td>
<td>1</td>
<td>0.69%</td>
<td>0.80%</td>
<td>-9.67%</td>
<td>-10.26%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Parcels</td>
<td>16000</td>
<td>2.75</td>
<td>1.77</td>
<td>0.45%</td>
<td>0.52%</td>
<td>7.09%</td>
<td>3.06%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>---------</td>
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<td>-------</td>
<td>-------</td>
<td>-------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Parcels</td>
<td>30000</td>
<td>2.75</td>
<td>1.77</td>
<td>0.80%</td>
<td>0.94%</td>
<td>-3.89%</td>
<td>-6.83%</td>
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</tr>
<tr>
<td>Parcels</td>
<td>45000</td>
<td>2.75</td>
<td>1.77</td>
<td>1.15%</td>
<td>1.34%</td>
<td>-9.63%</td>
<td>-10.21%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### 6.5 Conclusions

Using a numerical example, this chapter has demonstrated the noticeable (joint) effects of vehicle payload, vehicle speed, and dwell time on urban commercial vehicle emissions and energy consumption. For example, heavier vehicles with larger initial payloads can benefit more from the sustainable routing strategies which incorporate the effect of vehicle weight, and low speeds have the greater impact than high speeds, causing higher energy consumption and emissions. The analysis results have indicated that the vehicle payload and speed could affect the visiting order of a distribution tour if minimizing the energy consumption or emissions is the objective. Idling energy consumption/emissions at stops, although considerably low compared to on-road energy consumption/emissions, may not be ignored especially in congested urban areas where customer density is high with large drop-off/pick-up cargo weights and other special requirements are in place at the customer's (e.g., engine on to operate the refrigerator).

As an ongoing research effort, the research team at the University of Illinois-Chicago is currently working on the formulation of a new kind of sustainable CVRP problem which considers energy consumption/emissions as a function of, in addition to vehicle speed, vehicle weight (or payload) on links/arcs and nodes as well as vehicle dwell time. In
future research, other variations such as time window constraint and loading activities at the customers during the same route (which is also related to the capacity constraint) need to be incorporated. It is also necessary to test the new routing algorithms on selected real-world goods distribution cases based on real-world data.
7 CONCLUSION AND FUTURE WORK

7.1 Summary of Major Findings and Policy Implications

This research work has shed light on three areas of urban freight modeling:

First, the empirical efficiency study using the Texas Commercial Vehicle Survey data has compared the efficiency performance by tour pattern and commodity type. These findings have provided a better understanding of how urban commercial vehicles operate in the last-mile distribution. For example, efficiency comparison between the direct and the peddling pattern suggests that direct tours seem to be better suited with goods and service which require longer dwell time at a stop. Tours delivering construction materials might generate more pollutant for its higher annual mileage and higher emission rate than other commodities, although its trip level utilization (load factor) is higher and are typically conducted in direct shipping. The food distribution tours are generally more time sensitive and the goods are hard to handle than manufactured products; also they are underutilized for their low load factors.

In the second study of sustainable urban delivery consolidation strategies, we have demonstrated a cost-and-benefit analysis framework for Urban Consolidation Center (UCC), using a coupling of a modified Continuous Approximation modeling approach and the US EPA’s MOVES model, to examine what and how various factors are at work in UCC between the trade-offs of monetary logistics cost, energy consumption and PM\textsubscript{2.5} emissions. These factors are operational (e.g., rent cost, customer demand) and policy related (e.g., commercial vehicle size restriction in city centers). The major finding of the study is that the potential benefit of UCC could come from either maximizing the
utilization of the vehicle capacity by consolidation, or providing cheaper storage space at
the UCC for its customers. It is also found that the logistics cost and the environmental
impact (energy consumption and PM$_{2.5}$ emission) of UCC do not always trend in the
same direction. In other words, the general belief that consolidating urban goods
deliveries reduces truck trips and therefore truck VMT, congestion, and emissions does
not always apply. The good news is that with proper settings and favorable conditions,
UCC could achieve both monetary and environmental benefits compared to non-
consolidation strategy. For example, our study suggests that UCC could work well when
there is an economy of scale or high customer density. Certain value-added service at the
UCC, e.g., cheap storage space for its customers, may also make UCC more attractive.
Another added benefit of UCC noted in the study is its relative flexibility in using various
combination of vehicle sizes to meet the city ordinance of commercial vehicle size
restriction, because UCC can perform the "break-bulk" function at the terminal so that the
outbound shipments can be carried out by smaller and cleaner commercial vehicles (e.g.,
electrical trucks). In Europe and Japan, street designs in urban core areas require break-
bulk operations before shipments enter the city, and that may explain the greater level of
interest in UCC in those places. UCC could provide other value added services such as
electrical vehicle charging stations for its own and even outside electrical vehicles.

Thirdly, at the operational level, this research has demonstrated the noticeable (joint)
effects of vehicle payload, vehicle speed, and dwell time on urban commercial vehicle
emissions and energy consumption via a numerical example. For example, heavier
vehicles with larger initial payloads can benefit more from the sustainable routing
strategies which incorporate the effect of vehicle weight, and low speeds have the greater
impact than high speeds, causing higher energy consumption and emissions. The analysis results have indicated that the vehicle payload and speed could affect the visiting order of a distribution tour if minimizing the energy consumption or emissions is the objective. Idling energy consumption/emissions at stops, although considerably low compared to on-road energy consumption/emissions, may not be ignored especially in congested urban areas where customer density is high with large drop-off/pick-up cargo weights and other special requirements are in place at the customer's (e.g., engine on to operate the refrigerator).

7.2 Direction for Future Work

On the urban consolidation part, the next step is to consider the environmental costs (energy consumption and emissions) jointly in the objective function to optimize the last mile delivery problems according to sustainability measures. It is also interested to include scenarios such as considering rent/storage cost as a function of customer density, land value and UCC location, or using alternative fuel vehicle/push carts for UCC tour portion, which is popular with new types of UCC serves small and high density customer area. Furthermore, broader sets of urban freight policies and customer preferences will be incorporated in the model formulation, such as congestion pricing, time window restrictions (i.e. night time delivery) and carbon cap and trade.

At the operational level, a new line of VRP research called pollution routing problems (PRP) is emerging (e.g., Bektas and Laporte 2011). In PRP, routing strategies are jointly determined by distance/travel time, energy consumption and/or emissions. In particular, energy consumption and emissions are affected not only by vehicle speed but also vehicle
load during routing, which has not been considered in the traditional VRP. As a result, new types of VRP model formulation are being developed.

Furthermore, the research team at the University of Illinois-Chicago is currently investigating the so-called Dynamic Pollution-Routing Problem (DPRP), a coupling of Dynamic Vehicle Routing Problem (DVRP) and Pollution-Routing Problem (PRP) as referred to in the literature. DPRP takes into account not only the vehicle operational cost (due to travel time), but also the environmental cost including fuel cost and emission cost associated with a dynamic vehicle routing scheme in which new customer demand is introduced during routing. In DPRP, fuel cost is a function of both vehicle speed and load distribution on the route. Mathematical models and algorithms for the base DPRP with or without time window constraints have been developed. Several variants of DPRP are under investigation, including incorporating microscopic traffic flow models in representing the dynamics of traffic conditions and speed in routing, incorporating the travel time uncertainties in routing, and considering a mixed vehicle fleet composition in routing, etc.

Lastly, it is always important and of the research communities’ great interest to carry out first hand data collection in the field if all possible. 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. With the availability of probe data (or other types of survey data), we can have better understanding the urban freight behaviors. Applications such as echo driving, which provides freight drivers with real-time information based on signal phase and timing of
upcoming intersection, traffic, and road weather conditions so they can make decision about their driving behavior, will help to promoting a driving style that lowers vehicle emission as well as fuel consumption.
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