Freight Tricycle Operations in New York City

Final Report

October 2014

Report Number 14-33

Energy. Innovation. Solutions.

New York State Department of Transportation

Freight Tricycle Operations in New York City

Final Report

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NYSERDA Report 14-33

NYSERDA Agreement Number 25736
NYSDOT Task Assignment C-11-11
PIN R021.77.881

October 2014

DOT Form

1. Report No. C-11-11	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Freight Tricycle Operations in New York City		5. Report Date October 2014 6. Performing Organization Code
7. Author(s) Alison Conway, Camille Kamga, Jialei Cheng, Penny Eickemeyer, Quanquan Chen, Abhishek Singhal		8. Performing Organization Report No 14-33.
9. Performing Organization Name and Address The City College of the City University of New York Department of Civil Engineering 140th St. and Convent Avenue Steinman Hall, Room T-119 New York, NY 10031	University Transportation Research Center The City College of New York 138th St. and Convent Ave. Marshak Hall, Suite 910 New York, NY 10031	10. Work Unit No. 11. Contract or Grant No. NYSERDA Contract 25736
12. Sponsoring Agency Name and Address New York State Energy Research and Development Authority (NYSERDA) 17 Columbia Circle Albany, NY 12203	New York State Department of Transportation (NYSDOT) 50 Wolf Road Albany, NY 12232	13. Type of Report and Period Covered Final Report 4/2012-10/2014 14. Sponsoring Agency Code
15. Supplementary Notes: Project funded in part with funds from the Federal Highway Administration.		

16. Abstract

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17. Key Words	18. Distribution Statement		
Bicycle travel; Delivery vehicles; GPS data; Last-mile delivery; Logistics; Urban goods movement	No Restrictions		
19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	190	

Form DOT F 1700.7 (8-72)

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Abstract

As cities become more congested and increasingly focused on sustainability, cargo cycles offer a potential alternative to motorized vehicles for local and last-mile goods delivery. However, few studies have examined this mode in the North American context. This project seeks to address this existing gap in research on cargo cycles/freight tricycles in North America and in New York City (NYC). The goals of this project are: (1) to understand the potential commodities moved and sectors served by cargo cycles; (2) to identify the expected benefits, challenges, and barriers to operation for cargo cycles operating in NYC; (3) to understand freight tricycle traffic performance in NYC conditions; and (4) to understand the capability of cargo cycles for use in cold chains – such as food and pharmaceutical delivery – that require temperature control.

Keywords

Bicycle travel; Delivery vehicles; GPS data; Last-mile delivery; Logistics; Urban goods movement

Acknowledgments

The research team would like to acknowledge the efforts of many people who provided vital assistance in completion of this project. First, thank you to the project managers, Bob Ancar of the New York State Department of Transportation and Joe Tario of the New York State Energy Research and Development Authority, for continued guidance over the course of the project. Thanks to Gregg Zuman, Helen Zuman, and Julian Isaza of Revolution Rickshaws who provided critical advice regarding current freight tricycle operations and operators in New York City and who worked with the research team to determine the best method of GPS device installation. The research team greatly appreciates the efforts of both City Bakery and City Harvest, first for agreeing to participate in case study evaluations and then for providing ongoing information as new challenges emerged; thanks especially to the following individuals from these partner companies who contributed considerable time and information: Kyle Clifford, Allison Dees, Zachary McCullough, Alberto Oyola, and Maury Rubin. The research team would also like to acknowledge the efforts of Emmanuelle Lezais, who contributed to this project while completing an internship at the University Transportation Research Center in summer 2012, and Rianna Yuen, who contributed as an undergraduate research assistant.

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1 Introduction

Cities depend on safe and efficient goods movement to support community livability and a healthy economy. However, delivery of goods in an urban environment presents a tremendous challenge. Traditional motorized vehicles used for goods movement – ranging from cargo vans to box trucks – are inherently incompatible with the multimodal street environments of modern cities, with clean, quiet conditions preferred by residents, and with larger environmental sustainability goals. As freight flows continue to grow with the demands of global trade, new urban freight and city logistics solutions are needed. Cargo cycles offer one potential solution to replace large motorized vehicles in dense urban areas. Although these vehicles have recently proliferated in large European cities, their performance in the U.S. context is not yet well understood.

Cargo cycles are two or three-wheeled vehicles that are operated fully with human power or with an electric-assist. Freight tricycles are cargo cycles with three wheels. Distinct from simple passenger bicycles and tricycles, they are equipped to transport goods in an open or closed container or in a flatbed. These vehicles can be used to carry a large range of small commodities over short distances. While freight-carrying bicycles and tricycles have been in use in western countries since the 1800s (Basterfield 2011), they have received little recognition as an independent transportation mode. However, in recent years, they have gained traction in both Europe and the U.S. due to the fact that they demonstrate a number of characteristics desirable for operation in modern cities. They produce no local emissions, occupy little space for moving and parking, and operate at limited speeds friendly to pedestrians and bicycles. Although cargo cycles are in use in cities throughout the U.S., comprehensive studies of their operations have been conducted almost exclusively in Europe.

This project aims to provide a better understanding of cargo cycle performance in New York City and to inform the decision making of local freight stakeholders, including shippers, carriers, and public authorities. This project also seeks to address an existing gap in research on cargo cycles/freight tricycles in North America and in New York City. The goals of this project are to:

1. Understand the potential commodities moved and sectors served by cargo cycles.
2. Identify the expected benefits, challenges, and barriers to operation.
3. Understand freight tricycle traffic performance in NYC conditions.
4. Understand the capability of cargo cycles for use in cold chains – such as food and pharmaceutical delivery – that require temperature control.

To accomplish the first two aims, a number of tasks have been completed. First, a comprehensive review of European experience was conducted to identify lessons learned, expected impacts, and factors influencing successful implementation. Next, an original survey of North American carriers was conducted in summer 2012; eight operators from the United States and Canada participated in the survey. Finally, a review of the New York City market for cargo cycles was also completed.

To accomplish the third aim, this report presents the results from case studies of two local New York City cargo cycle operators. City Bakery, a small chain of "green" bakeries, uses freight tricycles primarily to carry goods between its multiple locations. City Harvest, a nonprofit food rescue organization, uses freight tricycles to pick up small donations from local retail and restaurant locations and deliver them to local food programs. Researchers first conducted detailed interviews with each operator. Each company's operations were then monitored for approximately two months using a GPS tracking device; for City Harvest, the company's delivery trucks were also tracked. This GPS data was then processed and analyzed to compare the two vehicle types using three performance measure categories: corridor moving speed, trip travel time and stopped-time delay, and stop durations.

Cargo cycle operations were also compared to motorized vehicle operations to evaluate space and emissions impacts. Vehicle dimensions for cargo cycles and a number of common urban delivery vehicles were examined to discuss the parking and road space implications of cargo cycle implementation. Emissions factors for these common delivery vehicles were estimated using the United States Environmental Protection Agency's (EPA's) Motor Vehicle Emission Simulator (MOVES) Model, with consideration for a number of variables, including vehicle type, fuel type, vehicle age, speed, temperature, and humidity. Emissions factors for carbon dioxide (CO_2) were estimated to examine greenhouse gas emissions; factors were also estimated for particulate matter (PM) 2.5 and 10 to evaluate air pollution impacts.

To accomplish the fourth aim, a comprehensive review of temperature control requirements for movement of sensitive goods was conducted. A detailed review of available temperature control technologies – ranging from simple ice to mechanical systems – was also completed. Each technology is evaluated to identify its suitability for transporting temperature sensitive goods via cargo cycle.

The following report summarizes findings from each project stage and discusses conclusions regarding the potential for broad implementation of freight tricycles in New York City.

2 The Context for Urban Freight in New York City

2.1 Urban Freight Challenges

With greater lengths, widths, and wheelbases than passenger vehicles, freight vehicles generally require wide lanes and large turning radii. These characteristics are incompatible with short crossing distances required for safe pedestrian movements. Accidents between freight vehicles and pedestrians and bicyclists – particularly those that occur due to truck blind spots – are extremely dangerous for the nonmotorized travelers. A comprehensive study of bicycle accidents in New York City found that large vehicles contributed to more than 30 percent of traffic fatalities despite constituting only between 5 and 17 percent of the vehicle population (Nicaj et al. 2006). Maclean and Graham (1996) found the same result to be true for accidents involving bicycles and heavy goods vehicles in the UK. Studies in Ohio (Moore et al. 2011), Japan (Enomoto and Akiyama, 2005), and New Zealand (Atkinson and Hurst 1983) also found that accidents between trucks and bicycles in urban areas are relatively frequent and often fatal. Bassock et al. (2013) suggest that both truck drivers and nonmotorized users would prefer to operate on separate facilities. However, provision of these is difficult when space is constrained; even when separate spaces are designated in theory, separation is difficult in practice. Conway et al. (2013) identified frequent obstruction of bicycle lanes by freight and other motorized vehicles in New York City. Freight vehicles also require large areas (on-street or off-street) for parking and loading. When space is unavailable, vehicles park in travel lanes, increasing congestion and becoming a safety hazard (OECD 2003).

In addition to affecting traffic and safety, urban freight operations have a number of environmental impacts; Browne et al. (2007) and Giuliano and Dablanc (2013) provide a summary of these operations. Impacts affecting the environment include nonrenewable energy use, production of air pollutants – including carbon monoxide, nitrous oxides, sulfur dioxide, volatile organic compounds and particulates, production of greenhouse gases, and generation of noise. Pollutant and greenhouse gas emissions are directly related to fuel consumption, as both air pollutants and greenhouse gas emissions result from fuel combustion. Heavy vehicles generally achieve worse fuel economies than lighter vehicles. When congestion is high and when delivery stops are frequent – as is the case in most urban delivery operations – rates are considerably higher than in free flowing conditions. While impacts are extremely sensitive to vehicle, traffic, and local environmental variables, Schoemaker et al. (2006) and Browne and Goodchild (2013) summarize findings from a number of quantitative evaluations from Europe and the U.S.

A number of jurisdictions have sought to limit freight externalities through policy implementations. Giuliano and Dablanc (2013) identified a number of approaches employed in the U.S. and Europe to reduce freight externalities; these include increasing standards for emissions and fuel economy; low emissions zones; incentives for fleet turnover to electric and other clean modes; efforts to shift freight to rail, transit, and nonmotorized modes; incentives to convert fleets to clean alternative fuels; and community environmental mitigation. However, as many authors have noted, efforts to influence freight vehicle choices and delivery behavior are often constrained by supply chain realities (Giuliano and Dablanc 2013, Holguin-Veras et al. 2012; Lindholm 2012; Quak and de Koster 2009; and Dablanc 2007). Policies designed without consideration for these constraints will be ineffective or will negatively impact freight productivity. For example, Browne and Goodchild (2013) note that low-emission zones can impose vehicle replacement and retrofitting costs on some vehicle operators, which increase transportation costs for stakeholders, and that implementation may lead to vehicle detours that simply shift the problem beyond defined zones. As noted by Cherrett et al. (2012), inadequate consideration for supply chain constraints often result from a lack of available data to understand freight operations. Cities generally collect little information on urban goods movements beyond traffic counts, which provide no information on trip origins and destinations, commodities, or downstream supply chains.

The already substantial challenge to balance urban policy aims and industry needs is being exacerbated by simultaneous changes in local government priorities and supply chain organization. Cities around the world aim to enhance urban sustainability by replacing motorized vehicle trips with use of non-motorized modes and public transportation (Giuliano and Dablanc, 2013). In the U.S., according to the National Complete Streets Coalition, Complete Streets Policies have been implemented rapidly by 610 jurisdictions in the US – including 27 states (as well as the District of Columbia and Commonwealth of Puerto Rico), 51 regional planning organizations, 48 counties, and 482 municipalities (Smart Growth America 2014). While by definition these policies are intended to meet the needs of all road users, the first priority of these policies is to enhance multimodal safety (New Jersey Bicycle and Pedestrian Resource Center 2013). In practice, implementations usually result in infrastructure designs, speeds, and space allocations that favor nonmotorized and transit modes at the expense of lost accessibility for freight vehicles and passenger cars. This lost accessibility does not come without an economic cost; Weisbrod and Fitzroy (2008) provide a comprehensive summary of the economic impacts of lost accessibility on supply chain stakeholders.

At the same time that infrastructure is becoming increasingly inhospitable, lengths and frequencies for urban delivery trips are increasing. Demand is being driven not only by population and business growth (Miodonski and Kawamura 2012), but also by a supply chain reorganization. In general, globalization had led to greater concentration of production activities in supply chains; fewer producers are distributing larger volumes of goods across longer distances (OECD 2003). These concentrated supply chains require considerable space for warehousing and distribution. As cities become dense and land values increase, space becomes sparse and expensive. Expensive land and the need for accessibility to global supply chains drive freight activities to the periphery of a metropolitan area (Cidell 2010 and 2011, Leigh and Hoelzel 2012, Rodrigue 2013). Suburban and exurban warehousing locations necessitate long trips for final delivery (Allen, Browne, and Cherret 2012; Dablanc and Ross 2012). The same high land values that push warehousing to the periphery also discourage retailers from holding large values of stock in storage. This leads businesses to shift to just-in-time delivery models that require frequent deliveries (Holguin-Veras et al. 2012). These shifts in traditional supply chains are further complicated by the growth of e-commerce, which has vastly increased demand for direct-to-home delivery of a broad range of goods (OECD 2003).

2.2 City Logistics

Recognition of the great challenge to ensure efficient goods movement while limiting externalities has led to the emergence in recent decades of a new field of study and practice called city logistics. Rodrigue and Dablanc (2013) define city logistics as:

> the means over which freight distribution can take place in urban areas as well as the strategies that can improve its overall efficiency while mitigating congestion and environmental externalities; it includes the provision of services contributing to efficiently managing the movements of goods in cities and providing innovative responses to customer demands.

A broad range of city logistics experiments and implementations have been conducted, primarily in Europe, in recent decades; Wolpert and Reuter (2012) provide a comprehensive summary and analysis of research in the field. Melo and Macharis (2011) bring together contributions from a number of experts to summarize needs and practices and present example case studies. Gonzalez-Feliu et al. (2014) also gather perspectives from a broad range of expert stakeholders, and provide guidance on methodological approaches to applied research. Two large European Union-funded projects – the Best Urban Freight Solutions (BESTUFS) project and the Sustainable Urban Goods Logistics Achieved by Regional and Local Policies (SUGAR) project – have produced comprehensive best-practices guidance. Giuliano and Dablanc (2013) performed a comprehensive transatlantic review of urban freight management strategies and examined their applicability in the U.S. From U.S. and European practice, these authors identified five types of approaches relevant to operations in the urban core including traffic and parking regulations; local planning policies; off hour-deliveries; voluntary certification/recognitions schemes (some of which provide benefit to carriers); and consolidation.

2.3 Freight in Manhattan

2.3.1 Current Conditions

The Manhattan Borough of New York City – one of the most challenging environments for urban freight operations in the U.S. – has a tremendous need for implementation of city logistics solutions. According to Holguin-Veras et al. (2011), more than 110,000 freight deliveries are made to businesses and residences in Manhattan daily. The drivers conducting these deliveries face extremely difficult conditions. According to the 2011 TTI Urban Mobility report, drivers in New York City daily face close to seven hours of congested traffic (Lomax, Schrank, and Eisele 2012). The global warehousing trends discussed previously have also impacted the New York City region, where large, multifunctional warehouses are primarily located across the Hudson River from Manhattan in New Jersey, which unlike the rest of the region offers good connectivity to rail networks (NYMTC 2001). John F. Kennedy International Airport (JFK), the nation's largest gateway for air cargo, is located in Queens, on the opposite side of the East River from Manhattan (USDOT 2009). With limited options for crossing both rivers, trucks have few options to bypass congestion. Once in the borough, trucks continue to face challenging conditions. In some areas, including far downtown Manhattan, vehicles must navigate extremely narrow streets with tight turning radii. Recent infrastructure changes have further limited accessibility; since 2006, bus-only lanes to support express bus services, pedestrian improvements such as intersection bulbouts, close to 100 lane-miles of bicycle infrastructure, and more than 300 bikeshare stations – some of which are off-street but some of which are in curbside lanes – have been installed. Many of these installations have resulted in lost parking and/or narrowing of motor vehicle lanes and turning radii. In their "2008 Congestion Survey," Baruch College researchers identified complaints from commercial vehicle operators concerned about parking losses due to the recent proliferation of bike lanes in NYC (Morris 2009).

In a study of parking demand in Manhattan, Jaller, Holguin-Veras, and Hodge (2013) concluded that in a number of zip codes, demand for truck parking already exceeds available spaces. The authors note that this is partially due to zoning; in 1982, parking requirements for new development were replaced with parking maximums in an attempt to discourage passenger motor vehicle use. Morris (2009) also notes the impacts of planning regulations; while deliveries to commercial properties in NYC have increased 300 percent over the past 30 years, regulations for off-site loading bays have not changed since 1972. She also recognizes that no zoning standards currently exist to require freight elevators; when freight elevators are not provided, delivery persons must wait for shared passenger elevators, which are often slow and crowded.

When parking is unavailable, drivers have a choice to circle until a spot is available at their destination – impacting local traffic and emissions – or to double-park, blocking traffic flows on bicycle lanes and vehicle lanes. While double parking in motor vehicle lanes (but not bicycle lanes) is legal for quick deliveries in many areas of the city, it is illegal in Midtown, where special parking rules apply (NYCDOT 2012). In the area from 14th Street to 60th Street between 1st Avenue and 8th Avenue, truck double parking is prohibited from 7 a.m.-7 p.m. Monday through Saturday. In the Garment District from 35th Street to 41st Street between the Avenue of the Americas and 8th Avenue, parking is restricted to trucks only from 7 a.m.-7 p.m. every day. Despite regulations, NYC experiences ongoing problems with delivery trucks parking illegally. Holguin-Veras et al. (2011) estimated that drivers accrue parking fines averaging $500 to $1,000 per truck per month for deliveries made during business hours. According to Salewski, Buckley, and Weinberger (2012), the public and politicians currently exhibit some degree of tolerance for illegal commercial parking; violation fees are simply viewed as a cost of doing business in the urban core. Some large delivery firms are provided with direct billing of fines; for example, UPS alone paid $18.8 million in fines for the fiscal year 2005.

2.3.2 City Logistics Solutions

In recent years, a number of efforts have been undertaken in New York City to both improve conditions for urban delivery drivers and to reduce the externalities generated by their trucks. Of the five categories of solutions identified by Giuliano and Dablanc (2013), two have not been implemented in New York. As previously noted, local planning policies in New York City are ineffective in meeting needs for commercial operators. Beyond acknowledging participation in specific pilots, such as the off-hour delivery program described below, no recognition schemes – voluntary participation programs that highlight company social responsibility – have been implemented locally in New York.

Attempts at road pricing have found mixed results. In an attempt to encourage commercial parking turnover, commercial loading zones have been replaced with commercial meters. Commercial meter rates in NYC are graduated, with costs increasing for longer parking durations; current rates are $4 for the first hour, $5 for two hours, and $6 for the third hour (NYCDOT 2014). A pilot study in 2000 yielded reductions in average parking durations from 160 minutes to 45 minutes, with only about 25 percent of the vehicles parked for over one hour (Schaller 2010). In 2005, an evaluation of time-of-day pricing on Hudson River crossings operated by the Port Authority of New York and New Jersey; this study found that pricing had little impact on the travel behavior of firms delivering to local addresses, as delivery times are primarily determined by receivers (Holguin-Veras et al. 2005).

Recognizing that receiver constraints are a key factor in determining delivery times, Holguin-Veras et al. (2011) proposed and implemented a pilot study of an off-hour delivery concept. Receivers were offered a financial incentive to accept deliveries during late night or early morning hours. This study was very successful in demonstrating the benefits of off hour-deliveries; carriers achieved considerable time and fuel savings. However, the study also highlighted challenges to expanding the scope of off-hour deliveries, including potential for noise impacts in mixed commercial-residential areas and a need to identify a long-term solution to incentivize receivers to participate.

The last of the five areas identified by Giuliano and Dablanc (2013) – consolidation – is of great interest in the New York City region, but is yet to be fully implemented. The general concept of a consolidation center is that large freight vehicles can deliver to a central location during off-peak hours, where they offload goods to be transloaded to smaller, cleaner vehicles more suitable for urban operations during business hours. The BESTUFs guide (Allen, Thorne, and Browne 2007) was developed through a major European initiative to identify and disseminate best practices in management of urban goods movements. This guide provides a summary of the factors leading to the success of consolidation centers; a number of these are applicable to New York City:

- “Significant existing transport problems within the area to be served (e.g. poor vehicle access, significant traffic congestion, constrained loading/ unloading facilities).”
- “An inadequate transport infrastructure to cope with increases in freight flows.”
- “Historic town centres and districts that are suffering from delivery traffic congestion where there is a common interest in improving the street environment.”

The guide also identifies key roles for different stakeholders. Consolidation is largely successfully when demand for it is generated by a group of potential users; when the regulatory framework incentivizes participation; when parking enforcement is effective; and when support (in terms of finances or space) is provided by the public sector. To date, these conditions have not been realized in New York City, although a study by Holguin-Veras, Silas, and Polimeni (2007) did find that a potential market for joint delivery operations does exist for deliveries to Manhattan and Brooklyn.

Panero, Shin, and Lopez (2011) performed a comprehensive review of global consolidation center implementations and explored their applicability in the New York context. One of the five models (of 39 reviewed) that they found to be suitable for operation in parts of New York City was that of La Petite Reine, which performs last-mile delivery from a consolidation center in central Paris using freight tricycles. Characteristics of this operation that they found to be of particular interest include its business model as a privately owned enterprise; its success in diversifying to new markets and locations; the participating company’s demonstrated social and environmental responsibility; and the fact that nonpolluting cargo-cycles offer flexibility in navigating streets and parking. This model seems increasingly applicable as New York City’s streets are being transformed for safer pedestrian and bicycle use.

Building the support from the public sector and interest from the private sector necessary to support an implementation of this type requires a clear understanding of the costs of, benefits of, and barriers to implementation. Firms will be unlikely to consider participation in a consolidation scheme using cargo cycles if their performance relative to traditional vehicles in local conditions is not well understood. Similarly, the public sector will be unlikely to invest scarce resources if risks and potential benefits are unclear. As mentioned previously, this study evaluates cargo cycle performance in New York City as an alternative option for last mile freight delivery and a potential mitigation measure for related negative externalities.

3 Cargo Cycles for Urban Delivery

The first step in examining the potential for increased implementation of cargo cycles in New York is to understand their current usage – both in New York City and in a more global context. As the vast majority of published research examining this vehicle type has been conducted in large European cities, Section 3.1of this chapter will describe the current implementations in Europe. In order to fill an existing research gap, Section 3.2 will discuss results from a survey of North American users conducted as part of this study. Section 3.3 will also briefly discuss findings from a review of New York City operations. Section 3.4 will synthesize findings from both European experience and the North American survey, identifying costs, benefits, and impacts of cargo cycles; barriers to implementation; and notable differences between U.S. and European experience.

3.1 Europe

Over the last decade, cargo cycles have proliferated in European cities, many of which are characterized by dense mixed land uses and by narrow streets with original design that often predates motor vehicles. These streets are difficult to navigate, and under modern traffic loads face severe congestion. Large vehicles commonly face difficulties in finding parking. Motorized freight vehicles are also a major contributor to urban emissions, including both greenhouse gases and air toxins. As discussed in the previous chapter, cities that have become increasingly focused on environmental sustainability and public health are implementing policies aimed at improving air quality. Combined with land use and traffic constraints, these new policies have created conditions favorable to growth in the use of freight tricycles and bicycles for urban delivery.

Cargo cycles are in use in a number of European cities as the last-mile link for consolidated deliveries. In Paris, La Petite Reine currently operates three logistics platforms (La Petite Reine 2009). Goods are delivered to the platforms by truck during off-peak hours, and are then transferred to cargo cycles for last-mile delivery (Dablanc 2011). A study funded by the City of Paris and the Agency for the Environment of Management and Energy (ADEME), and performed by an independent contractor, monitored the first two years of La Petite Reine's operations and developed performance metrics to quantify the social, economic, and environmental impacts of freight tricycle operations. While initially, this company primarily performed last mile parcel delivery for large couriers, they have since diversified to move other commodities, including food and pharmaceuticals.

Another trial was conducted in London by a large office supply company who, as a demonstration of their commitment to social and environmental responsibility, aimed to replace a previous delivery scheme using diesel vans with a new operation utilizing small, clean vehicles (Browne 2011). They established an "urban micro-consolidation" center served by one 18 tonne truck, from which a new "green logistics" company, Gnewt Cargo, performed last-mile delivery using electrically-assisted cargo tricycles as well as slightly larger electric vans. A study of trial operations was conducted by the University of Westminster, with support from the London Borough of Camden, to quantify the emissions benefits of the pilot (personal communications with Michael Browne). Since then, the company's operations have expanded; they now provide local deliveries for three major couriers and a green office supply company (Gnewt Cargo 2014).

Also in Paris, The Green Link operates three logistics platforms, from which they deliver parcels for a major courier, pharmaceuticals, prepared meals for organizations serving homebound customers, and beverages (The Green Link: Urban Mobility Solutions 2012). With support as part of the European Union (EU)-funded LAMILO Project, this company is also testing a multimodal sustainable supply chain concept, providing last mile delivery of goods transported into central Paris by barge (LAMILO, 2014). As part of the European Union (EU) funded STRAIGHTSOL project, TNT, a large international courier company, tested a mobile depot concept employing freight tricycles for last mile delivery; operations were monitored and compared with previous operations using traditional vehicles across a number of metrics (Kok, Macharis, and Verlinde 2013). In the Netherlands, another major international courier replaced 33 trucks with the same number of cargo bikes (European Cyclists Federation 2014). In Germany, the Federal Ministry for the Environment is currently funding the "Ich ersetze ein Auto" (i.e. "I substitute a car") project. For this project, local couriers and logistics providers in nine major German cities are testing the use of 40 cargo cycles in their daily operations (DLR 2014). As part of this ongoing effort, Gruber, Kihm, and Lenz (2014) completed a comprehensive review and survey of existing car and bicycle couriers to understand the potential market for cargo cycle implementation.

A few other studies to understand the larger market for cargo cycles have also been conducted. In 2009, Transport for London conducted a scoping study to understand the existing and potential use of cycles for goods movement (TFL 2009). The EU-funded CycleLogistics project was a three-year project aimed at promoting goods movement by bicycle and tricycle in 11 countries across Europe (CycleLogistics 2014). It included a variety of partners, including cycling advocates, logistics companies, local government authorities, and technical consultants.

The ultimate aim of this project was to expand the market for light goods movement (both commercial and personal) via bicycle and tricycle. To achieve this aim, partners conducted a number of activities, including compilation of experience from across Europe, conducting of stakeholder interviews, and testing of vehicles and components (e.g. trailers). Together, these projects have identified a number of smaller-scale uses of cargo cycles for individual business types, focusing particularly on the business to business (B2B) and business to customer (B2C) sectors (Barner and Wood 2014). General functions for cargo cycles identified include to move goods across large sites;

to move goods between multiple locations of a single business; to perform service activities involving light equipment (e.g. electricians, photographers); and to deliver goods directly to customers. Specific applications of cargo cycles identified include: delivery of retail goods from local shops; delivery of meals from restaurants and for social programs; delivery of pharmaceuticals to and from pharmacies; delivery of mail and documents; and hauling of garbage and recycling.

3.2 North America

Given that most of the available published literature on cargo cycles describes European experience, in the summer of 2012, an online search was conducted to identify freight tricycle/cargo cycle companies operating in North America. The survey focused only on logistics companies serving multiple customers and carrying a variety of commodities, rather than on individual businesses using cargo cycles for B2B or B2C deliveries. The search identified 12 companies in operation in the U.S. and Canada (Table 1). The research team reached out to these 12 companies to seek detailed information on their operations, including vehicle use, services provided, and commodities carried. Of the 12 companies identified, eight completed a detailed survey by email or by phone in the summer of 2012; a copy of this survey is provided in Appendix A.

Table 1. North American Cargo Cycle Operators

Company	Location	Participated in Survey
Bikes at Work Inc.	Ames, IA	X
B-Line Urban Delivery	Portland, OR	X
Checker Courier	New York, NY	
C.S. Courier	Columbus, OH	
Fresh Food Bike	Los Angeles Area, CA	
Metro Pedal Power	Somerville (Boston Area), MA	X
Pedal Express	Berkeley, CA	X
Revolution Rickshaws	New York, NY	X
Rob's Bike Courier Service	Fort Collins, CO	
Shift Urban Cargo Delivery	Vancouver, BC	X
Stick Dog Pedicabs	Salt Lake City, UT	X
The Hammer Active Alternative Transportation	Hamilton (Toronto Area), ON	X

The 2012 search and subsequent searches through 2014 have revealed that turnover in the sector is extremely high. Nearly all of the companies identified were relatively young businesses - only two of the companies identified were found to have been performing freight deliveries for more than five years prior to the survey. A number of additional companies identified through the initial search were found to be no longer in operation. Several of the surveyed companies noted that earning a profit in the sector is extremely challenging, and since the conduct of the survey in 2012, one of the companies appears to have closed.

As the CycleLogistics project found in Europe, survey results indicated that companies in the U.S. use cargo cycles to make a number of different types of deliveries, including B2B; B2C; and from wholesalers to restaurants, retailers, and individual customers. For wholesale operations, like in the European micro-consolidation centers, goods are often delivered by truck and transloaded to the cargo cycles. The most common commodities carried include baked goods, restaurant meals, groceries, local, organic, and CSA produce, and beverages, coffee, and other foods. A number of companies were also found to be hauling compost, garbage, and recycling.

The U.S. commodity mix described above provides a contrast to major operations in Europe, where nearly all of the operators perform parcel deliveries as a primary function. Only two North American carriers identified parcels as a commodity frequently moved; both of these operate independent delivery services. No North American company in current operation was found to be providing last-mile delivery for a large international (or even regional) courier. In North America, partner companies tend to be local “green” businesses primarily motivated to use cargo cycles to demonstrate a commitment to sustainable practices. Although European companies also seek to demonstrate a commitment to a healthy environment, the companies using the vehicles range far beyond the common “green” businesses – e.g., organic food vendors, CSA farm deliveries – that make up a large portion of U.S. cargo cycle users.

In Europe, among others, partner shippers include major international couriers, major grocery store chains, and large food and beverage corporations (Gnewt Cargo 2014; Kok, Macharis, and Verlinde 2013; The Greenlink 2014; Dablanc 2011). This lack of large corporate partners may be a challenge to operators; a study of operations in Paris found that while large transporters were willing to accept higher contract fees to demonstrate their commitment to green practices, smaller shippers found them to be too expensive relative to rates charged by competing modes (Panero, Shin, and Lopez 2011). In the U.S., shippers utilizing cargo cycle services are primarily small local businesses, with the majority moving primarily food products. Only a few major partners were identified: a single large office supply company, a single large grocery store chain, and single local municipality (who contracts with the carrier for recycling pick-up).

3.3 New York City

Cargo cycles are not an entirely new concept in New York City. A 1993 report from Transportation Alternatives identified two Manhattan operators utilizing cargo cycles in the city (Transportation Alternatives 1993). These included a major national courier service operating 150 tricycles from three Manhattan distribution centers as well as a local courier using five tricycles (in addition to a fleet of bicycles and vans). However, in 2003, the national courier was acquired by a major international courier, who subsequently ceased U.S. domestic delivery operations in 2008 (Kiviat 2008). It is unclear what happened to the local courier. Although a plethora of courier services exist in the city today, ongoing searches in New York City have identified only six freight service providers that have recently employed cargo cycles; these include:

- Revolution Rickshaws, a company that performs freight delivery in addition to larger pedicab operations (Revolution Rickshaws 2014).
- Zipments, a courier service that employs bicycles, cargo cycles, and motor vehicles to complete same day deliveries for customers requesting transportation through a web-based platform (Zipments 2014).
- Two individuals that operate single cargo cycles – Checker Courier and Small Haul NYC Cargo Bike Service - to perform courier services and deliveries for independent businesses (Checker Courier 2014; Small Haul NYC Cargo Bike Service 2011).
- Aqueduct Logistics, a small three-employee cargo cycle courier service.
- A collective offering courier services to independent businesses (Miller 2013).

Of these, Zipments has received investment from the New York City Economic Development Corporation to support its operations. Aqueduct Logistics closed in fewer than two years, primarily due to high salary and worker's compensation insurance costs (Miller 2013). No multi-employee company was found to be currently operating solely to conduct freight deliveries with cargo cycles.

While only a few very small independent services appear to be operating in the New York market, many local businesses – particularly restaurants and grocery stores – do use freight tricycles and bicycles for local B2B and B2C deliveries. The partners described in detail in the next chapter use freight tricycles for their daily operations. Local grocery stores in both Manhattan and Brooklyn have recently begun using freight tricycles for deliveries. Another company, Quinciple, partners with the Revolution Rickshaws to deliver artisanal food boxes twice weekly using freight tricycles (Revolution Rickshaws 2014). Restaurants and small retailers throughout the city use bicycles equipped with cargo boxes of various shapes and sizes.

3.4 Cargo Cycle Operations

Global experience has identified a number of benefits and costs from using cargo cycles for urban delivery. The extent to which these are realized may vary depending on local market, infrastructure, and political constraints. Carriers considering replacing motorized freight vehicles with cargo cycles must consider both the performance of these vehicles, and the costs associated with their operations. Table 2 summarizes the expected impacts for carrier operations from implementing cargo cycles. Details are provided in the following subsections.

Table 2. Expected Effects on Operations

Expected Effect	Increase (+), Decrease (-), or Varies Locally (L)
Operating Performance	
Travel speed	L
Travel time reliability	L
Building accessibility	L
Parking flexibility	+
Operating Costs	
Labor	+
Space	+
Fuel	-
Parking	-
Vehicle purchase	-
Vehicle maintenance	-
Vehicle insurance	-
Productivity	L
Other Considerations	
Driver health	+
Driver safety	L
Cargo Security	L

3.4.1 Operating Performance

Cargo cycle speeds are limited by human effort, or in the case of electric-assisted freight tricycles, by the relatively low power output of their batteries. Studies from Paris and London have estimated typical operating speeds of 7 to 9 miles per hour (mph), or 12-15 kilometers per hour (kph) for electrically assisted freight tricycles (Browne Allen and Leonardi 2011, Dablanc 2011). Although these speeds are relatively low, they are comparable to motor vehicle speeds in the same locations. Maximum speeds vary and are often determined by City regulations. In Paris, speeds are limited to 12.4 mph (20 kph) (Dablanc 2011), while in Germany, speeds up to 15.5 mph (25 kph) may be allowed (Gruber, Kihm, and Lenz 2014). In their scoping study, Transport for London noted that many cargo cycle operators choose the mode because it is more reliable in variable traffic conditions (TFL 2009). However, speed and reliability benefits depend on the flexibility of operations. When cargo cycles can use multiple types of infrastructure, they are more likely to have the ability to bypass congestion. Policies limiting vehicle operational flexibility are discussed in detail in Section 8.2.

Parking flexibility is consistently recognized as a major benefit of cargo cycles. In many cities, including New York, curb space is inadequate to accommodate all of the motor vehicles that require parking (Jaller, Holguin-Veras, and Hodge 2013). When parking is unavailable at a delivery location, trucks still need to make deliveries; as a result, they park illegally, obstructing travel lanes and accruing parking fines. Cargo cycles take up considerably less space than trucks or vans, and can often park in a space that would be inadequate for a larger vehicle. When curb widths and regulations allow, cargo cycles can park on sidewalks directly in front of delivery locations or access pedestrian plazas that are not open to motor vehicle traffic (Dablanc 2011). If vehicles are not able to park close to a delivery location, delivery of heavy goods may be difficult, as cargo cycles generally cannot carry handling equipment for use at the curb.

The speeds at which vehicles move and the service areas that they can cover are impacted by both terrain and technology. Where streets are flat, cargo cycles can complete tours more quickly and travel longer distances while expending the same amount of driver energy. In areas with significant hills or when goods need to be moved over long distances, moving heavy goods by cargo cycle on human power alone is difficult. This challenge can be addressed somewhat through the implementation of electric-assist on the cycle; however, this technology also adds a number of complications. Vehicles reliant on electric power have limited autonomy. Vehicles used in Paris and London have an estimated four hours of autonomy, covering approximately 18 miles (30 km) before the battery needs to be recharged (Dablanc 2011). The battery must then be charged for five hours (although on the vehicle used in these cities, the battery is changeable, so the vehicle does not need to be idle during charging) (Panero, Shin, and Lopez 2011). The system adds significant weight to the vehicle itself; for example, on the Cycles Maximus, a freight tricycle commonly used in the U.S., the electric-assist adds more than 120 pounds of weight, making the vehicle less maneuverable when the assist is not in use (Conway et al. 2012). The motor must also be maintained, at a higher cost than a solely human-powered vehicle. However, regardless of these complications, during a roundtable on freight tricycles held in New York City on October 4, 2013, Franklin Jones, the owner of B-Line Urban Delivery in Portland, OR, indicated that the use of electric-assist was critical to his company’s operations (UTRC 2013).

Operational flexibility can be limited by regulations. The scoping study by Transport for London identified parking flexibility and savings in "penalty charge notices" (PCNs) as major benefits of the mode. However, during the London pilot study, freight tricycles were only permitted to use on-street parking space due to their classification of a motor vehicle (personal communications with Matthew Linnecar). They not only were unable to achieve the same building accessibility as other operators, but they also received PCNs when parked in on-street loading zones from enforcement agents unfamiliar with the mode.

3.4.2 Operating Costs

Labor is an important cost consideration for cargo cycle operations. Although cargo cycle operators generally do not require specialized licensure like heavy vehicle operators, they do experience conditions that necessitate higher than minimum wages. Cargo cycles require expenditure of human energy; as they carry increasing volumes of goods and travel longer distances, operators become fatigued, impacting the speeds with which they complete operations. On these trips, cargo cycle operators are exposed both to weather elements and to other vehicles. In New York City, this exposure results in a very high expense for mandatory worker's compensation insurance (Miller 2013). Companies operating trucks and vans pay a much lower cost for this type of insurance because a high volume of vehicles translates to a large shared risk pool. While conditions require companies to pay competitive wages, vehicle capacities also limit the volume that can be carried by an individual driver. In the London pilot, while drivers operating tricycles were paid lower individual wages than previous van drivers, a greater number of drivers were needed to complete the same volume of deliveries (Browne, Allen, and Leonardi 2011). As a result, net labor costs increased for the new delivery scheme.

As discussed previously, another key factor in the success of urban consolidation centers is the availability of affordable space. This factor presents a dichotomy, as the dense urban areas in which cargo cycles offer benefits generally have very high land values. Space in desirable accessible locations likely demands an even higher premium,making space for storage of cycles or transloading of goods very expensive. Researchers in Brussels recognized that finding an accessible space – and one with power for vehicle charging – was a key challenge (Kok, Macharis, and Verlinde 2013). In the European cities where successful consolidation centers have been implemented, there have been some public sector interventions to manage costs. In Paris, the City provides "Urban Logistics Spaces"; in these locations, rents are limited to the average regional cost for warehousing (Dablanc 2011). As can be noted from both Paris and London, the space required for consolidation is fairly small. In Paris, the first space provided to La Petite Reine was about 6460 square feet (600 square meters). In London, the first "urban micro-consolidation" center was only about 1720 square feet (160 square meters; Browne, Allen, and Leonardi 2011).

Cargo cycles are less expensive than motor vehicles to purchase, maintain, and operate. CycleLogistics researchers estimated that purchase of a cargo bike is about two-thirds of the annual costs to lease a delivery van (including maintenance), and that vehicle insurance on a tricycle is about one-quarter of the costs for insuring a van (CycleLogistics 2011). In London, capital, fuel, insurance, excise duty, and maintenance costs all decreased from previous costs for delivery vans when freight tricycles and small electric vans were implemented (Browne, Allen, and Leonardi 2011). The study of Paris operations did find that due to heavy loads, cargo cycle tires needed to be replaced frequently; however, this requirement could be addressed through a change in vehicle design (Dablanc 2011).

Supportive policies such as low emissions zones and subsidy of expensive space can encourage the use of cargo cycles by increasing the competitiveness of their operations. In Paris, in addition to the provision of urban logistics spaces, trucks are not permitted to enter the city during much of the daytime (Panero, Shin, and Lopez 2011). In London, both trucks and vans are subject to both congestion charging and a low emissions zone (TFL 2014a and 2014b). However, other types of policies may limit the benefits of using this mode. In some locations, legal vehicle classifications limit when and how they operate. In most cities, cargo cycles do have the ability to operate on road shoulders and in bicycle lanes; however, vehicles equipped with an electric-assist may face some more restrictions. For example, despite the fact that identical vehicles were operated by La Petite Reine in Paris and Gnewt Cargo in London, regulations in London defined vehicles that weigh more than 60 kilograms as motor vehicles (personal communications with Matthew Linnecar). As a result, in London, the vehicles were required to be registered, the drivers were required to be licensed, and operations were limited only to motor vehicle infrastructure. In Paris, the same cargo cycles could operate in pedestrian areas, on bicycle infrastructure, and even in shared bus lanes (Dablanc 2011).

In New York, current state regulations prohibit the operation of any motor-assisted bicycles on “any street, highway, parking lot, sidewalk or other area in New York State that allows public motor vehicle traffic” (NYSDMV 2014); as a result, local operators cannot benefit from the improved speeds and higher payloads that this electric-assist makes possible. Operators in New York have also noted that security bollards installed at entrances to both the Manhattan and Williamsburg bridges render these bridges impassable to slightly-too-wide tricycles (ersonal communications with Gregg Zuman; Miller 2013). To address infrastructure challenges, operators may benefit from coordination with local cycling advocates. In the European CycleLogistics project, bicycle advocacy groups are working to actively promote implementation of cycle-friendly infrastructure in commercial areas. Nearly all of the U.S. survey respondents indicated that they had had positive interactions with the local cycling community; like in the European project, in Vancouver, the operator worked actively with local bicycle advocates to promote bicycle friendly policies and infrastructure.

The impact of cargo cycle use on productivity is complex. There are some obvious disadvantages for cargo cycles compared to trucks. Cargo cycles are much smaller; as a result they have lower volume capacities and payloads. For larger quantities of goods, economies of scale achieved by efficient truck or van operations may not be matched by a cargo cycle. In Brussels, researchers found that it was difficult to transport large parcels by cargo cycle (Kok, Macharis, and Verlinde 2013).

However, whether human-powered or electrically assisted, cargo cycles can produce productivity benefits where resources are being wasted through the use of excessively large vehicles. La Petite Reine was founded under the assumption that the heavy vans previously in use were oversized for delivering the 80 percent of parcels weighing less than 176 pounds (30 kilograms) (Dablanc 2011). Considering time, weight, and volume constraints, Gruber, Kihm, and Lenz (2014) estimated that 42 percent of goods currently moved by car courier in Berlin could be moved with an electric cargo cycle. As noted by Browne, Allen and Leonardi (2011), for cargo cycles to be successful, the delivery area profile must match the capacity of the vehicles. In London, under the old model, seven vans ran daily to a suburban depot; when this system was replaced with a single truck trip and an urban micro-consolidation center, the total distance traveled per parcel decreased by 20 percent.

Cargo cycle efficiency benefits may be greatest in areas where truck operations are restricted to a defined network. The CycleLogistics project recognized that cycles can use a denser roadway network than trucks. In Paris, cargo cycles can operate on a broad range of infrastructure, including in shared bus lanes, and in standard and contra-flow bicycles lanes, (Dablanc 2011). Under current regulations in New York, cycles can operate freely on the roadway network while large trucks are restricted to local truck routes (except to travel a shortest path to a final delivery location).

With consideration of space, labor, and vehicle related costs, cargo cycles have generally been found to be as expensive as or more expensive than competing modes. In London, the operator determined that costs were equivalent between motorized and non-motorized modes (Browne, Allen, and Leonardi 2011). During the mobile depot pilot in Brussels, operating costs doubled compared to previous motorized methods of delivery, although costs were likely inflated because load capacities were kept below 40 percent (Kok, Macharis, and Verlinde 2013). In Paris, overall operating costs were not found to be competitive with other modes in an extremely competitive market; however, companies seeking to demonstrate their environmental and social responsibility were willing to pay a premium (Dablanc 2011).

3.4.3 Other Considerations

The American Transportation Research Institute (ATRI) identified driver health and wellness as a one of the Top 10 Critical Issues in the Trucking Industry for 2013 (ATRI 2013). While long-haul truck drivers face challenges such as long, sedentary trips and difficulties finding parking for mandatory rest, urban drivers also face unique stresses. Daily, urban delivery drivers face uncertain traffic conditions and difficulties finding parking. The stresses resulting from these conditions are exacerbated by "just-in-time" delivery models that mandate specific delivery times (Shattell et al. 2010). Generally cargo cycle operators do not face the same stresses related to congestion and parking; a number of the U.S. operators surveyed noted that their drivers enjoy operating their vehicles.

Driver safety for cargo cycle operators compared to motor vehicle operators has not been studied in detail. As non-motorized roadway users, cycle operators are more vulnerable to injury from accidents with motorized vehicles; however, risk varies depending on the type of infrastructure on which the vehicles operate and the surrounding traffic conditions. Where traffic speeds are slow, injuries are less likely. None of the European studies and none of the surveys of North American operators identified a serious injury to a driver.

Similarly, cargo may be more vulnerable to theft from a cargo cycle compared to a motorized vehicle. Cargo boxes must be locked to protect goods from theft. The vehicle itself is easier to steal than a motor vehicle because it does not require a key for operation. However, despite perceived vulnerability to theft, no European study or U.S. operator found theft to be a serious concern during operations.

3.5 Cargo Cycle Broader Impacts

Although operators must consider costs and performance, public agencies considering supporting these operators must additionally understand the broader impacts of cargo cycle operation. Table 3 describes the expected impacts from replacing motorized delivery vehicles with cargo cycles.

Table 3. Expected Broader Impacts

Expected Effect	Increase (+), Decrease (-), or Varies Locally (L)
Fuel consumption	-
Emissions	-
Noise	-
Congestion	L
Demand for Parking	-
Accident severity	-
Low barrier-to-entry jobs	+

As discussed previously, urban freight vehicles have historically contributed a large share of greenhouse gas emissions, air toxins, and noise pollution in urban areas. Unlike fuel-burning motorized delivery vehicles, cargo cycles produce essentially no pollutants when entirely human-powered. Even those equipped with an electric-assist will not generate local emissions. Vehicles utilizing an electric-assist will generate some life-cycle emissions at the location of energy production; however, the rate of these emissions will vary with the power source (e.g. coal versus wind). For example, during the London pilot, power was purchased from a "green energy" company to ensure local delivery operations remained "zero-emissions" (Browne, Allen, and Leonardi 2011). Overall, the study found a 54 percent reduction in total CO_2 emissions per parcel, including the truck trip from the warehouse to the micro-consolidation center. The Parisian study estimated that 89 tonnes of fuel were conserved, leading to savings of about 224 tonnes (203 metric ton) of carbon dioxide (CO_2) and 84 kg of particle emissions in one year of cargo cycle of operations. The implementation in Brussels found a 24 percent reduction in CO_2 emissions, a 22.1 percent reduction in PM 10 emissions, and a 98.5 percent reduction in PM 2.5 emissions.

Urban freight vehicles operate at slow speeds in congested traffic making frequent deliveries; they also contribute to the congestion faced by all roadway users. By replacing trucks that consume a large amount of roadspace with a smaller vehicle, cargo cycle implementation can also positively impact network emissions by generally reducing urban congestion. The Paris implementation was estimated to save 411,000 annual ton-miles (600,000 tonne-km) of van travel (Dablanc 2011). In the London pilot, a single off-peak truck trip replaced seven daytime van trips from a suburban warehouse to the central business district (CBD); as a result, the total distance traveled per parcel was reduced by 82 percent, and all peak trips between the warehouse and CBD were eliminated (Browne, Allen, and Leonardi 2011). However, the total distance traveled within the CBD increased significantly, as the smaller vehicles used for last-mile delivery carried smaller volumes on more tours. As noted by Melo, Baptista, and Costa (2014), if space is limited and cargo cycles are unable to operate on separate infrastructure from motor vehicles, slow cargo cycles could potentially negatively impact traffic flow and resulting emissions. However, Paris researchers concluded that implementation there had no measurable impact on traffic due to the very low volume of vehicles (Dablanc 2011).

Both Paris and London studies note the significant decrease in miles traveled by heavy vehicles in the CBD. In addition to reducing the congestion impacts from these vehicles, cargo cycle implementations also reduce the exposure of vulnerable roadway users – bicyclists and pedestrians – to dangerous accidents from heavy vehicles. Researchers in Brussels noted that implementation of the mobile depot should lead to fewer confrontations between because trucks and other road users (Kok, Macharis, and Verlinde 2013). Although total miles traveled for delivery may actually increase – as occurred in London – accidents involving smaller, slower delivery vehicles are likely to be far less severe than those involving a heavier truck or van.

In addition to emissions, traffic, and safety impacts, cargo cycle operations can also provide a source of low-barrier-to-entry local jobs. While heavy vehicle operators often require commercial driver's licenses and expensive training, cargo cycles require training only in basic road safety. The London scoping study noted that driver licensing has reduced the available pool of drivers for medium-heavy duty trucks (TFL 2009). ATRI (2013) has identified a U.S. commercial vehicle driver shortage as an existing problem likely to worsen with continued economic recovery. In Paris, La Petite Reine works with the Ares Group to hire drivers; this company works to integrate those who have been without employment for a long time back into the job market (Panero, Shin, and Lopez 2011). A company in Bucharest, Romania, identified as part of the CycleLogistics project also hires drivers at risk for unemployment (CycleLogistics 2013).

3.6 Stakeholders

Another notable difference between European and North American experience is in the relationship between stakeholders. Like in North America, most cargo cycle companies in Europe are for-profit businesses. Few rely on long-term subsidies for daily operations. However, as noted previously, many of the operators in Europe have benefitted at the outset of their operations from EU, national, or local government investment in pilot studies for testing of innovative logistics concepts. Governments have primarily contributed in two ways: first, they have subsidized or helped with the search for logistics spaces for sorting and transfer of goods to cargo cycle. For example, in the first three years of La Petite Reine's operations, the City of Paris provided them an "urban logistics space" for a very low rent (Dablanc 2011). Although this space is now provided at a slightly higher cost, it is still considerably lower than the standard market rate for space in central Paris and comparable to the cost of a suburban logistics facility. Provision of this space comes at an additional opportunity cost for the city due to lost parking revenue. In London, for the initial pilot study, the Borough of Camden attempted to help the operator find a logistics space, but was unable to find a suitable facility to accommodate trucks dropping off deliveries (personal communications with Michael Browne). However, the Crown Estate later provided a small loading space, equivalent in size to a 40 ft container for goods transfer and for parking of one delivery vehicle in an area near the Regent Street retail district.

The other primary contribution from the public sector has been support for conducting pilot studies, and evaluation of these pilots. Both the Borough of Camden in London and the City of Paris and the Agency for the Environment of Management and Energy (ADEME) in Paris financed studies to evaluate the impact of operations (Browne, Allen, and Leonardi, 2011; Dablanc, 2011). These studies provided independent assessments of the benefits of the mode, and provided operators a means to market their services to future customers.

As in any logistics operation, tricycle operators begin to profit once they have reached necessary economies of scale. Early investment on the part of the public sector can allow a small or new business the opportunity to establish new services with minimized risk and limited capital investment. Before the city-funded pilot study, La Petite Reine had performed delivery operations for local retailers. Investment by the City allowed them to expand their customer base and operations considerably (Panero, Shin, and Lopez 2011), and to develop a custom vehicle better suited to these operations (Dablanc 2011). Evidence from Paris showed a period of financial loss in the second year of operation, when costs (primarily labor) exceeded revenue. By the following quarter, when sales increased, the company returned to profitability. Initial investment in a pilot can help carriers survive this initial instability (Panero, Shin, and Lopez 2011).

Demand for cargo cycle services may be limited by shipper perceptions of reliability. As discussed previously, despite a lack of evidence from existing operators, concerns about cargo safety and security persist. While Transport for London (TfL; 2009) found that nearly all shippers not using cargo cycles were concerned about security, almost no instances of theft were identified by users. This perception may be exacerbated by perceived hostility between cyclists and motor vehicles. In many US cities where space is limited, including New York, some cyclist and motorist view each other as adversaries. Ultimately, the poor perceptions can cause shippers to doubt the seriousness of cargo cycles as a mode of transportation. In discussing demand for cargo cycles in NYC, one operator noted that when he previously worked for a courier utilizing both motor vehicles and bicycles, some shippers were unsatisfied with receiving delivery via bicycle, despite superior performance (Miller 2013). While U.S. operators were found to be taking steps to demonstrate their professionalism – for example, operators in Portland and the Boston use uniformed drivers – operators in the U.S. have generally not yet achieved the level of recognition afforded to European operators by the participation of major shipping partners.

Large partners, such as international courier companies, may be more likely to participate in a risky pilot study that has been recognized by a funder to be of value and that provides broad exposure for their participation. Support from a major partner provides stability in ensuring regular, relatively high volume demand for service. Evidence from Paris suggests that finding a critical mass of customers operating in the limited area that can be served by freight tricycles can be a major challenge (Dablanc 2011). Although not only for cargo cycle operations, the German study examining market potential found that courier companies are highly dependent on key accounts (Gruber, Kihm, and Lenz 2014).

Despite the recognized importance of both public and private sector support from European experience, both Panero, Shin, and Lopez (2011) and Giuliano and Dablanc (2013) have suggested that public investment in private sector operations would be particularly difficult in the U.S. political climate. For this type of investment to me made, public sector benefits must be clearly demonstrated. In the survey of North American operators, only a single Canadian company was found to have received financial support for operations from a local government – the City of Vancouver.

In their scoping study, TfL also noted the importance of consumer pressures in inducing companies to switch modes (TFL 2009). As discussed previously, costs may increase when goods are delivered by cycle; however, successful implementations have demonstrated that partners are willing to pay a premium when use of cycles meets their sustainable worldview. This thinking reflects a broader market demand for socially and environmentally conscious products- for example organic produce and fair-trade goods. The relative invisibility of the supply chain may limit consumer understanding of the impacts of transportation mode choice. However, recognition schemes (Giuliano and Dablanc 2013), public campaigns (CycleLogistics 2014) and simply visibility of branded vehicles can heighten awareness to increase consumer driven demand for sustainable transportation.

4 Case Study Methodology

To investigate the traffic performance of cargo cycles in New York City conditions, and related emissions savings, case studies were conducted with two local users – City Bakery and City Harvest. Each of these partners uses a specific type of cargo cycle – a freight tricycle – in their daily operations. The following section describes the operations of each user and the data collection and analysis methods employed in each case study.

4.1 Project Partners

The first step in understanding the operations of each freight tricycle user was to conduct a detailed interview with each partner. The questions asked during this interview process are provided in Appendix A. The following sections summarize the general operations and interview results for each user.

4.1.1 City Bakery

City Bakery operates a local chain of green bakeries. The company has been in operation for 22 years, and now includes City Bakery and Birdbath Bakery locations throughout lower Manhattan (as well as recently added locations at Grand Central Station and on the Upper West Side). The company seeks to be green in all of its operations – products are made primarily from organic ingredients; bakery locations are built from green materials; and locations are powered by renewable energy sources. For seven years, the company has been delivering goods between its own locations, to a few third-party retailers in lower Manhattan, and to infrequent catering locations using two Cycles Maximus general cargo freight tricycles. The specifications for these vehicles are given in Table 4. Deliveries to more distant locations recently opened on the Upper West Side are made using cargo vans, and some small deliveries are also made using bicycles. During the time of the data collection, frequent pickups and deliveries were made between six bakery locations and the Union Square Green Market, all located in midtown and lower Manhattan. City Harvest's cargo cycles are leased from and maintained by Revolution Rickshaws, a local pedicab and cargo cycle logistics company located on W. 31st St. in Midtown Manhattan. While City Bakery stores its freight tricycles on-site, the freight tricycles regularly travel to this location for maintenance.

Table 4. Cycles Maximus General Cargo TricycleSpecifications

Power System	Human
Weight	187 lbs
Length	8' 6.44"
Width	3' 11.2"
Cargo Capacity	35.3 ft^3
Maximum Payload	551 lbs

City Bakery produces and sells a number of fresh products, including but not limited to breads, cookies, hot chocolate, coffee, sandwiches, and biscuits. Generally, these goods cannot be stored for long periods of time; most products must be sold on the day that they are produced. These goods are primarily produced at three locations: City Bakery located at 3 West 18th St., a Birdbath Bakery located at 200 Church Street, and a Birdbath Bakery located at 160 Prince St.

At the time of data collection, City Bakery employed five tricycle drivers. At the beginning of each business day (typically between 7:00 a.m. and 9:00 a.m.), these drivers deliver a fixed amount of goods from the flagship locations to each retail location. During these deliveries, freight tricycles are typically full to the volume capacity with baking sheets, four gallon jugs, and/or boxed lunches. However, the daily demand of each branch is highly variable and difficult to predict; when individual locations need more food to meet higher demand, they request additional products to be delivered from the closest flagship store. Until about 7 p.m., additional goods are delivered on-demand via freight tricycle; typically, between seven and 12 deliveries are made to each store daily.

Previous to implementation of the freight tricycles, City Bakery made pickups and deliveries using cargo vans. When asked to compare operations between the two modes, City Bakery identified a number of benefits and challenges of using freight tricycles. The primary operational benefits identified included higher speeds in congested traffic and parking flexibility. Because they can be parked on wide sidewalks at many locations, the freight tricycles do not face the same challenges as trucks in attempting to park in dense areas of lower Manhattan. Similarly, the freight tricycles can generally bypass traffic congestion by traveling on wide road shoulders or on bicycle lanes; this flexibility allows them to travel with greater reliability than motorized vehicles. Given the relatively small number of pick-up and delivery points, City Bakery freight tricycles operate on relatively fixed routes. The tricycle operators travel the same or very similar routes between the same fixed points on a daily basis. Experienced drivers have found the most efficient routes to travel from the flagship stores to different branches under varying traffic conditions.

As an unusual vehicle type, the freight tricycles are highly visible. By branding the freight tricycles with their logo, the bakery can simultaneously perform deliveries and advertising. City Bakery also identified some intangible benefits of using the freight tricycles. First, using the freight tricycles allows them to maintain transportation operations consistent with the other aspects of their "green" business. Second, their drivers simply enjoy using the bikes, leading to a high level of employee satisfaction.

Motorized vehicles do offer some benefits compared to the freight tricycles. Vans can carry larger capacities and can be better temperature controlled. They also provide better protection of both drivers and goods from collisions and pavement damage. However, City Bakery has been able to mitigate these challenges. Given the relatively short travel distances between locations (around two miles maximum), temperature control is not a major concern despite potential for freezing or overheating of goods. Security has also not been found to be a concern during operations. During the day, City Bakery's freight tricycles are generally parked on the sidewalk outside the flagship City Bakery location or at the Birdbath Bakery located at 200 Church Street. Overnight, the freight tricycles are brought into the City Bakery for storage. The company has not experienced any major damage or injuries from accidents. The company is proactive to promote safety. The drivers wear yellow vests and helmets, and receive guidance on specific routes to avoid based on past experience. By law, drivers are required to carry workman's compensation insurance, which is costly. While product integrity can be impacted by jostling of goods from infrastructure damage and stop-and-go operations, loading procedures (e.g. stacking cookies only one high) to minimize impacts have been developed through experience.

4.1.2 City Harvest

City Harvest operates a very different business model from City Bakery. City Harvest is a not-for-profit food rescue organization that has been in operation since 1981. The organization picks up excess food daily from all segments of the local food industry (e.g., restaurants, grocers, bakeries, greenmarkets, corporate cafeterias, manufacturers, and farms;City Harvest 2014). The organization then distributes these goods to more than 500 local community food programs throughout New York City, including to more than 120 locations in Manhattan. Since the opening of its 45,400 square ft "Food Rescue Facility" in Long Island City, Queens in 2011, City Harvest has the capacity to move more than 125,000 lbs of food daily (City Harvest 2014). City Harvest transports this food using 19 refrigerated trucks and three freight tricycles. The Cycles Maximus General Cargo freight tricycles were initially implemented in 2008 at the suggestion of a financial investor.

City Harvest accepts both perishable and durable goods. Durable goods and large shipments of perishable goods are carried by truck and are stored and sorted at the Food Rescue Facility in Queens. Delivery volumes are limited by storage available at the location of each food program. According to the City Harvest drivers and logistics manager, some shelters and churches have their own storage areas (some with specialized equipment). Programs with available storage usually accept large, infrequent deliveries of non-perishable goods (e.g., bottled water) that are made by truck from the Food Rescue Facility. These programs generally contact City Harvest for new deliveries once their stock has been depleted below a specific level.

For programs that serve fresh foods – for example, dairy products, fruits and vegetables, and prepared meals – frequent deliveries of smaller quantities are needed. For these delivery types, freight tricycles are used to make small pick-ups, usually of perishable goods, from Manhattan restaurants and retailers. These goods are transported directly from the donor to a local food program. Deliveries may be made to these locations infrequently or as often as multiple times daily; delivery frequencies are determined by the operating days and hours of the participating food programs. For example, some churches serve meals only one or a few days per week. Programs that both store and distribute non-perishable goods and serve fresh foods may receive delivery from both trucks and freight tricycles. The freight tricycles are used primarily for movement of individual shipments weighing less than 50 lbs. Two freight tricycles operate primarily in Midtown, with a third operating on the lower west side of Manhattan. The Downtown tricycle makes about 24 pickups each morning; the Midtown freight tricycles operate in the afternoon and evening, and typically make 17 pickups. Generally, the freight tricycles will be filled to more than 400 lbs before goods are delivered to a local program.

City Harvest employs one driver per trike. Although the organization owns the freight tricycles, they contract with Revolution Rickshaws for maintenance and storage of the vehicles. Like City Bakery, City Harvest identified a number of operational and intangible benefits and challenges for using freight tricycles versus motorized vehicles. City Harvest also identified ease of parking as a major benefit of freight tricycles; generally, freight tricycles are not subject to the parking fines that are a frequent cost of operation for truck deliveries in dense areas throughout New York City. The freight tricycles allow for pickup of goods in shipment sizes smaller than would be efficient for trucks; while the costs associated with moving these goods to and through the sorting facility might exceed their value, they can easily be moved a short distance to a local user via trike. City Harvest also noted that the branded freight tricycles provide marketing and demonstrate the organization’s commitment to sustainable practices. City Harvest noted that the experience of the tricycle driver is more “personal” than that of a truck driver; small pickups transported directly from a donor to a user provide a reminder of the roots of the organization.

City Harvest also identified some challenges associated with tricycle operations. The freight tricycles operate in all weather conditions except under a city warning or severe snow. Potential driver exposure to these conditions can pose a difficulty in recruiting new personnel. City Harvest is working on methods to mitigate this challenge, such as providing weather appropriate clothing to drivers. Weather exposure is also a major concern in ensuring product

integrity given than most of the goods being transported are perishable. Drivers do log temperatures using a handheld device to ensure that foods remain at a safe temperature while being transported. As a nonprofit organization, City Harvest's legal liability for a temperature control failure may be limited by "Good Samaritan" laws; however, the organization aims to always maintain the integrity of products it transports.

4.2 Data Collection Methods

The primary data source used to examine vehicle performance in the study is global positioning system (GPS) data. The U.S. GPS system consists of 24 satellites; each of these transmits a radio signal containing its precise location and the time from an onboard atomic clock (GPS 2014). These signals travel at the speed of light to reach an earthbound GPS receiver. Once the location of four satellites relative to the receiver is measured, a sphere can be defined to identify the location of the receiver.

Some error is associated with the use of GPS to identify a receiver's instantaneous location, particularly in areas where there may be signal interference. Jun, Guensler, and Ogle (2006) identify a number of sources of random GPS error, including satellite orbit, clock, and receiver issues, atmospheric effects, signal reflection, and signal blockage. In New York City, numerous objects can impede signal transmission, including skyscrapers and other tall buildings. These objects can lead to deflection or misdirection of a signal, and ultimately to a miscalculation of the receiver's location. These points can be observed as obvious deviations when a receiver's path is mapped. There is also a very small amount of error associated with the motion of the satellite itself. Although the signal travels at the speed of light, the satellite will continue to move before the signal reaches the GPS receiver. This can lead to a drift point – a non-zero speed reading even when a vehicle is parked.

A number of studies have demonstrated the usefulness of GPS data to estimate traffic performance measures. Quiroga and Bullock (1998) conducted a study examining the use of GPS data to evaluate travel times on an urban highway network in Louisiana. They developed and tested a methodology to estimate typical segment speeds from GPS data. Taylor, Woolley, and Zito (2000) demonstrated the potential for using geographic information systems (GIS) to map and evaluate traffic performance measures. Cortes et al. (2011) used GPS data to estimate commercial bus speeds. Zhao, McCormack, and Goodchild (2011) investigated the use of GPS data to estimate truck travel speeds. Comparing GPS speed estimates with those from traditional loop detectors, these authors found a mean absolute difference in estimated speeds of less than 6 percent. Du and Aultman-Hall (2007) evaluated the accuracy of GPS data for identifying trip ends.

4.2.1 Device Specifications

To determine a suitable device for urban application in this study, the research team reviewed a number of commercially available products. The team also consulted with the New York City Department of Transportation to identify specific devices employed in similar studies. The team obtained and tested two devices for accuracy and ease of use. Members of the research team traveled with each device in the vicinity of the City College campus to evaluate device performance (primarily existence of drift points) in a dense urban environment. The devices were also evaluated for ease of use. The most suitable device identified by the research team was the QSTARZ BT-Q1000XT travel recorder; its characteristics are described as follows.

The team sought a device that would maximize battery life and data storage capacity. The QSTARZ BT-Q1000XT was found to have a useful battery life of about 30 hours on a full charge. The manufacturer's published battery life is 42 hours; however, frequent signal loss will lead to higher consumption in an urban area. The storage capacity of the device was found to be about 400,000 data points. Even data collected at the maximum frequency of one reading per second would not fill the device's capacity within its useful battery life; therefore, battery life is the limiting factor in determining how often the device must be cleared and recharged.

The team also sought a device that would require no operation by the vehicle driver. The device can either be turned on continuously or it can be pre-programmed to operate only during certain hours. Because the freight tricycles and trucks being observed operate only during certain hours of a day, the programming feature was desirable to maximize battery life. The device has several available modes for recording walking, cycling, and driving. In this study, the devices placed on City Harvest trucks were programmed to record only during certain hours since the daily operation of trucks was for longer hours than the freight tricycles. For consistency across modes, the devices were set to record in "bicycle" mode on all vehicles. In "bicycle" mode, the device logs data at two second intervals. When the device is turned on (or programmed to turn on) in log mode, it immediately searches for a signal and starts recording. However, if no motion is detected by the device's vibration sensor for 10 minutes, the device will enter sleep mode until motion is again detected. When this occurs, a "break" sign will be generated.

The "sleep mode" is beneficial for battery life, but also presents a challenge for data collection. When the receiver wakes from sleep mode, it needs to search for the satellite signals. The manufacturer's published start-up time to find a signal is 35 seconds; however actual performance may vary. If the vehicle leaves the buffer zone for a pick-up or delivery location before the signal is found, some speed readings may be lost. This feature is unlikely to cause a major problem while a vehicle is traveling; although a vehicle may stop at a traffic light or in congested traffic, it is very unlikely to be motionless for more than 10 minutes.

Among other data required for device operation, the QSTARZ BT-Q1000XT records the following variables at each data point. Due to signal interference and the potential for bad location readings, distance calculated directly by the device is a poor measure of vehicle travel. As a result, the primary value recorded at each data point that was used to examine the critical traffic performance measures was the speed.

Table 5. Variables Recorded by GPS

Variable	Definition
Local Date and Time	Time at which a measurement is taken, including both calendar day and time-of-day
Latitude	A north/south measurement of position perpendicular to the earth's polar axis
Longitude	An east/west measurement of position in relation to the Prime Meridian
Speed	Rate of object motion
Distance	The distance between two logging points
Heading	The compass direction in which the longitudinal axis of an object points

The speed variable is an instantaneous spot speed. While speed readings may also be erroneous due to signal interference, the impact of these bad readings will be minimal when averaged across an entire corridor or trip path.

4.2.2 Device Installation

The research team worked with mechanics at Revolution Rickshaws to determine an appropriate method to install the travel recorder on a freight tricycle. After consideration of locations on the vehicle frame and in the cargo box, it was determined that the best location to minimize interference with delivery operations was underneath the cargo box on the vehicle frame (Figure 1). On City Harvest trucks, the device was fastened under the driver's seat.

Figure 1. GPS Installation Location on Trike

The devices were placed in a weather-proof Otterboxes and secured to the frame using high-strength Velcro (Figure 2). For added security, the devices were further secured to the tricycle frame using zipties. Initial testing of this configuration revealed that movement of the device within the Otterbox led to incorrect readings of the vehicle's heading (direction of movement). To address this issue, the devices were further secured to the inside of the box using the same high-strength Velcro.

Figure 2. QSTARZ Devices in Preparation for Installation

4.2.3 Field Data Collection

Devices were installed on City Bakery's two freight tricycles in December 2012. Twice weekly, a member of the research team traveled to City Bakery's W. 18th St. location to swap the GPS receiver with an identical charged device. Data was collected from December 6, 2012 to February 6, 2013. In total, 53 unique days of data were collected. On 44 of the 53 days, data was collected from both freight tricycles.

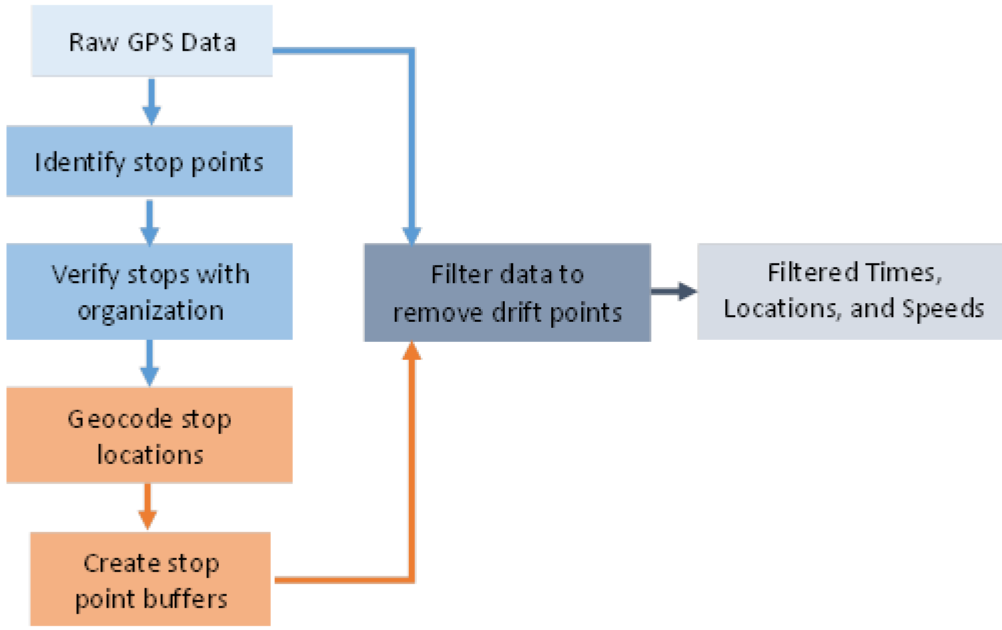
For City Harvest, devices were installed on two of the organization's three freight tricycles and on two of their 18-ft box trucks. The City Harvest trucks depart from and return to the organization's warehouse in Long Island City, Queens. The City Harvest Tricycles are stored at Revolution Rickshaws on W. 31st St. on the west side of midtown Manhattan. To swap out the City Harvest devices, a member of the research team twice weekly traveled in the morning to the Long Island City warehouse and then to Revolution Rickshaws. Generally, the trucks depart from Queens at around 8 a.m., while the freight tricycles generally do not begin their routes until midday. Data from City Harvest tricycles was collected from March 29 to June 4, 2013. City Harvest Truck Data was collected from March 28 until May 31, 2013. Since City Harvest employs only one driver per trike, the freight tricycles are not operational if the driver is not working. For the City Harvest freight tricycles, 40 unique days of data were collected. On 28 of these days, data were collected from both freight tricycles. City Harvest freight tricycles perform deliveries throughout the city, so the monitored vehicles did not enter the study area every day that they were monitored. In total, 29 unique days of data were collected from City Harvest trucks, including five days on which both monitored trucks made deliveries to the study area.

Each time a device was swapped out, the data was downloaded. The device allows export as a Microsoft Excel file as well as an .itm file, which is a proprietary project file format that allows for display of the data in Google Maps.

4.3 Data Processing

The QSTARZ BT-Q1000XT device manufacturer provides proprietary software that allows for visualization of trips in Google Maps from the raw collected data. Using the location and heading variables, the software allows the user to map and trace the path of the device. Using this software, all data collected from both City Bakery and City Harvest could be visualized to identify the vehicle path and vehicle stops. In visualizing the raw dataset, "drift points" could be observed, particularly at the location of vehicle stops; when it was clear a vehicle was parked, but it appeared to be moving slightly within a very small area. This software also has built in function to remove drift points. This function was found to be effective for removing drift points for vehicles parked for less than 45 minutes; however, for stops exceeding that duration, the software was ineffective in removing drift points. }To address this problem - and to ensure the removal of drift points given the lack of clarity in the algorithms employed by the proprietary software - an iterative process was also developed and implemented (Figure 3).

Figure 3. Data Filtering Process



Through manual review of each data set, approximate stop locations could be identified. These stop locations were then compared against lists of known stop locations. For City Bakery, identification of stop locations was relatively easy, as the freight tricycles mostly operate on fixed routes between a few locations. Stop locations that could not be easily identified were discussed and confirmed with vehicle operators. Once stop locations were identified, their addresses were geocoded as point locations in ArcGIS. A geographic buffer of 164 × 164 ft was then identified around the expected stop location; any vehicle entering the stop location for more than 120 seconds was assumed to be stopped until exit from the buffer. Any movement within the buffer was excluded from the analysis. The only point not coded in this manner was the Union Square Greenmarket. Because the vehicle's stop point could be anywhere within the market, the standard buffer was not sufficient to enclose all potential parking locations. Drift points within the Greenmarket were identified and corrected manually using the visualization software.

For City Harvest, the process of identifying stop locations was much more challenging, as City Harvest makes pickup and delivery stops in more than 120 Manhattan locations. First, stop locations were identified. Next, a list of donating partners was obtained from the City Harvest website. Google Maps was then utilized to search the blocks of the stop locations. If a stop was found to occur within one street block or 1/2 an avenue block of a donating partner location, it was identified as a pickup location. Recipient organizations were even more difficult to identify. While recipient partner names are published, their addresses were not as easily identified. Recipients were searched using an online database of homeless shelters (HSD 2014). From this database, a list of potential recipient addresses was generated. This list was then cross-referenced with stop locations using the same procedure as to identify delivery locations. In a few cases, both a potential donor and a potential recipient were within the defined area for a stop location. Generated lists of known and unknown stop locations were discussed with the City Harvest logistics manager; for some "unknown" locations, the drivers were able to identify the stop. Additional "unknown" stop locations remained; however, it was unclear if these locations were actual pickups or deliveries, or if they served other driver activities. Once final stop locations were identified, the same buffer procedure used to remove City Bakery drift points was used to remove City Harvest drift points. Stop locations that were not verified with the organizations were used to filter drift points, but were excluded from the analysis of stop durations to be discussed in the next chapter.

After application of these spatial buffers, data was further corrected through manual inspection. Tricycle speeds considered to be unreasonable (exceeding 30 mph or individual observations exceeding all other values by more than 5 mph) were removed from the analysis dataset. Similarly, for two specific corridors where vehicles were parked for long durations – 3rd Avenue and Avenue of the Americas (6th Avenue), a number of unexplained very low speeds were observed on four days; it is likely that these measures are additional drift-points not accounted for by the buffering technique. Because the reason for these unexpected values could not be determined definitively, data collected on these days was eliminated from the analysis.

4.4 Traffic Analysis Methods

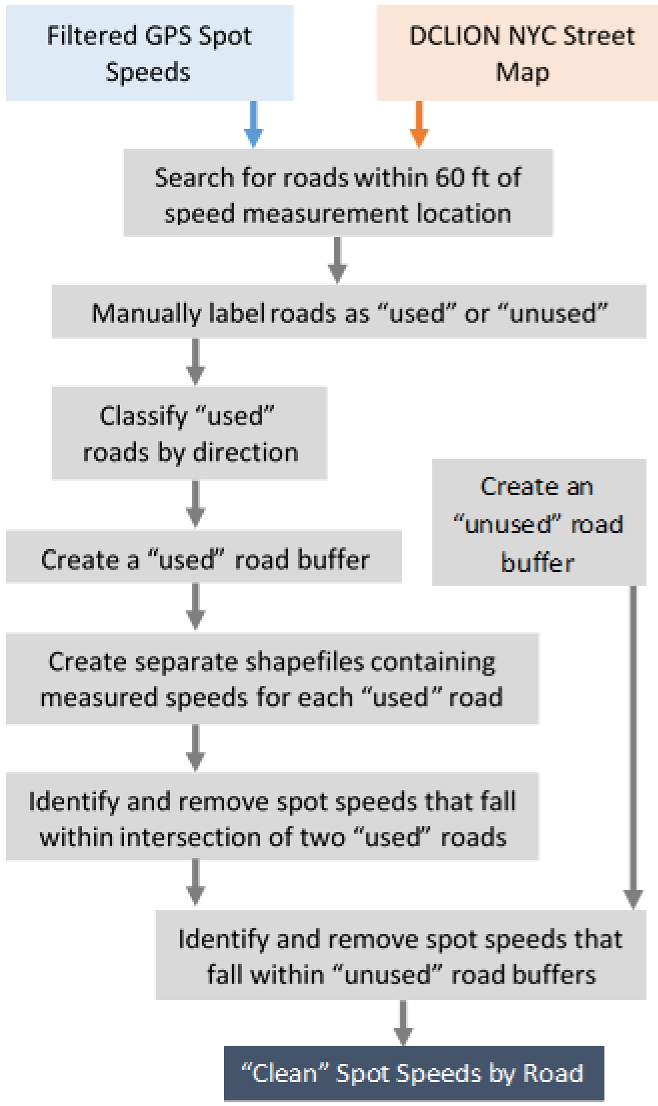
After initial filtering of the data and identification of vehicle stops, vehicle performance measures were estimated using spatial analysis in ArcGIS and data mining programs were developed in Visual Basic for Applications (VBA). The specific performance measures examined and the methods applied for their estimation and examination are described as follows.

4.4.1 Corridor Moving Speed

The aim of the corridor speed analysis is to understand the typical speed at which freight tricycles and trucks move on local streets, and to compare the results for each mode. The estimated values represent a moving speed; they do not account for vehicle stopped-time, which will be evaluated and discussed in Section 4.4.2.

This study seeks adapt methodologies from the previous studies discussed above for application in Manhattan's congested urban corridors. Given the relatively small size of the collected data set, speed measures were aggregated across blocks within each corridor. To account for traffic flow disruptions imposed by intersections, and to distinguish directional movements where "used" roadways intersect, spot speeds within 60 ft of any point of intersection were removed from the analysis dataset. A buffer distance of 60 ft was chosen to account for corridor widths (including vehicle and bicycle travel lanes, medians, parking lanes, and sidewalks) up to 120 ft. The procedure for removal of these data points is shown in Figure 4.

Figure 4. Process for Removing Intersection Spot Speeds



In traditional traffic studies, a harmonic mean speed is estimated to characterize traffic speeds; this mean is calculated by dividing the number of observations by the sum of the inverses of each observed spot speed. However, when using GPS data, extremely small speeds resulting from congested conditions result in a very large inverse, and ultimately skew the mean speed toward these low measures. In Manhattan conditions, where congestion is common, the impact of these points on the mean will be extreme. Quiroga and Bullock (1998) concluded that the median, or the 50th percentile speed, is a more robust estimator of central tendency (typical flow conditions) than harmonic mean speed. To account for the potential distortion due to the heavily congested conditions in the study area, median observed speeds have been estimated to characterize speeds on each road.

While the median provides an estimate of the typical speed on a roadway, it does not provide any information about the distribution of speeds along the roadway. In uncongested travel conditions, vehicle speeds are generally expected to be distributed approximately normally. However, when driver's speeds are limited by traffic congestion and other obstructions, the distribution of speeds will likely include a high frequency of low-speed observations and few high-speed observations. To visualize the distribution of speeds within each corridor, sample probability density functions have been plotted for each mode and for various categorizations within each mode. Corridor characteristics examined include directionality, classification as a truck route, presence of dedicated bicycle facility, and neighborhood.

The Manhattan road network is primarily a grid. Generally north-south "Avenues" are relatively wide corridors with much lower intersection densities than east-west "Streets." The majority of both Avenues and Streets carry one-directional traffic. In New York City, trucks are required to travel on designated local truck routes; they may only deviate from these routes to take the shortest path to their final destination. Figure 5 shows the designated local truck routes in the study area. In the last decade, the City of New York has also installed considerable mileage of designated on-street bicycle facilities. Figure 6 shows the Class 1 (buffer protected or grade separated) and Class 2 (standard on-street bicycle lanes) bicycle facilities in the study area.

Figure 5. Study Area Truck Routes

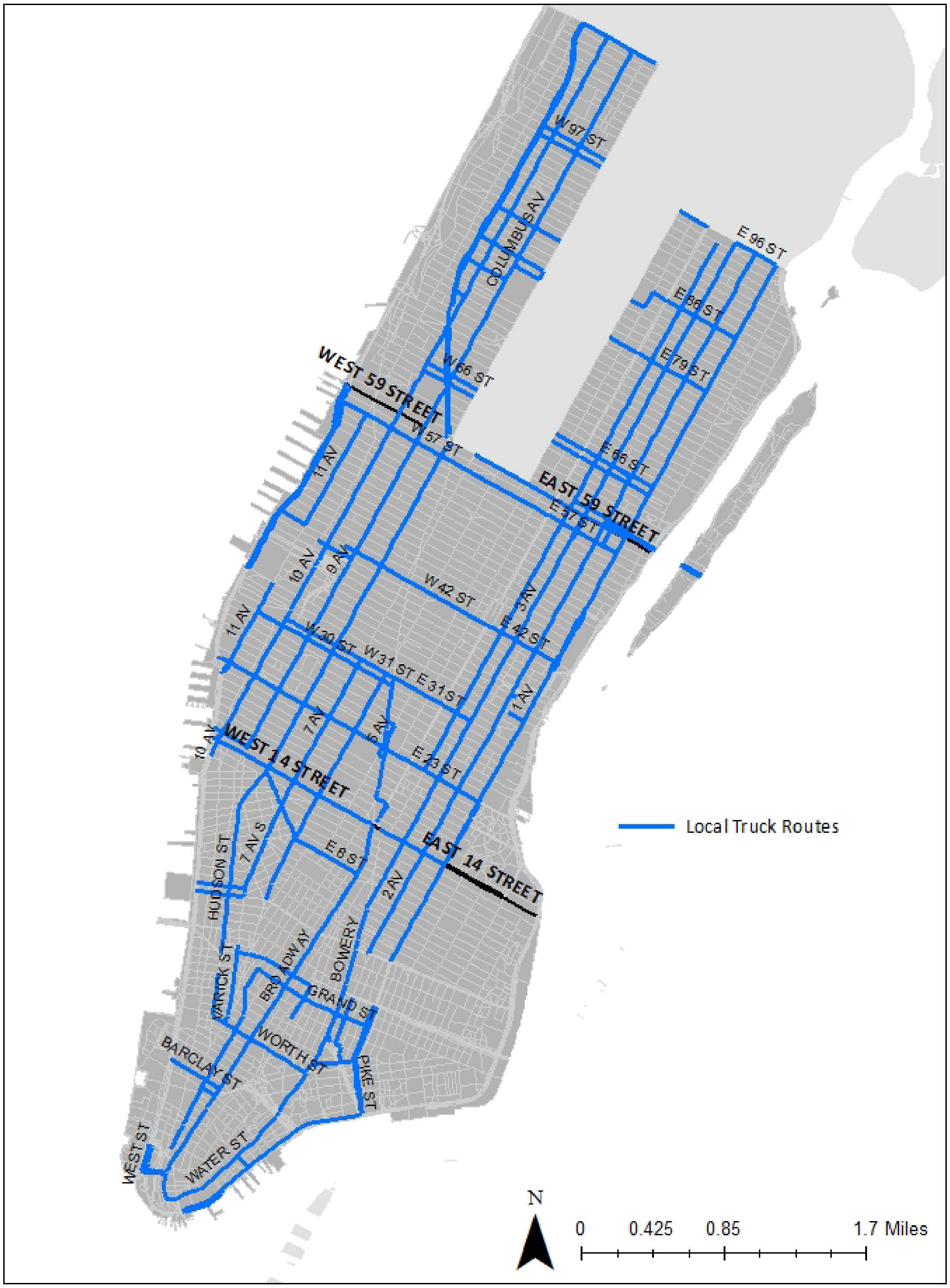
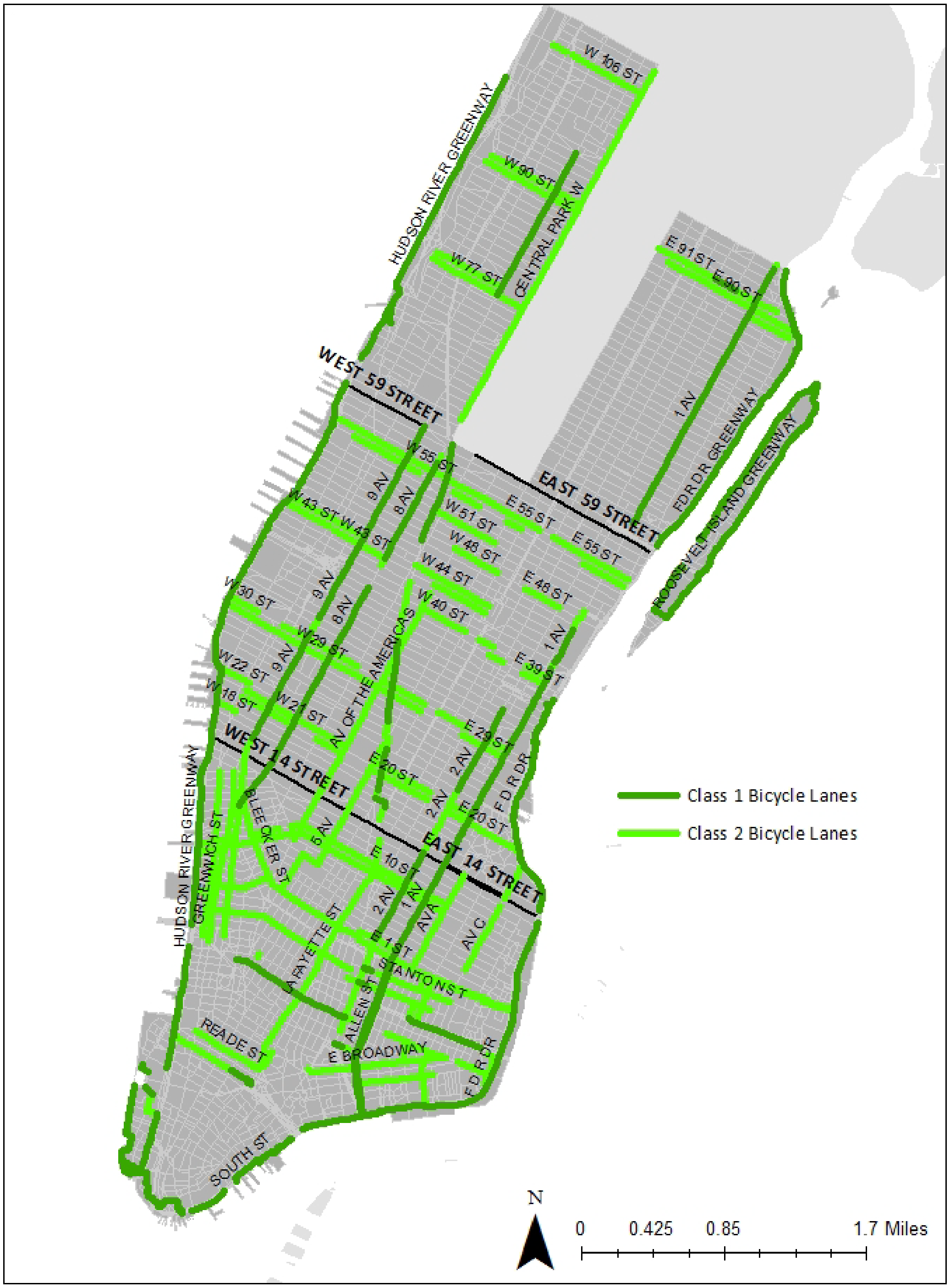


Figure 6. Study Area Dedicated Bicycle Infrastructure



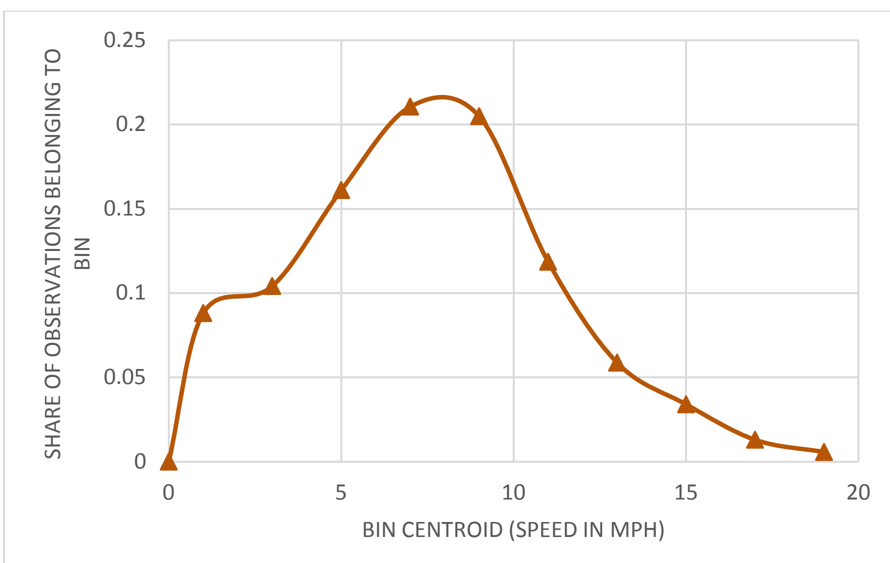
To plot the sample PDF for a filtered speed data set, the data had to first be sorted into speed range bins. For freight tricycles, speeds generally ranged from 0 to between 11 and 19 miles per hour, so a bin size of 2 mph was used to develop initial PDFs. For trucks, which mostly range from 0 to 30 mph, a bin size of 3 mph was used to maintain the same quantity of bins (10). For plotting of comparative distributions, a bin size of 3 mph was also used for freight tricycles. For each bin, the frequency of observations within the given speed range was determined. To allow for comparison of distributions across roadways with varying numbers of speed observations, the observed frequencies in each bin were divided by the total number of speed observations in the total dataset to obtain the percentage of observations belonging to that bin (Equation 1). Finally, the estimated percent of observations was plotted vs. the centroid of the speed range (e.g., for bin 0 to 2 mph, the centroid is 1). Figure 7 provides an example of a sample PDF.

$$p_b = \frac{F_b}{\sum_B F_x} \quad (1)$$

where:

p_b= share of observation belonging to bin b
F_b = frequency of observations belonging to bin b
F_X = frequency of observations belonging to bin x
B = set of all observed bins

Figure 7. Sample PDF Example



Speed observations were also aggregated across corridors to evaluate time-of-day differences. Four time periods were defined for analysis: the morning peak from 6:30 to 9:30 a.m.; the midday peak from 12:00 noon to 2:00 p.m., the evening peak from 4:00 p.m. to 7:30 p.m.; and the off-peak, which includes all other time periods between 9:30 a.m. and 10:00 p.m. These periods were identified based both on general operating hours for City Bakery and City Harvest and on typical Manhattan traffic conditions. While City Harvest trucks do operate in later hours, no truck data were collected during these periods due to limited battery life of the GPS device.

Once speed behavior was evaluated for each variable, the cumulative distribution of truck speeds was evaluated to examine the share of truck observations that feasibly could be reached by a freight tricycle. This evaluation also required the development of data bins; however, rather than identifying bin categories as regular intervals, bins were established with boundaries relating to the observed speeds for City Bakery and City Harvest freight tricycles. Operational characteristics impacting these observed speeds are discussed in detail in Section 5.

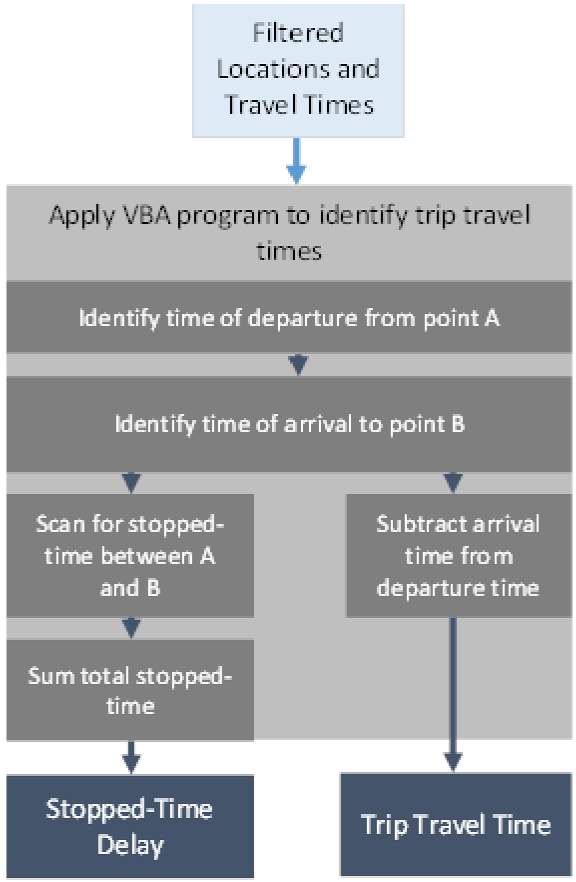
4.4.2 Trip Travel Time and Stopped-Time Delay

To examine the travel time reliability of freight tricycles in New York City conditions, two variables were estimated: travel time and stopped-time delay. The travel time measures the total time from when a vehicle departs an origin until it reaches a destination. Both origins and destinations are defined by their buffers. Once a vehicle enters the buffer, it is assumed to have arrived at a location; once it leaves the buffer, it is assumed to have departed. The stopped-time delay is the time that the vehicle is not moving during that trip. In this analysis, any vehicle standing in location for between 10 and 120 seconds was considered to be stopped. The maximum stopped-time value of 120 seconds corresponds to the maximum cycle length for traffic signals in Manhattan. A vehicle stopped for more than 120 seconds is assumed to be making a pick-up, delivery, or other unknown stop.

4.4.2.1 Variable Estimation

A VBA program was developed to estimate the total travel time and the stopped-time delay between two points. Figure 8 describes the functions of the program.

Figure 8. Process to Estimate Point-to-Point Trip Travel Times and Stopped-Time Delays

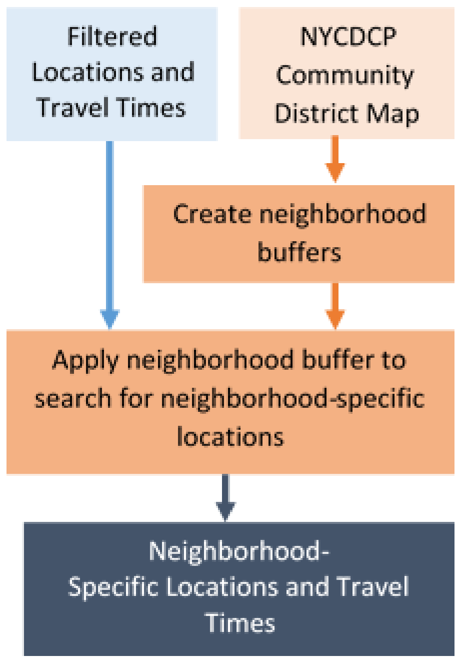


City Bakery operates on a limited network, with frequent and repeated trips primarily between eight locations – six bakeries, a market, and a maintenance location. Throughout the period of data collection, City Bakery's freight tricycles operated on consistent routes and daily schedules. As a result, specific point-to-point trips could be analyzed and compared directly.

City Harvest operates on a much more irregular network, with more than 120 Manhattan stop locations; as a result, repetition of individual trips during the period of data collection was not sufficient to examine the reliability of specific point-to-point trip pairs. Rather, City Harvest data was evaluated by examining trips classified by neighborhood and by time-of-day.

To evaluate trips within and between neighborhoods, City Harvest truck and tricycle stop locations were first coded by neighborhood before application of the VBA program. Four neighborhoods in Manhattan were identified: Lower Manhattan, which includes anything below 14th St; Midtown, which covers 14th St to 59th St (the lower end of Central Park), the Upper East and West Sides (59th St to 96th St on the East Side and 59th St to 110th St on the West Side), and Upper Manhattan, which covers any part of Manhattan further north. Upper Manhattan locations were excluded from further analysis due to lack of freight tricycle activity in that area. A neighborhood shapefile was then generated from the NYC Department of City Planning's Community District Map (NYCDCP 2014). Stop locations were then mapped in ArcGIS; using each defined neighborhood as a buffer, neighborhood-specific trip locations could be extracted (Figure 9). To evaluate time-of-day impacts on travel time reliability, start and end times were post-processed to identify trips beginning during certain time periods.

Figure 9. Process for Neighborhood Coding



4.4.2.2 Variable Analysis

Once travel times and stopped-time delays were estimated for each observed trip, comparative analysis could be performed. For City Bakery, point-to-point trip travel times and stopped-time delays could be evaluated directly to identify trip characteristics affecting these variables.

First, travel time and stopped-time delay mean and standard deviation for each point-to-point trip-end pair was estimated using Equation 2 and Equation 3. The mean is the average travel time for tricycles traveling from point a to point b. The standard deviation measures how much the observed speeds vary from the mean.

$$\bar{t}_{a,b} = \frac{\sum_i t_{a,b,i}}{N} \quad (2)$$

where:

- $\bar{\boldsymbol{t}}_{\boldsymbol{a,b}}$= average travel time from point a to point b
- $\boldsymbol{t}_{\boldsymbol{a,b,i}}$= travel time from point a to point b for observation i
- N = total number of observed trips from point a to point b

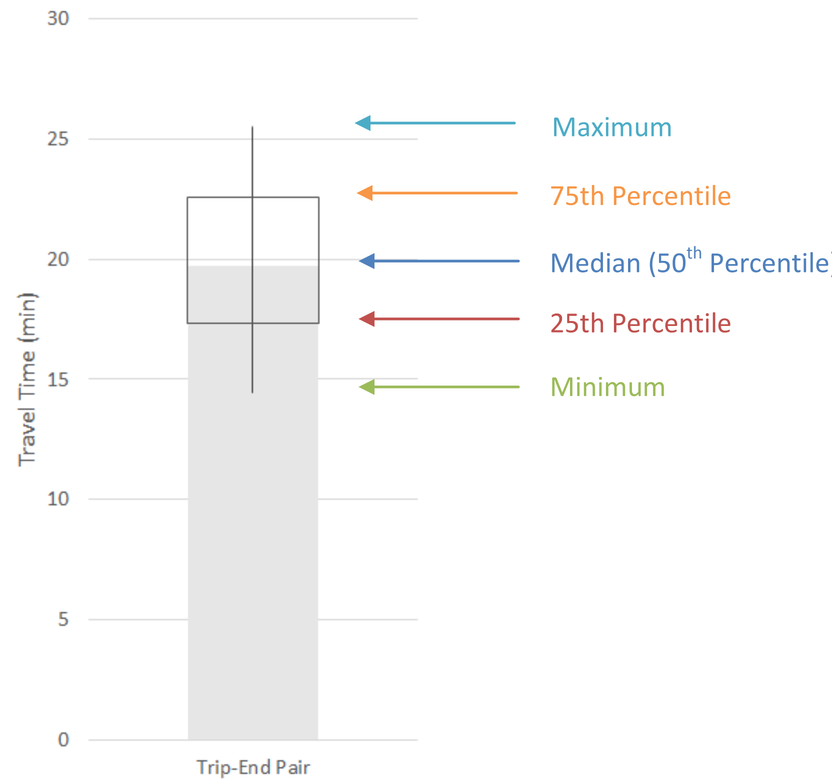
$$s_{a,b} = \sqrt{\frac{\sum_{i=1}^{N}(t_{a,b,i} - \bar{t}_{a,b})^2}{N-1}} \quad (3)$$

where:

- $\boldsymbol{s}_{\boldsymbol{a,b}}$ = standard deviation of travel times from point a to point b
- $\bar{\boldsymbol{t}}$ = average travel time from point a to point b
- $\boldsymbol{t}_{\boldsymbol{a,b,i}}$= travel time from point a to point b for observation i
- N = total number of observations in filtered dataset

For City Bakery, the variability in travel times was visualized through generation of a box plot. In a box plot, the spread of observed values is observed by plotting the median (50th percentile), minimum, maximum, and quartile (25th and 75th percentile) values. Figure 10 provides an example of a box plot.

Figure 10. Sample Travel Time Box Plot



Several trip characteristics were also examined to determine their influence on travel times and stopped-time delay. To examine the relationship between trip distance and trip travel time, the minimum distance path from origin to destination was estimated for each trip-end pair. Since the primary factor expected to influence delay for tricycles is stopped-time at intersections, a trip intersection density was also estimated by dividing the total number of intersections along the minimum distance path by the estimated trip distance (Equation 4).

$$\boldsymbol{k} = \frac{\boldsymbol{d_{a,b}}}{\boldsymbol{I_{a,b}}} \qquad (4)$$

where:

- $\boldsymbol{k_{a,b}}$= estimated intersection density along path from origin a to destination b
- $\boldsymbol{d_{a,b}}$= travel distance along minimum distance path from origin a to destination b
- I = estimated number of intersections crossed along minimum distance path

Finally, the average moving speed for trips traveling across variable distances was evaluated. This average moving speed was estimated as shown in Equation 5 by first identifying the moving time as the difference between the travel time and the stopped-time delay, and then dividing by the estimated distance traveled:

$$\boldsymbol{u_{a,b}} = \frac{\boldsymbol{d_{a,b}}}{\boldsymbol{\bar{t}_{a,b} - st_{a,b}}} \qquad (5)$$

where:

- $\boldsymbol{u_{a,b}}$= average moving speed from point a to point b
- $\boldsymbol{d_{a,b,i}}$= travel distance along minimum distance path from origin a to destination b
- $\boldsymbol{st_{a,b}}$= average stopped-time for trips from point a to point b
- $\boldsymbol{\bar{t}_{a,b}}$= average travel time from point a to point b

For City Harvest freight tricycles and trucks, point-to-point trip travel time and stopped-time delay variability could not be directly evaluated because trip patterns were highly variable. However, trip behavior could still be explored by estimating the ratio of stopped-time delay to travel time for different trip types. Ratio values range from zero to one. A ratio of zero indicates that a vehicle experiences no delay during a trip. A ratio of 0.5 indicates that half of the total trip time is accounted for by stopped-time delay. Once ratios were calculated for each observation (Equation 6), the distribution of these variables could be examined.

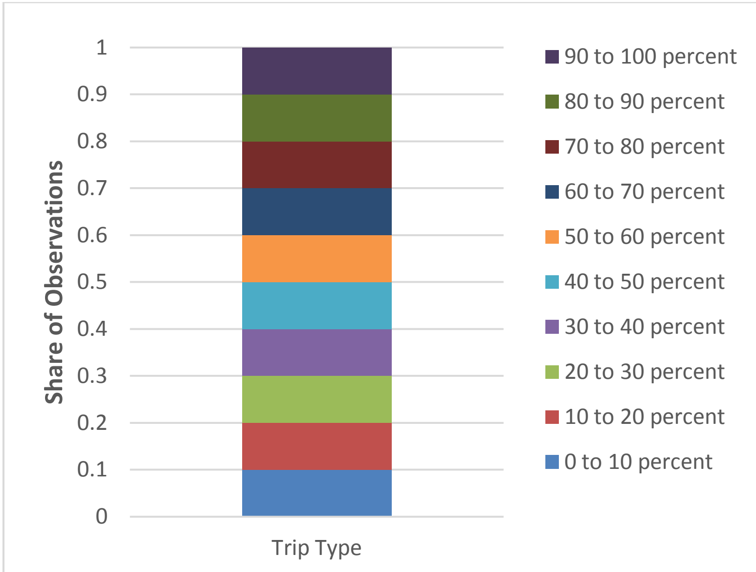
$$\boldsymbol{r_i} = \frac{\boldsymbol{st_i}}{\boldsymbol{t_i}} \qquad (6)$$

where:

- $\boldsymbol{r_i}$= stopped-time to travel time ratio for trip observation i
- $\boldsymbol{st_i}$ = estimated stopped-time for trip observation i
- $\boldsymbol{t_i}$= estimated travel time for trip observation i

Ratios were sorted into bins at 10 percent intervals; each bin contains the frequency of observations for that ratio interval. For example, the “0 to 10 percent” bin contains the number of trip observations for which the ratio of stopped-time delay falls between zero and 0.1. Next, share of observations in each bin for each trip type can be determined by dividing the bin frequency by the total number of trip observations. For City Bakery, trip types were defined by the end points of the trip; for City Harvest, trip types were defined by neighborhood and time-of-day. Distributions could then be plotted as described above for speed observations. Ratios could also be plotted cumulatively to determine the share of total observations less than the maximum bin value by examining its position along the y axis (Figure 11).

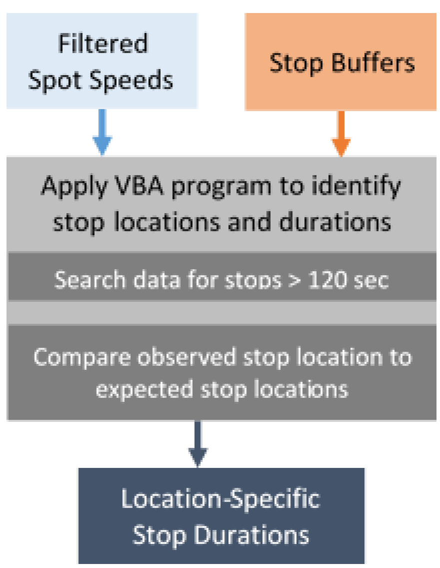
Figure 11. Cumulative Plot of Ratio Observations



4.4.3 Stop Durations

To evaluate the stopping behavior – and related parking demand – for each partner and mode, stop durations were estimated. Like trip travel time, stop durations were estimated through implementation of a VBA program, as shown in Figure 12.

Figure 12. Process to Estimate Location-Specific Stop Durations

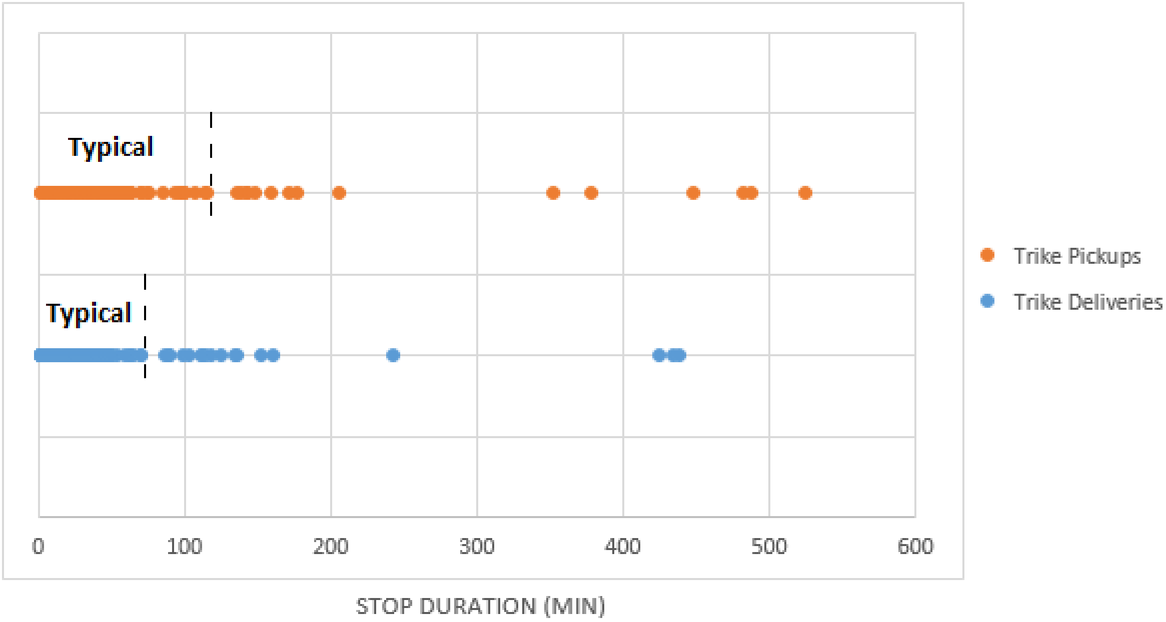


Stop purposes vary between and even within partner operations. As discussed previously, City Bakery performs both scheduled and on-demand deliveries between a small set of stores. City Bakery's freight tricycles are expected to spend longer durations at the flagship locations, where they will load goods, and relatively shorter durations at satellite locations, to which they deliver the demanded goods.

As discussed previously, with very high and overlapping densities of donors and recipients, it was more difficult to 1) identify stop locations and 2) to distinguish pick-ups from deliveries for City Harvest freight tricycles. In Manhattan, City Harvest trucks exclusively deliver goods; their loading activity occurs at the Long Island City warehouse, which is outside the scope of this analysis. As a result, all stops made by the trucks in the vicinity of a partner organization were assumed to be delivery stops. City Harvest's trucks generally carry large quantities of non-perishable goods, and can carry up to 2,200 lbs. In contrast, City Harvest's freight tricycles carry much smaller loads (50 to 500 lbs) of fresh or perishable goods. The tricycle operators have more autonomy than the truck drivers; they make multiple pickup and delivery stops on each tour, and they use their own discretion to determine routes and orders of recipients.

For City Harvest freight tricycles, highly variable stop times were observed with some very long stop durations. Some variability is expected due to the nature of City Harvest's operations as discussed in detail in Section 5. However, the extreme long durations are very unlikely to represent typical pick-ups and deliveries. To distinguish typical operations from unusual events, both pick-up and delivery durations were plotted. As shown in Figure 13, for each dataset, a natural break in the data was clear. For City Harvest tricycle pickups, this break occurred at a duration of 115.1 minutes; for tricycle deliveries, it occurred at a duration of 70.1 minutes. These values were assumed to be the dividing point between typical and atypical operations. Stop duration analysis was performed considering only typical values, which encompassed 325 of the initial 353 observed stops. For City Harvest trucks, only a single outlier duration was identified and removed from the analysis.

Figure 13. Observed Stop Durations



Once the final set of stop durations was identified, stop duration trends were evaluated by operator, stop type, neighborhood, and time of day. Means and standard deviations were estimated using the same procedures described above for trip travel time. Data was again sorted into bins, here using 10-minute stop duration ranges. These bins were then plotted as a histogram to examine trends.

4.5 Impact Analysis Methods

In addition to understanding the performance of freight tricycles compared to motorized vehicles, it is also necessary to understand their impacts on the communities they serve and the streets on which they operate. Here two types of impacts are quantified: road and parking space consumed and emissions generated – including both air quality pollutants and greenhouse gas. To provide a broad discussion of these impacts, City Harvest and City Bakery case studies were examined.

4.5.1 Space Consumption Rates

A primary benefit of freight tricycles compared to motorized delivery vehicles is their flexibility to operate and park on a variety of infrastructure types. Where policies allow, they can travel either on motorized travel lanes or on dedicated bicycle infrastructure. Where space allows, they can also park on the street or on the sidewalk.

4.5.1.1 Vehicle Dimensions

To quantify the space savings for freight tricycles compared to motorized vehicles, their length and footprints were examined first. In this analysis, four comparative motorized vehicle types were examined: a passenger car, a cargo van, a 14-ft step van, and box trucks ranging from 14 ft to 24 ft. The estimated passenger car specifications were based on the Ford Crown Victoria –the most common vehicle in New York City's taxi fleet (Schenkman 2006). Cargo Van specifications were estimated using dimensions from a specific cargo van, the GMC Savannah. Step van dimensions are highly variable, as these vehicles are generally custom built on a chassis, making estimation of a standard payload difficult; however, the estimated specifications were based on those of a Freightliner MT45 14 Step Van, which has a nearly identical footprint to the Hino 195H – the most common 14-ft box truck currently operated in City Harvest's truck fleet. City Harvest also operates a number of Freightliner M2106 18 ft box trucks and Hino 338 24-ft box trucks; these vehicles were also evaluated. A second type of cargo tricycle– the Lovelo CargoCycle© V2, which is used in delivery operations in both Paris and London – was also examined. Although the selected vehicles are not nearly exhaustive of all of the possible configurations of urban delivery vehicles, they do provide a sample to discuss the trade-offs between vehicle types.

4.5.1.2 Travel Time

Although the trike's small length and footprint are desirable in urban conditions, these characteristics do come at the cost of lost speed potential. To quantify road space consumption, the amount of time over which it occupies road space must be considered in addition to the vehicle's footprint. While larger vehicles occupy less instantaneous space, if they travel at a higher speed, they could occupy fewer square foot * hours than a smaller vehicle traveling at a lower speed. To quantify road space consumption in New York City conditions, expected travel times can be estimated from the observed median speeds discussed in the previous section, and from newly estimated delay time to moving time ratios calculated for all City Bakery and City Harvest trips. These ratios were estimated using Equation 6:

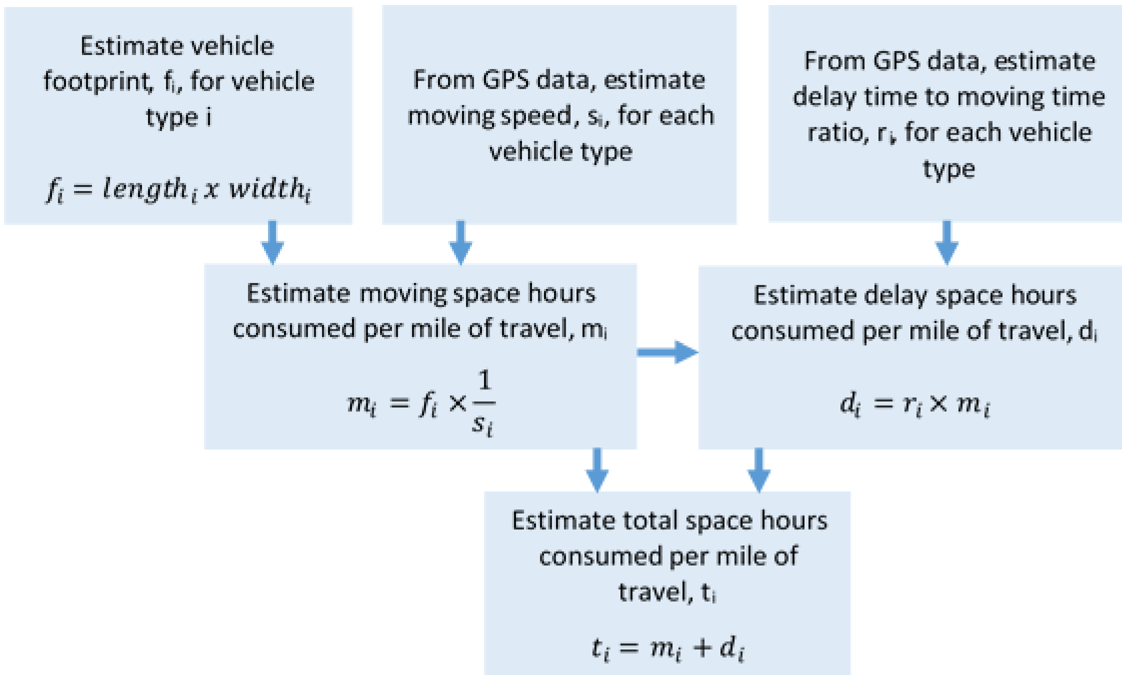
$$\boldsymbol{r_i} = \frac{\boldsymbol{st_i}}{\boldsymbol{t_i} - \boldsymbol{st_i}} \qquad (\boldsymbol{6})$$

where:

- $\boldsymbol{r_i}$= stopped-time to travel time ratio for trip observation i
- $\boldsymbol{st_i}$ = estimated stopped-time for trip observation i
- $\boldsymbol{t_i}$= estimated travel time for trip observation i

Assuming that all motorized delivery vehicles will travel at the same speeds observed for City Harvest trucks, space consumption rates per mile of travel for each vehicle type could be estimated (Figure 14).

Figure 14. Process to Estimate Vehicle Type Road Consumption Rates



4.5.1.3 Parking Time

Parking space consumption was determined by multiplying the vehicle's footprint by it parking duration. As discussed in Section 5, parking duration will vary depending on the size of the pickup or delivery made and the characteristics of the producer or receiver. Due to this variability and observed differences between operators, average consumption rates were not estimated; however, specific conditions are discussed in the City Bakery and City Harvest case studies.

4.5.1.4 Vehicle Capacities

Freight tricycles also have limited cargo volumes and payloads compared to motorized vehicles; these measures can be identified and directly compared for each vehicle type. Although cargo cycles generally carry smaller loads and may be less efficient for moving large loads, they may be a more efficient means of transportation in supply chains where individual loads are small and storage space in larger vehicles would be underutilized. For both of the tricycle users examined in detail in this study, freight tricycles provide a "right size" vehicle for their operations. Trade-offs related to vehicle capacity are also discussed in each case study.

4.5.2 Emissions Impacts

Another major benefit of freight tricycles compared to motorized delivery vehicles is savings in both air pollutant and greenhouse gas emissions. The freight tricycles in use by both City Bakery and City Harvest are completely human-powered; they consume no fossil fuels and require no external energy production. As discussed previously, urban delivery vehicles contribute a considerable portion of mobile-source air pollutants in urban areas. They also contribute considerable greenhouse gas emissions. To quantify the pollutant and greenhouse gas savings for freight tricycles compared to motorized vehicles, the U.S. Environmental Protection Agency's (EPA's) Motor Vehicle Emissions Simulator (MOVES) was used to estimate emissions factors for the four vehicle types previously described. Pitera, Sandoval, and Goodchild (2011) identified the equivalent MOVES vehicle classes for each of the four vehicle types: passenger car, passenger truck (cargo can), light commercial truck (LCT) (step van), and single-unit short-haul truck.

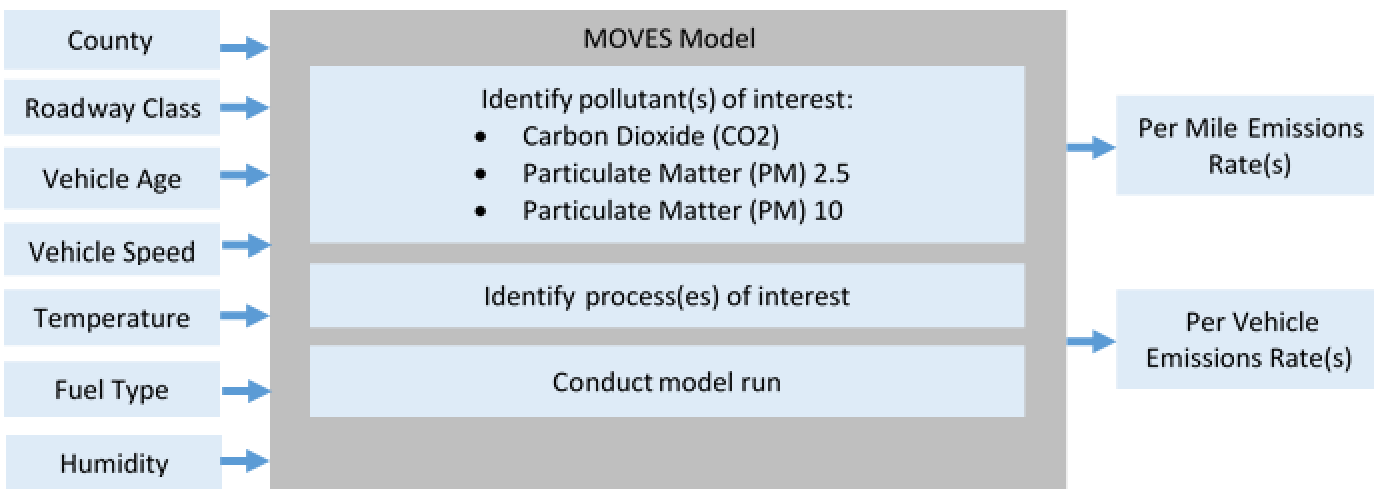
While the MOVES model provides estimates for a broad range of pollutants, three specific pollutants were chosen for comparison – particulate matter less than 10 µm in diameter (PM10), PM 2.5, and carbon dioxide (CO_2). Particulate matter (PM) is produced during fossil fuel combustion when organic compounds and oxides adhere to a carbon core (Schoemaker 2006). The human upper respiratory tract can block entry of particles larger than 10 µm, but when particle sizes are smaller, they can enter the lungs and bloodstream, causing heart and respiratory problems. Additionally, particulates can damage buildings, waterways, and other structures, and very fine particulates (< 2.5 µm) are also a primary cause of visibility problems in many U.S. cities. CO_2 is the most common greenhouse gas generated by human activity. Greenhouse gases trap heat in the Earth's atmosphere, impacting climate and related natural processes. In the U.S., transportation sources – including motor vehicles – produce close to a third of total greenhouse gas emissions (U.S. EPA 2014).

Vehicles emit pollutants during a number of processes, including start up, acceleration, deceleration, parking, and while moving. The MOVES model estimates emissions rates associated with specific engine processes. The model then combines processes that occur while moving and during idle conditions to provide estimates of per mile and per vehicle emissions rates. Because per vehicle estimates assume a cold engine start – a condition that would only be true at the initial origin location during a dense urban tour – this study focuses only on the moving emissions, applying estimated per mile rates to quantify emissions generated during travel. The MOVES model's estimated emissions rates are sensitive to a number of vehicle, fuel, and environmental variables; estimated rates will change depending on road type, fuel type, vehicle age, vehicle speed, temperature, and humidity (Figure 15).

As acceleration and deceleration significantly increase emissions rates, greater emissions would be expected on local urban streets than on access-controlled freeways. Because emissions are a direct function of fuel consumed, rates will vary when fuel types or fuel components vary. Engine efficiencies also vary with age; as federal fuel economy standards and engine emissions standards have become more stringent, newer vehicles burn less fuel more efficiently.

Similarly, vehicles operating at high speeds burn fuel more efficiently; as a result, emissions rates per mile are higher for slow-moving vehicles. The environment where vehicles operate – including both temperature and humidity – can also influence emissions rates. For example, the Kansas City Light-Duty Vehicle Emissions Study, which served as a basis for development of light-duty components of the MOVES model, found that PM emissions rates grow exponentially when temperatures decrease (Nam et. al. 2010). Because the study area encompasses only urban Manhattan streets, the road type in this study was fixed as “Urban Unrestricted Access.” For the passenger car, the fuel type analyzed was gasoline; for the other vehicle types, diesel fuel was assumed. Vehicles ranging from 1 to 10 years in age were evaluated to examine the impacts of age variables on the emissions rate. Speeds ranging from 3 mph (extreme congestion) to 15 mph (about 73rd percentile observed speed) were examined to understand speed impacts. Emissions were also estimated under typical January and July NYC weather conditions to identify weather-sensitivity for each pollutant. Finally, emissions factors were estimated under observed median speed conditions and applied to typical City Bakery and City Harvest operations to identify a range of potential emissions savings for each case study.

Figure 15. MOVES Model Inputs and Outputs



5 Traffic Data Analysis Results

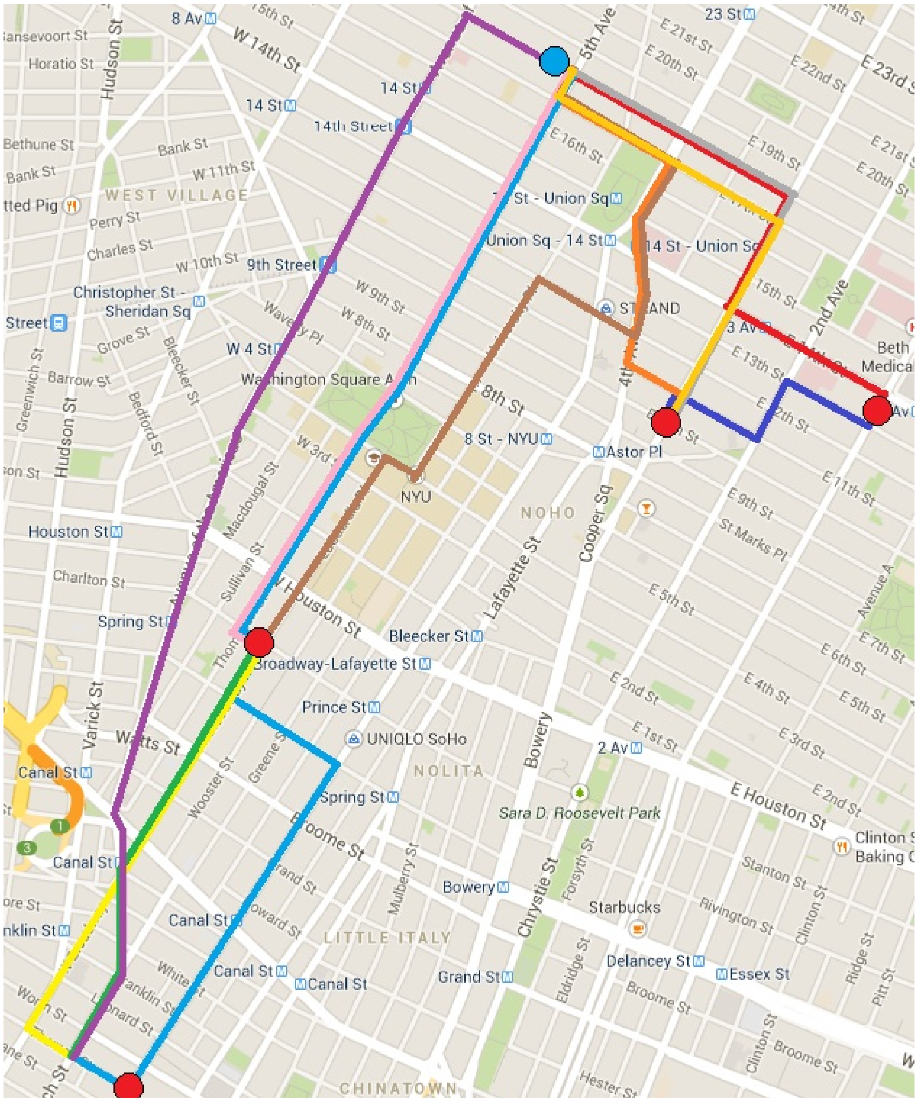
5.1 Typical Operations

As discussed in the previous chapter, City Bakery and City Harvest operate very different pick-up and delivery models. City Bakery's two tricycles primarily operate from their flagship bakery at 3 West 18th Street. At the beginning of the day (usually around 8 a.m., although occasionally as early as 6:30 a.m.), the freight tricycles make a morning tour; together the freight tricycles visit each of the company's bakery locations. Goods are primarily produced at three locations – the flagship store as well as two Birdbath Bakery locations at 200 Church Street and 160 Prince Street. After this tour, the tricycles return to the flagship location. Throughout the day, they are dispatched on-demand as needed to move goods between "producer" and "recipient" locations. Goods move fluidly throughout the network; while three of the bakery locations are the primary producers of goods, as demands shift, goods may move to between "recipient" locations or even back to locations where they were produced. Figure 16 shows a typical daily route for a City Bakery trike. This route consists of two multi-stop tours as well as two direct trips to a single location, and covers an estimated total distance of 11.7 miles.

While City Bakery freight tricycles operate from a central hub, City Harvest freight tricycles operate very long and complex tours, with no intermediate return to a base location. City Harvest drivers begin their tour at midday from Revolution Rickshaws' warehouse on W. 31st St. The freight tricycles then complete alternating pick-ups and deliveries throughout the course of the day. After picking up a sufficient volume of materials from one or more donor locations, tricycle drivers deliver these goods to recipient locations. Generally, they return to Revolution Rickshaws very late in the evening between 11 p.m. and midnight. Figure 17 shows a typical tour for a City Harvest trike. This tour consists of 20 total stops, with 12 pickups from donors and 8 deliveries to recipients. The total distance traveled during this tour is 15.1 miles.

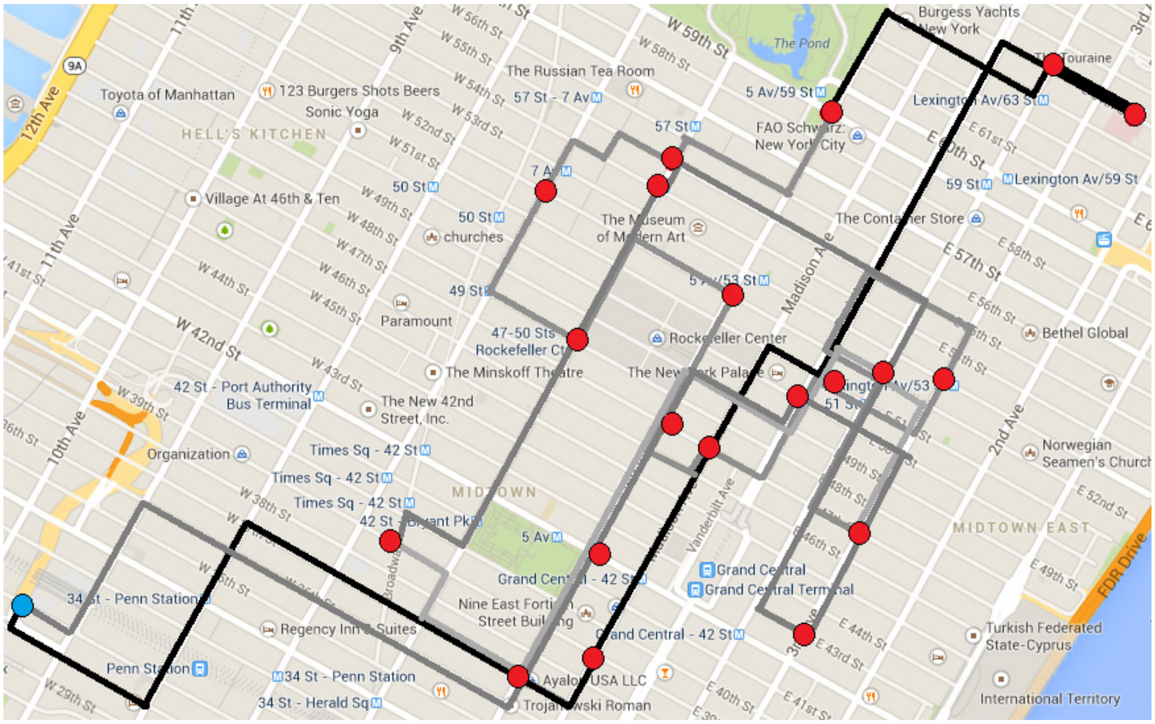
City Harvest trucks operate from the warehouse in Long Island City. Generally, they leave the warehouse around 8 a.m. to complete a delivery tour, usually concentrated in Uptown Manhattan and on the Upper East and West Sides. This early tour usually lasts until around 2:30 - 3 p.m., at which time the vehicles return to the Long Island City warehouse. Upon return the truck may be reloaded, and will return for an evening tour with stops in Midtown and the Upper East Side, usually arriving around 5:30 p.m. and returning to Long Island City late in the evening.

Figure 16. City Bakery Typical Tricycle Tour



Link	Origin	Destination	Distance (mi)
1	3 West 18 St	223 1st Avenue	0.9
2	223 1st Avenue	35 3rd Ave	0.5
3	35 3rd Ave	3 West 18 St	0.9
4	3 West 18 St	200 Church St	1.9
5	200 Church St	160 Prince St	0.8
6	160 Prince St	200 Church St	0.8
7	200 Church St	3 West 18 St	1.9
8	3 West 18 St	160 Prince St	1.1
9	160 Prince St	3 West 18 St	1.1
10	3 West 18 St	35 3rd Ave	0.9
11	35 3rd Ave	3 West 18 St	0.9
Total Distance Traveled			**11.7**

Figure 17. City Harvest Typical Daily Tour



Link	Origin	Destination	Destination Type	Distance (mi)
1	31st/Dyer	39th/ Madison	Pickup	1.4
2	39th/ Madison	51st/ Lexington	Delivery	0.8
3	51st/ Lexington	64th/ 3rd	Pickup	0.8
4	64th/ 3rd	64th/ Lexington	Delivery	0.2
5	64th/ Lexington	59th/ 5th	Delivery	0.5
6	59th/ 5th	55th/ 6th	Pickup	0.4
7	55th/ 6th	52nd/ 7th	Pickup	0.3
8	52nd/ 7th	48th/ 6th	Pickup	0.4
9	48th/ 6th	52nd/ 5th	Delivery	0.4
10	52nd/ 5th	47th/ Madison	Pickup	0.5
11	47th/ Madison	53rd/ 3rd	Pickup	0.6
12	53rd/ 3rd	47th/ 3rd	Pickup	0.9
13	47th/ 3rd	52nd/ Lexington	Pickup	0.4
14	52nd/ Lexington	37th/ 5th	Pickup	1
15	37th/ 5th	39th/ Broadway	Pickup	0.6
16	39th/ Broadway	54th/ 6th	Pickup	0.9
17	54th/ 6th	43rd/ 3rd	Delivery	1.3
18	43rd/ 3rd	50th/ Park	Delivery	0.9
19	50th/ Park	47th/ 5th	Delivery	0.5
20	47th/ 5th	43rd/ 5th	Delivery	0.2
21	43rd/ 5th	31st/Dyer	Storage	2.1
Total Distance Traveled				15.1

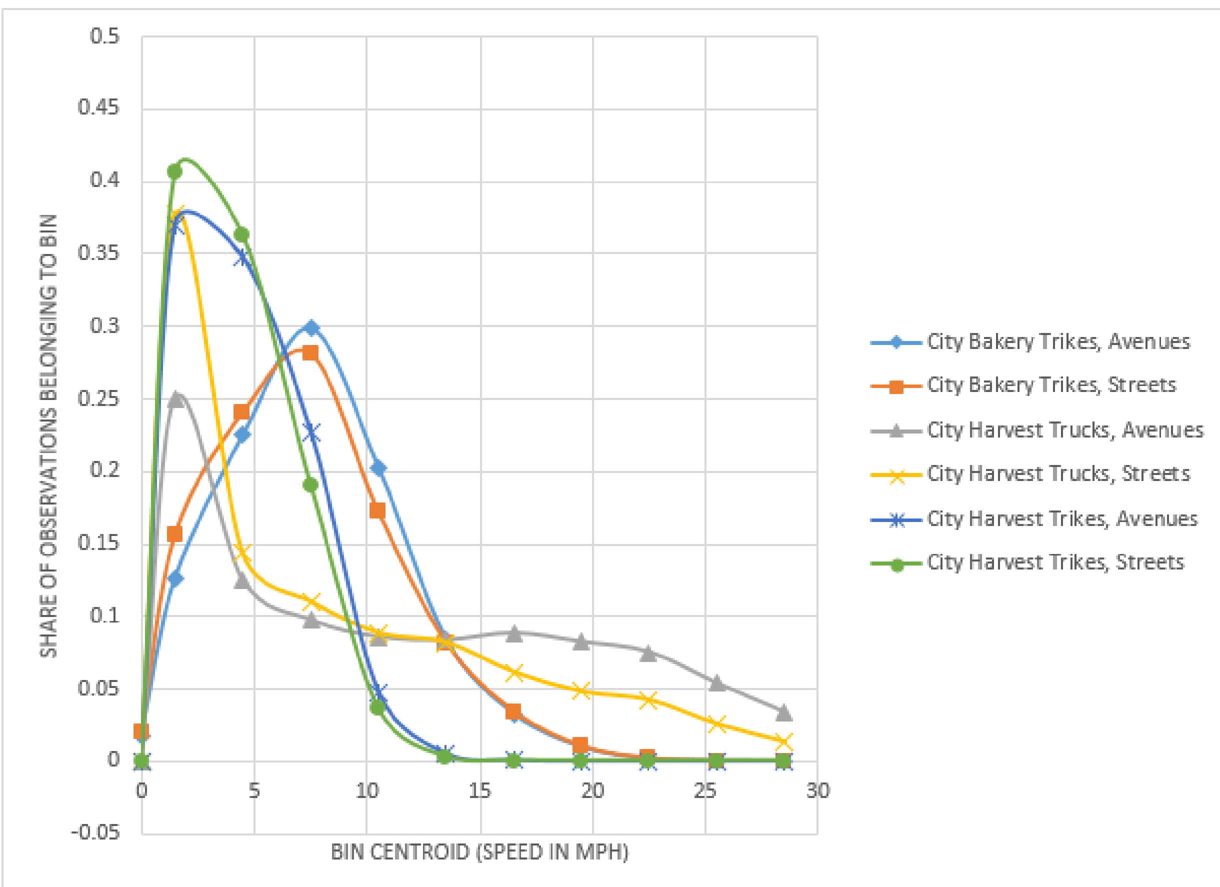
5.2 Traffic Performance Measures

To evaluate the traffic performance of these freight tricycles in New York City conditions, three separate analyses were conducted to examine corridor moving speeds, trip travel times and stopped-time delays, and stop durations.

5.2.1 Corridor Moving Speeds

Applying the methods described in the previous chapter, median moving speeds were estimated for City Bakery tricycles, City Harvest tricycles, and City Harvest trucks. Figure 18 shows the distributions of aggregated speed observations for each partner and mode over the course of all trips within the study area. Distributions for each individual corridor are provided in Appendix B. It is clear from this figure that the operating characteristics are very different between modes, as well as between the different tricycle operators. The following sections examine each distribution in detail to identify the factors influencing these speed differences.

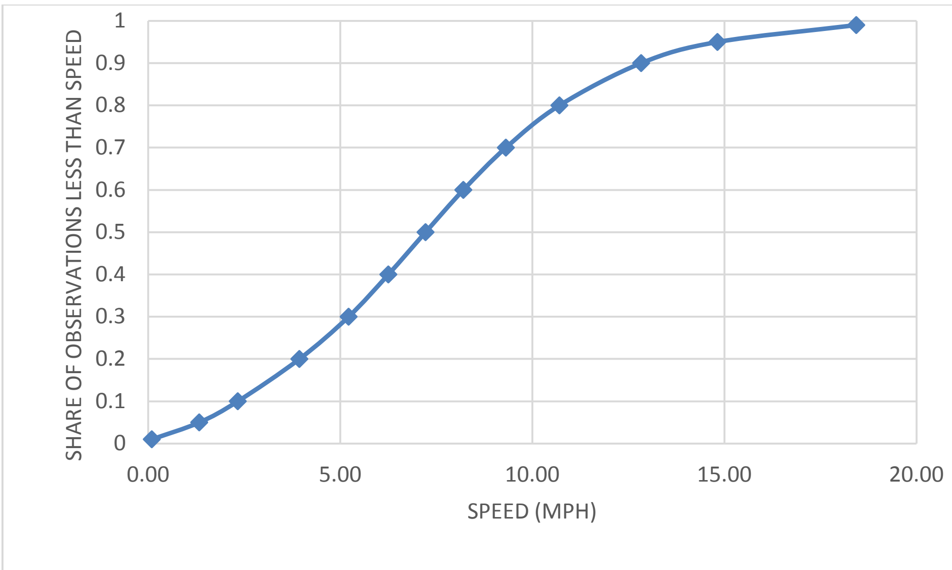
Figure 18. Observed Speed Distributions by Partner, Mode, and Direction



5.2.1.1 City Bakery

City Bakery freight tricycles operate primarily in downtown and lower Midtown Manhattan; a map of the City Bakery service area, including the locations of final observed speeds for analysis, is provided in Appendix C. The freight tricycles operate at a median speed of 7.2 miles per hour. Speeds generally range from zero to 15 mph, with about five percent of observations exceeding those speeds (Figure 19).

Figure 19. City Bakery Tricycles - Cumulative Distribution of Speeds



As demonstrated in Table 6, speeds are generally consistent across all corridors. Observed median speeds on Avenues (7.4 mph) are slightly higher than on Streets (6.9 mph); this is expected because Avenues consist of longer blocks with a lower density of intersections, allowing travelers to travel at sustained higher speeds for longer durations. Despite the slight difference in medians, however, the speed distributions on each road type are very similar; speeds appear to be distributed lognormally, with few very low speed observations, and even fewer outlying high speeds observed.

Table 6. City Bakery Tricycle Median Observed Speeds

Roadway	Observations		Median Speed (mph)	Truck Route	Dedicated Bike Lane
	Count	Minutes			
All Avenues	**52467**	**1748.9**	**7.4**		
9th Ave	367	12.2	9.2	X	Class 1
8th Ave	485	16.2	8.7	X	Class 1
Union Sq W/University Pl/Washington Sq E	3015	100.5	8		
4th Ave/Union Sq E /Lafayette St	2520	84	7.8	X	Class 2
1st Ave	674	22.5	7.7	X	Class 1
6th Ave	14928	497.6	7.5	X	Class 2
LaGuardia Pl/W Broadway	7696	256.5	7.5		
5th Ave	8105	270.2	7.4		Class 2
3rd Ave	1428	47.6	7.3	X	
2nd Ave	4258	141.9	7.2	X	Class 1,2
Bowery/Cooper_Sq	1508	50.3	7	X	
Irving	1171	39	6.7		
Broadway	3719	124	6.6	X	Class 2
Thompson	2593	86.4	6.4		
All Streets	**30598**	**1019.9**	**6.9**		
8th St	602	20.1	8.3	X	
E 11th St	1214	40.5	7.5		
E 12th St	2142	71.4	7.5		
E 13th St	1528	50.9	7.5		
Prince	2047	68.2	7.5		Class 2
14th St	2956	98.5	7.4	X	
Houston	585	19.5	7.4		
W 30th St	102	3.4	7.2	X	Class 2
16th St	6667	222.2	6.9		
9th St	843	28.1	6.7		Class 2
17th St	673	22.4	6.7		
W 31st St	354	11.8	6.7	X	Class 2
15th St	1093	36.4	6.6		
18th St	5254	175.1	6.6		
Thomas	324	10.8	6.5		
E 10th St	3439	114.6	6.4		Class 2
Stanton	359	12	5.8		

Infrastructure factors may impact the speed at which vehicles travel. On roads with wide lanes or shoulders or with dedicated bicycle infrastructure, freight tricycles may be able to bypass stopped or slow-moving motor vehicles. As discussed in the previous chapter, in Manhattan, north-south moving Avenues are generally higher capacity corridors than east-west Streets. The Avenues have longer blocks (and as a result, fewer intersections) and more and wider lanes than Streets, with the exception of a few major cross-town corridors. Many of these major cross-town connectors are designated local truck routes. Figure 20 shows the distribution of speeds on designated truck routes of each road type. The shapes of the distributions are very similar for truck and non-truck routes for both Avenues and Streets, although frequencies of the lowest speeds (zero to 2 mph) are higher on non-truck routes. Examining the medians, there is very little difference between Avenues designated as truck routes and those that are not; both have median observed speeds of 7.4 mph. However, for Streets, there is a notable difference in speeds; at 7.5 mph, the observed median on the designated truck routes is actually higher than those on both sets of Avenues. Non-truck route Street speeds are slightly lower, with a median of 6.9 mph.

Figure 20. City Bakery Tricycle Speed Distributions, Truck Route vs. Non-Truck Route

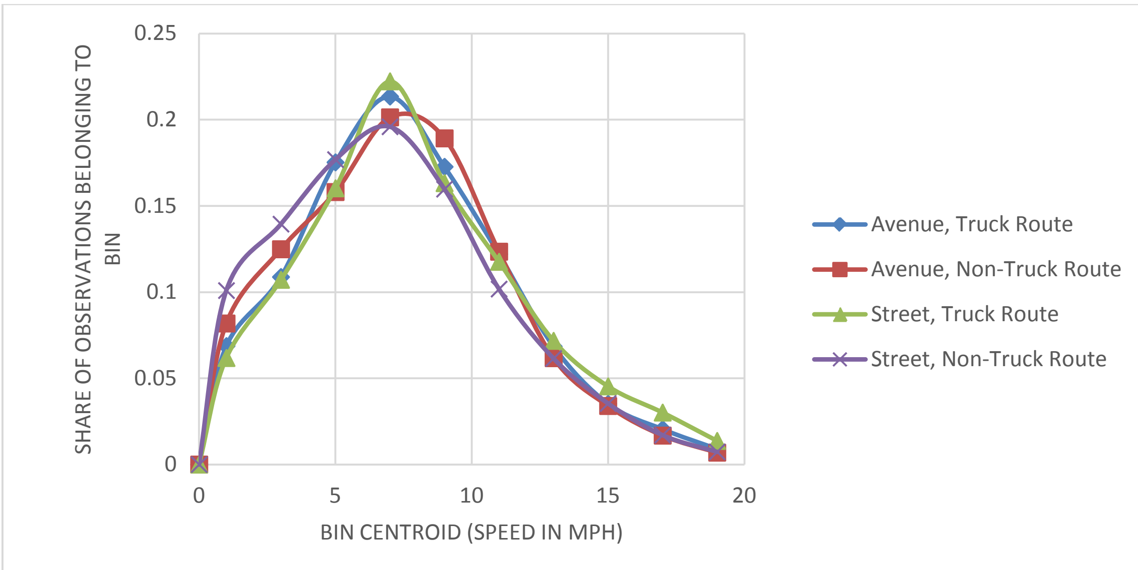


Figure 21 demonstrates the speeds of City Bakery freight tricycles on roads that include dedicated bicycle infrastructure. For Avenues, median observed speeds increase with the amount of protection provided to the cyclist, but the absolute difference is very small. Median speeds on Avenues with Class 1 lanes, Class 2 lanes, and no dedicated bike lanes are 7.5 mph, 7.4 mph, and 7.3 mph, respectively. In should be noted from Table 6 that three of the five fastest observed Avenue median speeds occurred on roads with Class 1 bicycle lanes; however, the fourth, on which speeds were considerably lower, has a dominant sample size, resulting in a smaller median value. On crosstown Streets, bicycle lanes do not appear to have a positive impact on speed; the median speed on the four streets with dedicated Class 2 bicycle lanes (6.8 mph) is slightly slower than on those with no dedicated bicycle infrastructure (7.0 mph).

Figure 21. City Bakery Tricycle Speed Distributions, Dedicated Bicycle Lanes vs. No Dedicated Bicycle Lane

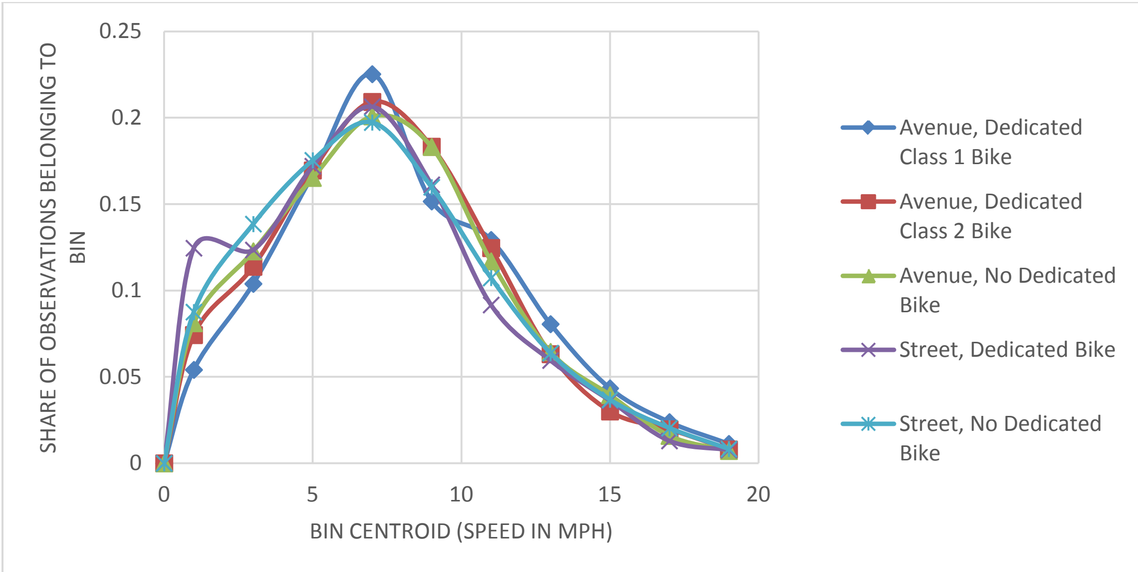
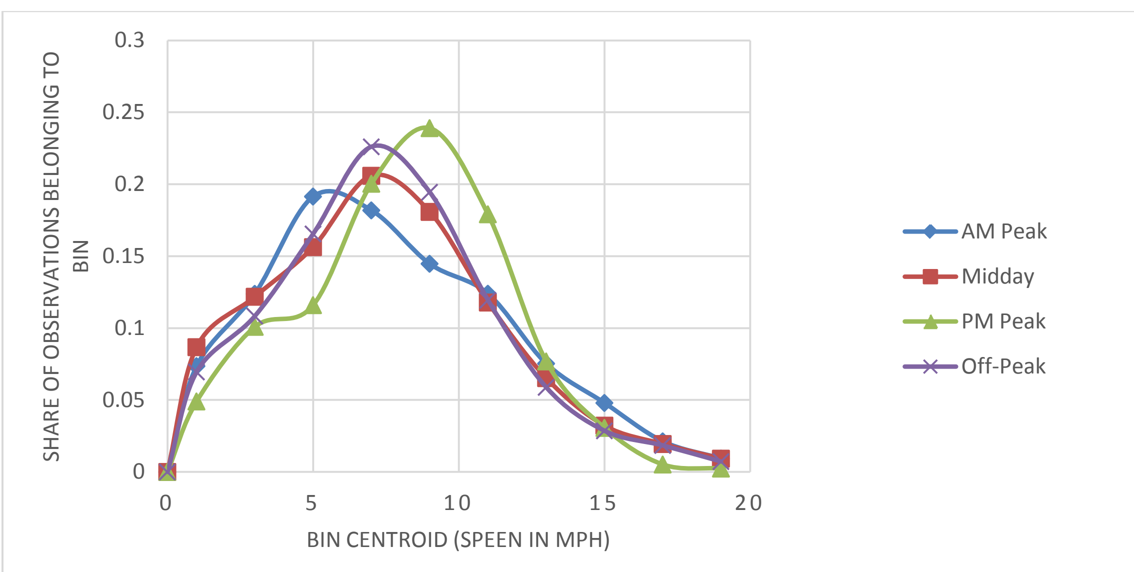


Figure 22 shows the distributions of speeds for City Bakery operators during each time period. At 7.2 mph, the observed median speed during the morning peak is very close to, but slightly lower than, that during the off-peak (7.4 mph) and midday (7.3 mph). For City Bakery, off-peak hours include daytime travel between the other time periods. Much higher speeds are observed during the evening peak, with a median of 8.3 mph.

Figure 22. City Bakery Tricycle Speed Distributions by Time-of-Day



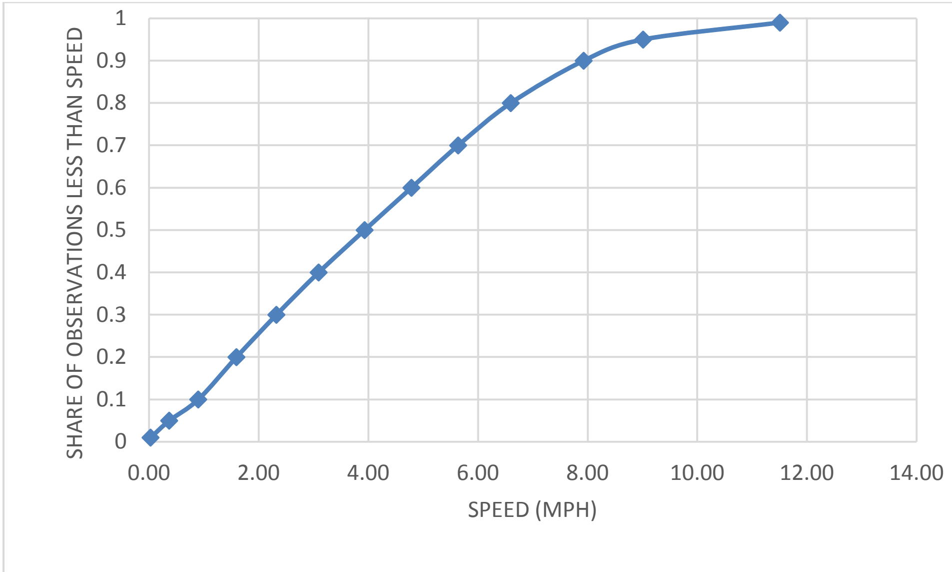
These differences may be influenced by a number of factors. Traffic congestion is expected to impact speeds; however, these results do not confirm this supposition, given the high speeds observed during the PM peak. These differences are likely influenced by two other factors. First, the vehicle's payload will impact the speed at which a driver travels, as heavier weights will require more exertion from the driver to travel at high speeds. During the morning peak hour, freight tricycles leave the flagship stores fully loaded to make multiple deliveries of daily goods; later in the day they carry much smaller loads of goods on demand. The influence of payload can also be observed in Table 6; the highest observed median speed is on 9th Avenue, a route primarily used for travel returning from Revolution Rickshaws, where City Bakery freight tricycles receive maintenance. Although some of this speed difference may be explained by the designated Class 1 bicycle infrastructure, it is likely also influenced by the vehicle weight. Most, if not all, of the trips using 9th Avenue are completed with an empty container.

A driver also indicated that tricycle travel speed will be influenced by the urgency of the delivery. If goods are needed immediately, the driver may travel faster than usual; on the contrary, a driver performing a scheduled delivery or returning from a delivery may travel at a more leisurely pace. Drivers aiming to finish their shifts will return eagerly from an end-of-the-day delivery, as is observed with the higher PM peak travel times. A final source of speed variation identified by a driver but not directly observed in the data is the impact of weather conditions. Like motor vehicle operators, tricycle drivers will travel more slowly in hazardous conditions such as rain or snow. In the event of snow, roads that are plowed and/or treated will be more passable than those on which travel is obstructed by snow.

5.2.1.2 City Harvest Tricycles

City Harvest freight tricycles operate primarily in Midtown Manhattan and to points in the extreme southern end of the Upper East Side; a map of the City Harvest Tricycle service area is also provided in Appendix C. These freight tricycles operate considerably more slowly than City Bakery's. A notably higher share of very slow speeds (between 0 and 3 mph) can be observed in Figure 18. The observed median speed for City Harvest freight tricycles is 3.9 mph. Speeds generally range from zero to 9 mph, with about 5 percent of observations exceeding 9 mph (Figure 23).

Figure 23. City Harvest Tricycle Cumulative Distribution of Speeds



There are likely a number of reasons for the difference in observed speeds between City Harvest and City Bakery freight tricycles. First, City Bakery's operations are concentrated downtown, while City Harvest's are concentrated in the heavily congested heart of Midtown. Second, City Harvest operates a very different business model from City Bakery. With the exception of fixed morning deliveries, City Bakery's deliveries are made "just-in-time" on demand to stores in need of products. Drivers make short point-to-point trips, and return to offices at the flagship store between deliveries. Alternately, City Harvest drivers work very long shifts; they leave Revolution Rickshaws, where the bikes are stored, at around noon, and return between 11 p.m. and midnight. Drivers make very long tours with on the order of 20 stops per day, often making lengthy stops to wait for goods donations. Their tour begins with one or more pick-ups from donors; once a tricycle is full to about 400 lbs, the driver will deliver the goods to one or more recipients. The routes used and the order of delivery are often at the discretion of the driver. The long hours, heavy payloads, and lacking urgency of "just-in-time" deliveries together result in lower observed speeds.

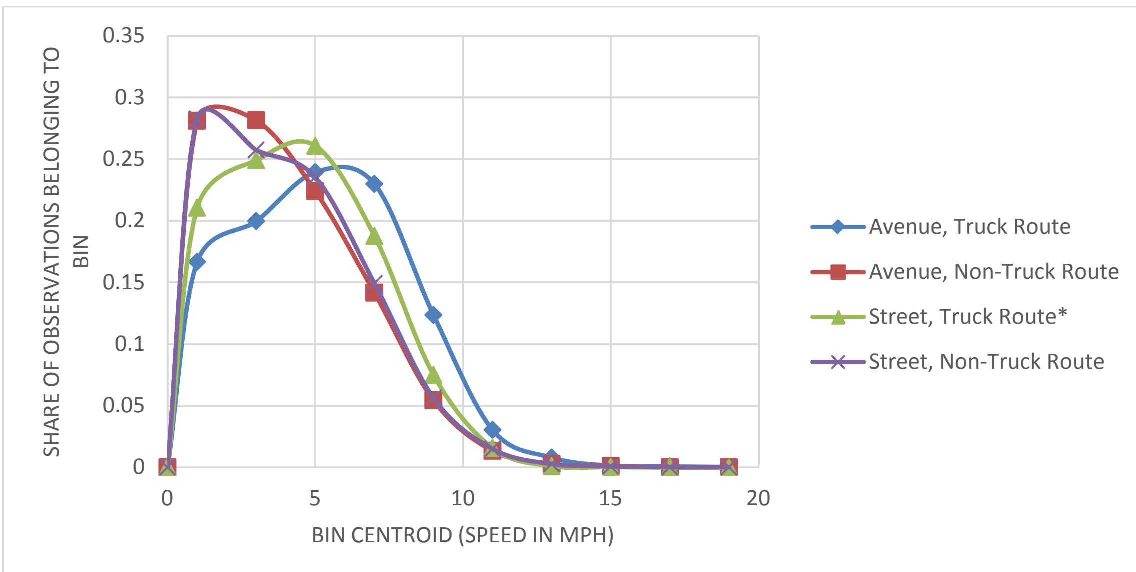
Although City Harvest operators generally move at lower speeds, many of the trends observed are similar to those seen for City Bakery. Again, tricycle speeds are slightly higher on Avenues than on Streets (Table 7). The highest observed speeds are on the Avenues on the west side. These routes are used to travel to and from Revolution Rickshaws while empty at the beginning and end of the day.

Table 7. City Harvest Tricycle Median Observed Speeds

Roadway	Observations		Median Speed (mph)	Truck Route	Dedicated Bike Lane
	Count	Minutes			
All Avenues	18700	623.3	4.1		
10th Ave	1055	35.2	6.3	X	
9th Ave	2615	87.2	6	X	Class 1
11th Ave	112	3.7	5.3	X	
8th Ave	983	32.8	4.2	X	Class 1
Lexington Ave	1688	56.3	4.2	X	
5th Ave	2589	86.3	3.9		
3rd Ave	639	21.3	3.8	X	
7th Ave	900	30	3.7		
Park Ave	3468	115.6	3.7		
Madison Ave	1877	62.6	3.4		
6th Ave	2082	69.4	3		
Broadway	692	23.1	2.8		Class 1,2
All Streets	**24793**	**826.4**	**3.7**		
20th St	162	5.4	5.8		Class 2
35th St	813	27.1	5.2		
63rd St	656	21.9	5.2		
33rd St	599	20	4.6		
55th St	1958	65.3	4.4		Class 2
30th St	2750	91.7	4.3	X	Class 2
56th St	1100	36.7	4.1		
37th St	1070	35.7	4		
39th St	651	21.7	3.9		
46th St	1281	42.7	3.8		
49th St	856	28.5	3.8		
51st St	1449	48.3	3.8		
50th St	1006	33.5	3.7		
40th St	611	20.4	3.6		Class 2 (Partial)
53rd St	733	24.4	3.6		
54th St	670	22.3	3.6		Class 2
36th St	1240	41.3	3.5		
48th St	1967	65.6	3.3		Class 2 (Partial)
32nd St	757	25.2	3.1		
52nd St	956	31.9	3.1		Class 2 (Partial)
64th St	698	23.3	2.8		
38th St	1151	38.4	2.7		
47th St	1659	55.3	2.7		

As for City Bakery, median observed speeds are higher on truck routes than on non-truck routes (Figure 24). As seen in Table 7, nearly all of the highest speed Avenues are designated truck routes; at 5.1 mph, the median observed speed on these roads is notably much higher than the 3.5 mph median observed on non-truck route Avenues. It should be noted that the truck routes are concentrated on the far west and east sides, with the slower moving Avenues primarily located in the center of the city. City Harvest drivers regularly used only one Street designated as a truck route; at 4.3 mph, speeds on this street were observed to be faster than the 3.7 mph median on nontruck Streets.

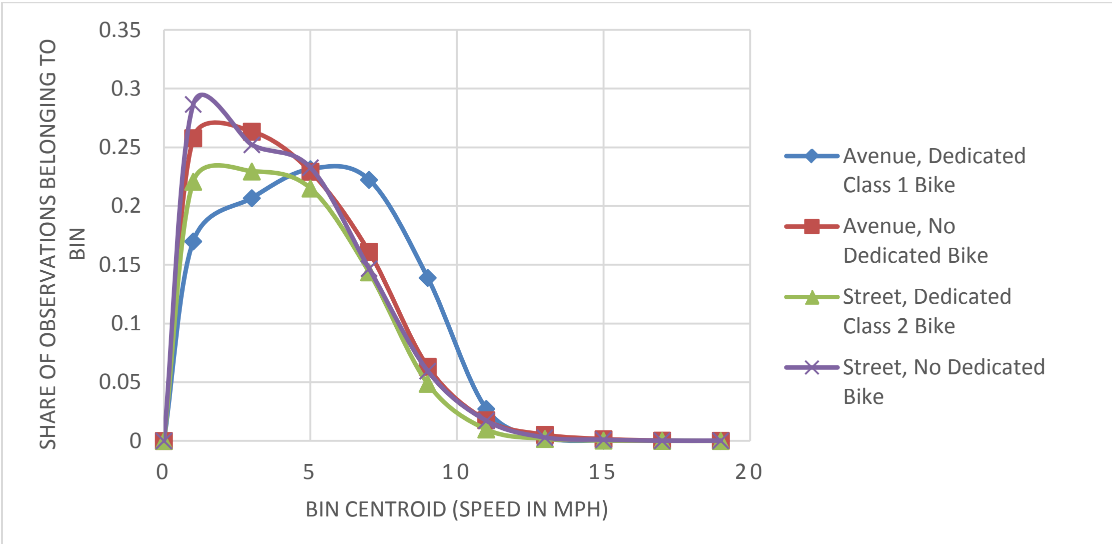
Figure 24. City Harvest Tricycle Speed Distributions, Truck Route vs. Nontruck Route



* Includes only a single street

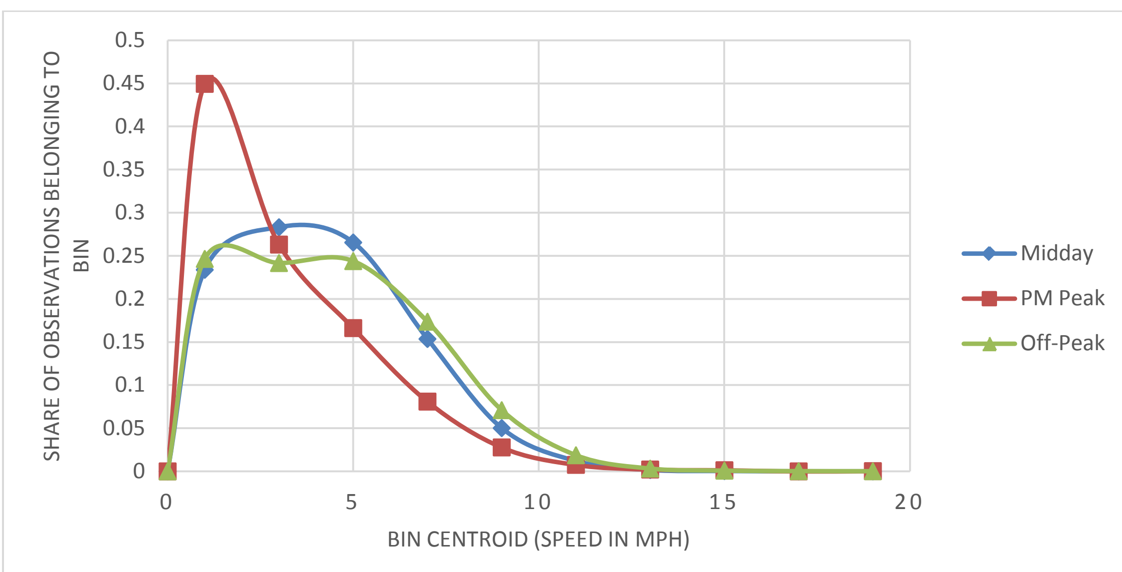
Again like for City Harvest, tricycle speeds appear to be higher on routes that include Class 1 bicycle infrastructure (Figure 25). The median observed speed on Avenues with protected bike lines was found to be 5.1 mph compared to 3.8 mph for routes without dedicated bicycle infrastructure. However, as with City Bakery, there is a route that proves to be an exception. The lowest Avenue speeds are observed on Broadway, which includes Class 1 and Class 2 bike lanes on different segments (Table 7). A slightly higher median speed (3.9 mph) is observed on “Streets” with standard Class 2 bicycle lanes compared to those with no bicycle lanes (3.7 mph); however, the difference is very small and speeds vary considerably on roads in each category.

Figure 25. City Harvest Tricycle Speed Distributions, Dedicated Bicycle Lanes vs. No Dedicated Bicycle Lane



For City Harvest, the slowest speeds are observed during the evening peak hour (median 2.3 mph; Figure 26). During this period, traffic conditions are expected to be the worst. Observed medians are much higher during the midday (3.9 mph) and off-peak, which includes the late afternoon as well as late evening hours (4.1 mph). During the evening peak, freight tricycles are unlikely to be empty. The midday will generally include empty trips from Revolution Rickshaws to the first pick-up location; during this time, drivers have just begun their shift and should not be fatigued. The off-peak includes return empty trips; while drivers are likely to be fatigued at the end of the day, they also have an incentive to return quickly and finish their shift.

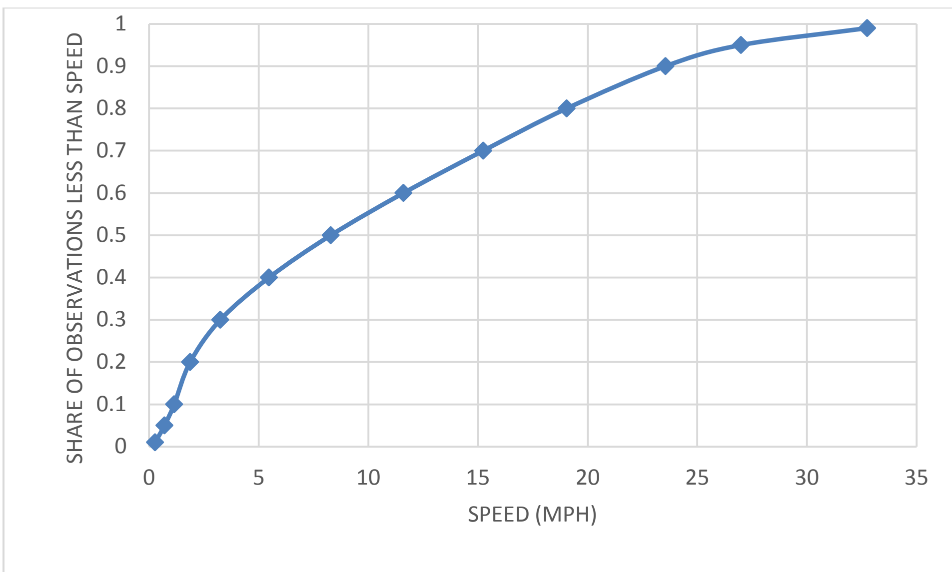
Figure 26. City Harvest Tricycle Speed Distributions by Time-of-Day



5.2.1.3 City Harvest Trucks

Operating from a base in Long Island City, Queens, City Harvests trucks serve a much larger section of the city. In this analysis, only operations within the study area encompassing downtown and Midtown Manhattan and the Upper East and West Sides are considered. A map of this area is included in Appendix C. City Harvest trucks operate at higher median speeds than either freight tricycle operator; however, while the share of very slow speeds (between 0 and 3 mph) is lower for City Harvest trucks than freight tricycles, it is higher than that observed for City Bakery freight tricycles (Figure 18). Unlike for freight tricycles, these very slow speeds cannot be explained as a function of vehicle payload or driver fatigue. Rather, these values are likely due to roadway congestion. The observed median speed for City Harvest trucks is 8.3 mph. Speeds generally range from zero to 27 mph, with about 5 percent of observations exceeding that speed (Figure 27).

Figure 27. City Harvest Truck Cumulative Distribution of Speeds



Variables impacting truck speeds are different than those impacting tricycle speeds. Table 8 and Table 9 show the median observed speeds for each Avenue and Street, classified by neighborhood. First, it is clear from Figure 18 that the distribution of speeds on Avenues is different from that on Streets. Table 8 and Table 9 below show the median observed travel speeds on individual corridors. The median observed truck speed on all Avenues is notably higher than on all Streets; on Avenues, the median speed is 9.8 mph compared to only 5.5 mph on cross-town Streets.

Table 8. City Harvest Truck Median Observed Speeds - Avenues

Roadway	Observations		Median Speed (mph)	Truck Route	Dedicated Bike Lane
	Count	Minutes			
All Avenues	**13122**	**437.4**	**9.8**		
Downtown	**441**	**14.7**	**8.7**		
Ave C	31	1.03	17.4		
1st Ave/ Allen St	184	6.13	10.9	X	Class 1
2nd Ave	66	2.2	8.5	X	Class 1
Norfolk St	160	5.33	4		
Midtown	**6175**	**205.83**	**8**		
12th Ave	106	3.53	21.8		
2nd Ave	145	4.83	13.6	X	
Lexington	584	19.47	12.7	X	
7th Ave	420	14	12.7		
1st Ave	413	13.77	9.8	X	Class 1
9th Ave	230	7.67	9.5	X	Class 1
3rd Ave	451	15.03	8.8	X	
5th Ave	451	15.03	8.8		
11th Ave	56	1.87	8.2	X	
8th Ave	254	8.47	6.8	X	Class 1
10th Ave	1130	37.67	6.8	X	
6th Ave	1332	44.4	5.3		Class 2
Madison	432	14.4	5.2		
Park	171	5.7	4.8		
Upper East	**8449**	**281.63**	**12**		
Lexington	1543	51.43	14.4	X	
York	246	8.2	13.1		
Madison	843	28.1	12.8		
1st Ave	682	22.73	11.8	X	Class 1
2nd Ave	682	22.73	10	X	
Park	274	9.13	6.5		
Upper West	**2189**	**72.97**	**12.3**		
Manhattan	47	1.57	14.7		
Amsterdam	496	16.53	14.2		
Broadway	1085	36.17	12.6		
Columbus	608	20.27	11		Class 1

Table 9. City Harvest Truck Median Observed Speeds - Streets

Roadway	Observations		Median Speed (mph)	Truck Route	Dedicated Bike Lane
	Count	Minutes			
All Streets	**5659**	**188.6**	**5.5**		
Downtown	1140	38	6.4		
E 13th St	91	3.03	8		
W 13th St	219	7.3	6.9		
14th St	830	27.67	6	X	
Midtown	**2759**	**91.97**	**5**		
Central Park South	60	2	17.8	X	
W 23rd St	155	5.17	6.9	X	
45th St	836	27.87	5.5		
34th St	226	7.53	4.9		
W 21st St	212	7.07	4.8		Class 2 (Partial)
W 26th St	318	10.6	4.8		
E 42nd St	307	10.23	4.7	X	
W 42nd St	307	10.23	4.7	X	
E 35th St	173	5.77	4.4		
E 27th St	165	5.5	3.9		
Upper East Side	**1009**	**33.63**	**4.4**		
E 88th St	216	7.2	7.3		
E 74th St	265	8.83	3.2		
E 65th St	125	4.17	3.9	X	
E 64th St	187	6.23	2.4		
Upper West Side	**751**	**25.03**	**6.9**		
W 96th St	371	12.37	8	X	
W 77th St	144	4.8	7.2		Class 2
Cathedral Parkway	236	7.87	5.9	X	

To investigate the impacts of traffic congestion, data were sorted by neighborhood. Although only a few speed observations were made downtown, sufficient observations were collected in Midtown and on the Upper East and West Sides to conduct a comparison. Figure 28 shows the distributions of speeds for Midtown and Uptown Avenues and Streets. When sorted by neighborhood, distributions for Streets and Avenues are nearly identical. As expected, the share of very slow speed observations is greater and the share of high speed (greater than 15 mph) observations is lower in Midtown than in relatively less congested Uptown. As a result, the median observed speed on Uptown Avenues (12.1 mph) is considerably higher than that on Midtown Avenues (8.0 mph). Although the difference is smaller, speeds on Uptown streets (median 6.9 mph) are faster than on Midtown streets (median 5.5. mph).

Figure 28. City Harvest Truck Speed Distributions by Neighborhood

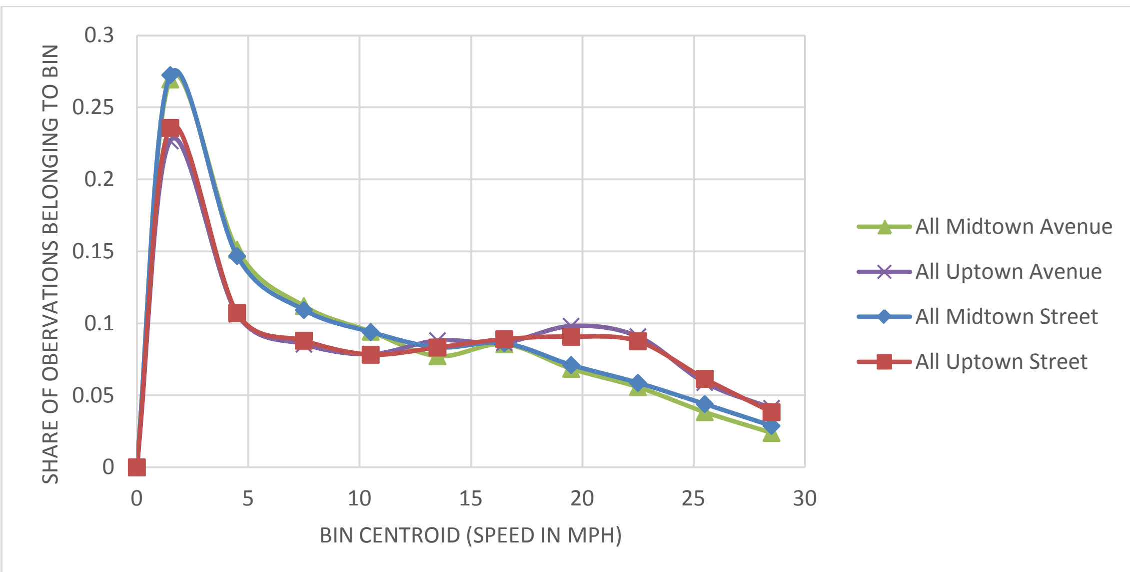
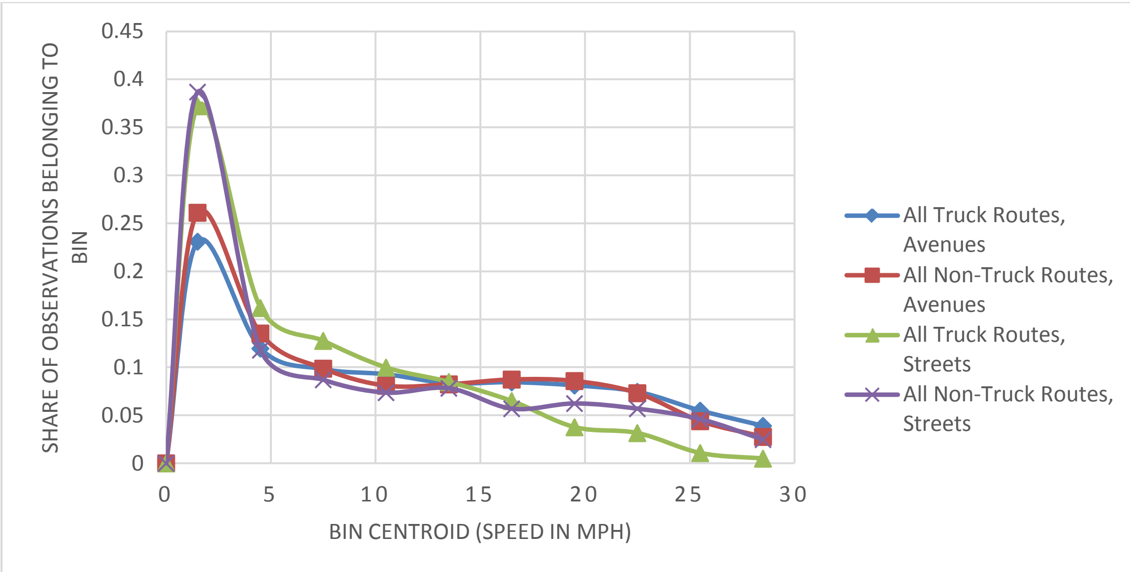


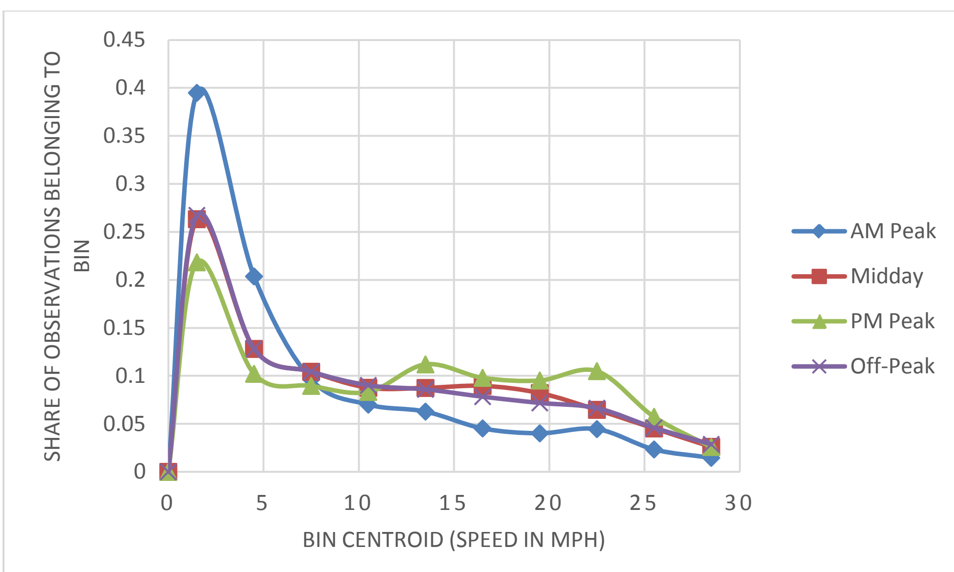
Figure 29 shows the speed distributions for truck routes compared to nontruck routes. On Avenues, there is little change in the shape of the distribution between truck routes and nontruck routes, although the median observed speed is slightly higher on truck routes (12.4 mph vs. 11.8 mph). For Streets, the median observed speed is higher for nontruck routes (5.9 mph) compared to truck routes (5.2 mph). This speed indicates that in Midtown, speeds are lower on the major crosstown streets that are designated as truck routes (and that trucks are required to use by law).

Figure 29. City Harvest Truck Speed Distributions, Truck Route vs. Nontruck Route



City Harvest trucks usually perform a daytime run, leaving Long Island City around 8 a.m. and returning between 2:30 and 3:00 p.m.; they then return to Manhattan in the evening around 5:30 p.m., making deliveries in the Midtown area. Figure 30 shows the City Harvest truck speed distributions by time-of-day. Not surprisingly, the lowest speeds (with a median of 4.12 mph) are observed during the morning peak hour. Speeds during the midday and off-peak are slightly slower, with very similar distributions and medians of 9.1 and 9.0 mph. Somewhat surprisingly, maximum speeds, with a median of 12.3 are observed during the evening peak hour.

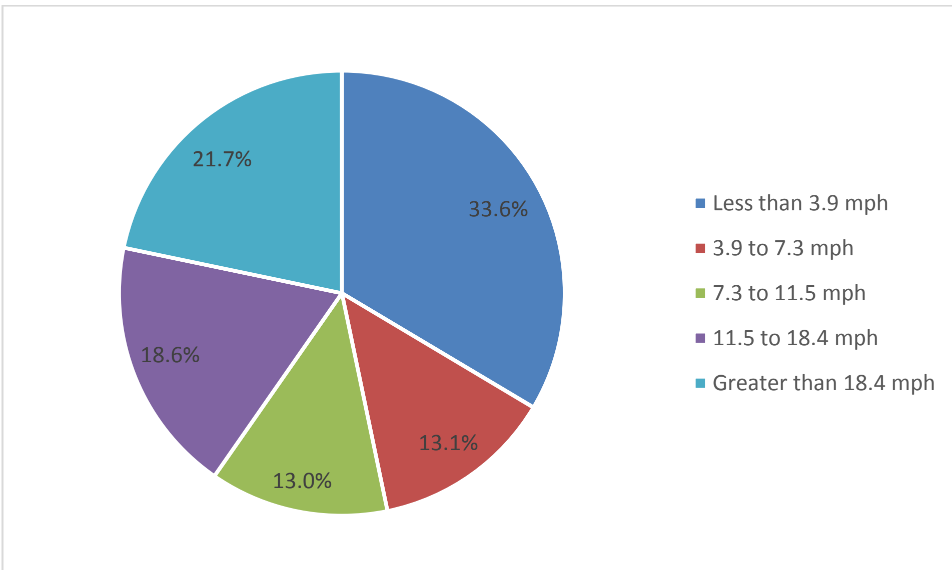
Figure 30. City Harvest Truck Speed Distributions by Time-of-Day



5.2.1.4 Summary of Findings

Overall, these speed results demonstrate that a considerable proportion of truck speeds are feasibly replicable by tricycle. Figure 31 shows the shares of observed truck speeds that fall within categories defined by observed tricycle speeds. About a third of observed truck speeds are below the median travel speed by the relatively slow moving City Harvest freight tricycles; nearly 47 percent are below 7.3 mph, the median speed for a City Bakery trike. About 60 percent of trucks speeds are below the 99th percentile speed for City Harvest freight tricycles, and about 78 percent are below the 99th percentile speed for City Bakery freight tricycles.

Figure 31. Observed Truck Moving Speed Shares by Tricycle Bin



Carriers considering a mode switch should recognize a number of benefits and limitations for operating freight tricycles in Manhattan. City Bakery freight tricycles, which carry relatively light loads for short trips, operate at consistent speeds between zero and 15 mph. With longer tour lengths, heavier City Harvest freight tricycles travel at slower speeds, with most observed values below 9 mph. It appears that variations in speed are influenced by load and driver characteristics; vehicles travel faster when carrying light loads, when drivers are well-rested, and when drivers operate with a sense of urgency. Performance may also vary with different infrastructure characteristics. Although there is some variation in speeds between freight tricycles traveling north-south on Avenues and crosstown on Streets these differences are slight; for both operators, the difference in the median speed between the fastest Avenue and the slowest Street is about 3.5 mph. Median observed values appear to increase on roads where freight tricycles have adequate space to maneuver – including on wide avenues, on major cross-town truck routes, and on routes with Class 1 bicycle infrastructure.

For trucks, payload and driver fatigue have little influence on travel speeds. The primary factors impacting truck speeds in Manhattan appear to be traffic congestion and infrastructure characteristics. The slowest travel times occur during the congested morning peak hour, and in congested sections of the city such as central Midtown. For trucks, travel speeds on crosstown Streets are considerably slower than on north-south Avenues. In general, crosstown Streets have a higher density of intersections and fewer and narrower travel lanes than Avenues. For deliveries of relatively light goods during morning peak hours or traveling crosstown, tricycles may offer a more reliable, if not faster, option.

5.2.2 Travel Time and Delay

To characterize travel time reliability by freight tricycle and to identify influential trip, driver, and infrastructure factors, three performance measures were examined: travel time, stopped-time delay, and ratio of stopped-time delay to travel time.

5.2.2.1 City Bakery

In the City Bakery data set, nine trip-end pairs with 30 or more observations were identified. The locations of these trip ends, and the characteristics of the trips between them are described in Table 10.

Table 10. City Bakery Trip Characteristics

Trip	Trip Ends		Count	Estimated Distance (mile)	Estimated Intersection Density (number/mile)
	End 1	End 2			
A	200 Church St	3 West 18th St	51	1.9	16.3
B	3 West 18th St	160 Prince St	190	1.1	16.4
C	223 1st Ave	Bowery/Prince	30	1	17
D	3 West 18th St	223 1st Ave	84	0.9	13.3
E	35 3rd Ave	3 West 18th St	112	0.9	14.4
F	160 Prince St	200 Church St	38	0.8	16.3
G	35 3rd Ave	Bowery/Prince	37	0.6	16.7
H	223 1st Ave	35 3rd Ave	64	0.5	12
I	Bowery/Prince	160 Prince St	45	0.5	22

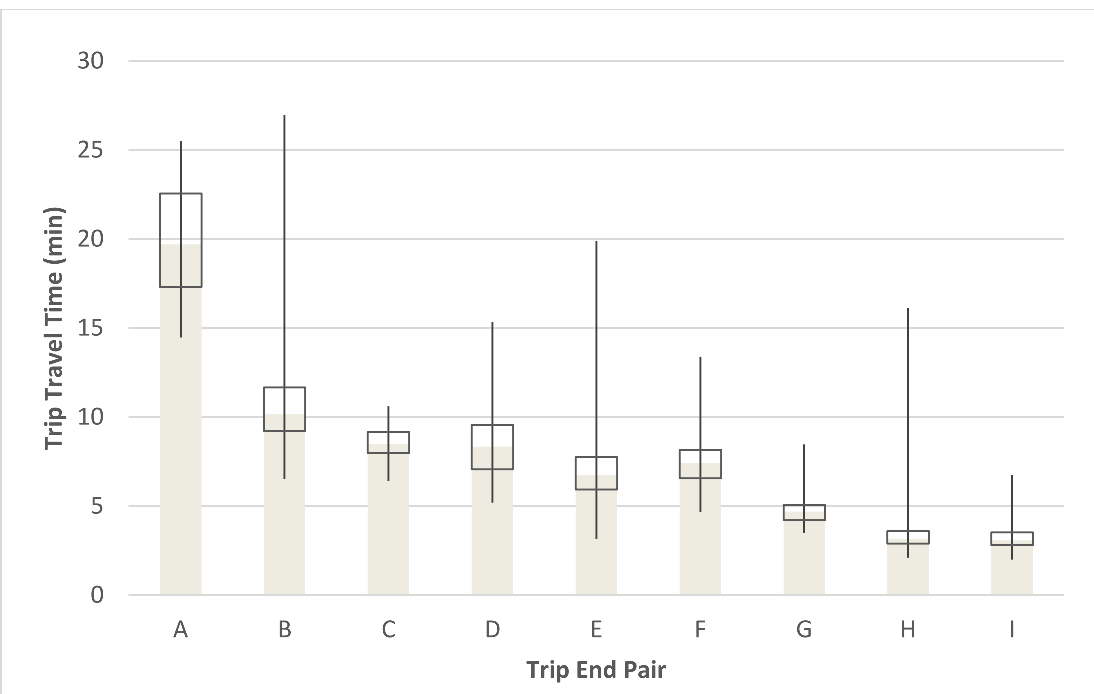
Table 11 shows the performance measures estimated for each trip-end pair.

Table 11. City Bakery Trip Performance Measures

Trip	Travel Time (min)		Stopped-Time Delay (min)		Ratio	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
A	19.8	3	2.6	1.5	0.12	0.06
B	10.7	2.6	1.3	0.9	0.11	0.06
C	8.6	1.1	0.9	0.9	0.09	0.08
D	8.5	1.9	1.5	1.2	0.16	0.10
E	7.3	2.7	0.9	0.8	0.11	0.06
F	7.6	1.5	1	0.9	0.11	0.08
G	4.9	1.2	0.7	0.6	0.12	0.08
H	3.8	2.6	0.4	0.5	0.09	0.08
I	3.3	0.9	0.9	1.1	0.23	0.23

Figure 32 shows the variability in travel time for trips between each trip-end pair. The gray bar represents the height of the median (50th percentile) observation. The top and bottom of the black box represent the 25th and 75th percentiles, and the thin black line represents the minimum and maximum travel times observed.

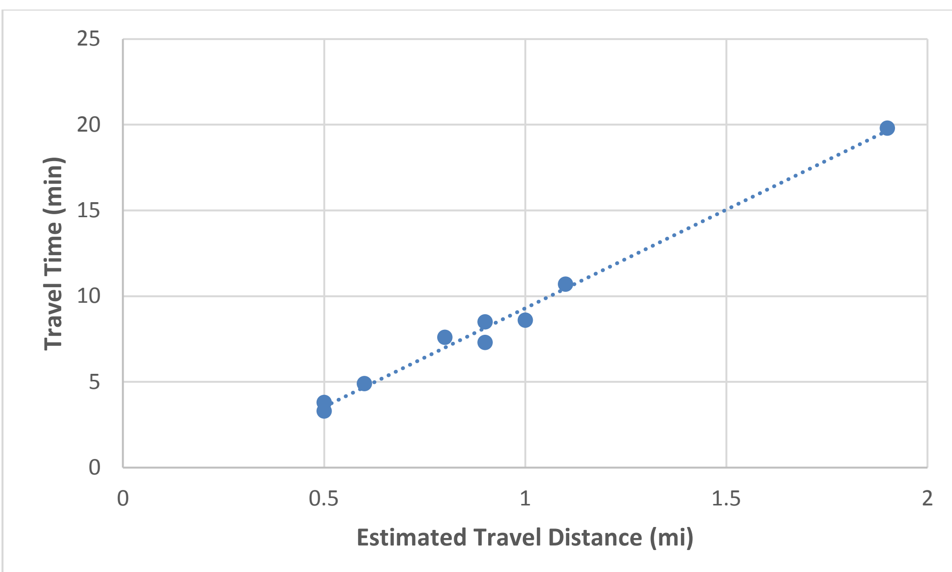
Figure 32. City Bakery Trip Travel Time Box Plots



It is clear from Figure 32 that while the distributions for most trip end pairs are relatively small, there is some variation in travel times. For example, while the trip between 1st Avenue and 3rd Avenue is generally very short and there is very little spread in the middle 50 percent of observed values, at least one outlier has a longer travel time. Several of the other trip-end pairs (B, D, and E) demonstrate a similar trend. Detailed examination of these trip-end pairs using the visualization software revealed the most common explanation for these outlier values: deviation from a usual shortest-distance path. Because Manhattan's road network is primarily a grid, there may be multiple routes of similar distance between two points; however, for these cases alternative routes that added significant distance were used. In at least some of these cases, these trips included intermediate stops in an area that was not geocoded as a regular stop location, including the Union Square Greenmarket. While the data was manually corrected to remove time actually spent at an unusual stop location, added travel distance associated with this stop may also contribute to an increase in travel time.

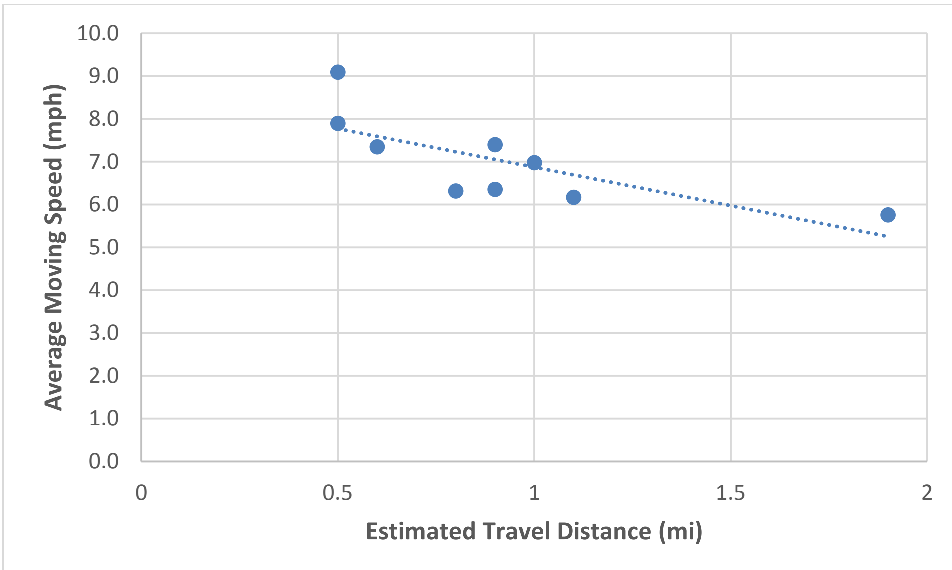
By examining characteristics across these trip-end pairs, some factors that influence tricycle travel time were observed. Two basic variables will determine the travel time between two points; the total distance to be traveled and the amount of delay incurred between those two points. Table 10 provides the estimated travel distance between the trips ends; this is the length of the minimum-distance path between the two points. As expected, average travel time is almost perfectly linearly related to this estimated distance traveled (Figure 33); as travel distances increase, so do average travel times.

Figure 33. City Bakery Trip Distance vs. Travel Time



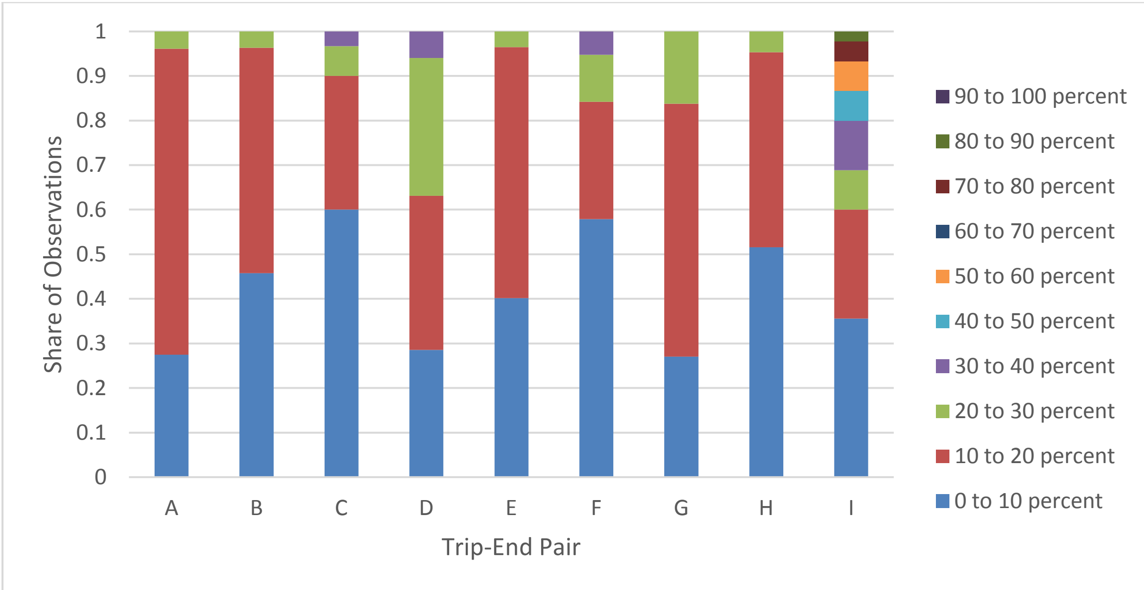
By subtracting the stopped-time delay from the travel time, the total moving time of the vehicle was estimated. Dividing the estimated travel distance by this value, average trip moving speed was estimated. Plotting this value against the estimated travel distance highlights another trend: in general, as travel distances get longer, moving speeds become slower. This result is not unexpected, as drivers traveling longer distances may become fatigued or travel at a slower pace to avoid fatigue.

Figure 34. City Bakery Average Moving Speed vs. Estimated Travel Distance



Finally, developing a cumulative chart of the ratios of stopped-time delay to travel time (Figure 35) shows overall that trips via freight tricycle have relatively low delay to travel time ratios, generally ranging from 0.1 to 0.3. This result indicates that freight tricycles only spend 10 to 30 percent of their total travel time stopped by traffic lights and other obstructions. Only one frequent trip was found to include higher observed shares of stopped-time delay. Freight tricycles traveling between Bowery/Prince St and 160 Prince St travel a very short distance (0.5 mi) east-west on Prince Street, which has the highest intersection density of the routes observed. On this route, higher ratios are expected since 1) stopped-time delay will be high due to the intersection density and 2) travel times will be low due to high moving speeds over a short distance.

Figure 35. City Bakery Cumulative Stopped-Time Delay to Travel Time Ratios by Trip



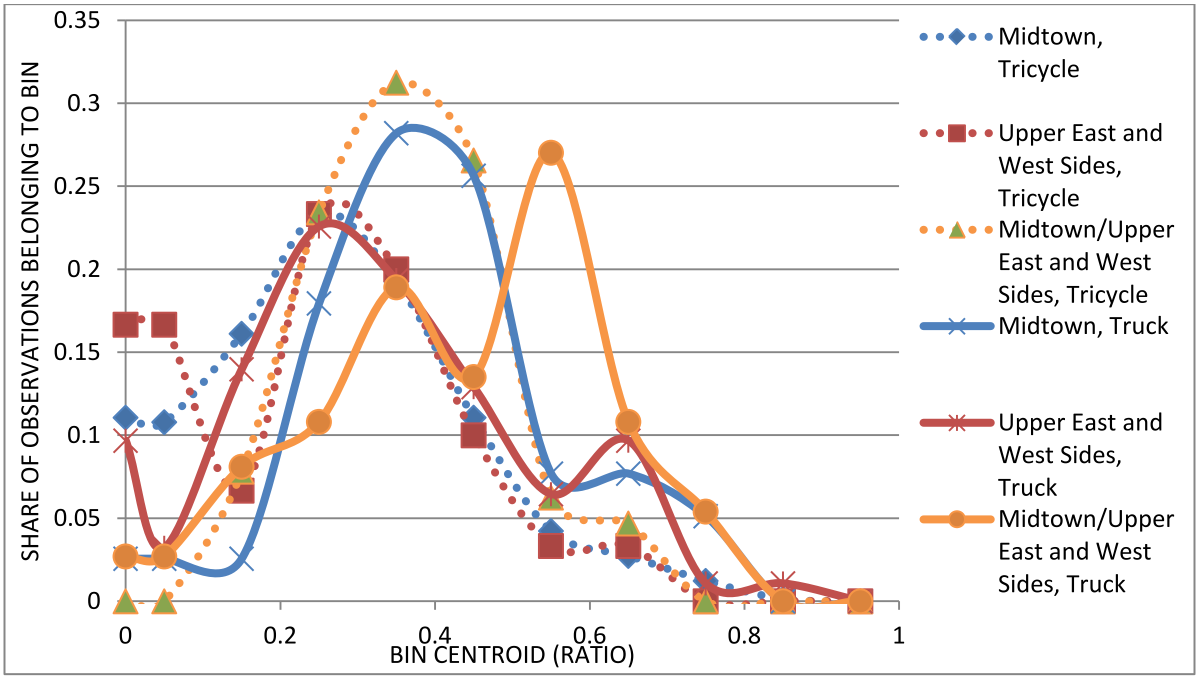
5.2.2.2 City Harvest Tricycle and Truck

As discussed previously, for City Harvest, the number and density of stop locations for both tricycles and trucks did not allow for direct evaluation of repeated end-to-end trips. As a proxy, City Harvest trips were measured from neighborhood to neighborhood. Table 12 shows the mean and standard deviation of trip times and delay times for trips by each mode between each neighborhood pair. These should not be compared directly, as distances traveled vary considerably between and within neighborhood pairs. To compare across trips of varying length, a ratio of stopped-time to travel time was calculated for each observation. Figure 36 shows the distribution of these ratios for each neighborhood pair and mode.

Table 12. City Harvest Trip Characteristics

Neighborhood	Count	Travel Time (min)		Stopped-Time Delay (min)		Ratio	
		Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
City Harvest Tricycles							
Midtown	732	1.9	2	6.6	4.7	0.26	0.17
Midtown/ Upper East and West	64	3.3	2.2	8.2	3.7	0.23	0.18
Upper East and West	30	0.7	0.7	3	1.4	0.37	0.12
City Harvest Trucks							
Midtown	39	12.3	8.7	5.3	4.8	0.40	0.17
Midtown/ Upper East and West	37	19.5	13.2	9.6	8.2	0.42	0.18
Upper East and West	93	7.8	6	3.1	3.7	0.32	0.19

Figure 36. City Harvest Delay-to-Travel Time Ratio Distributions by Neighborhood and Mode



It is clear from Figure 36 that on trips within Midtown and between Midtown and the Upper East and West Sides, trucks experience considerably more delay as a percentage of total travel time than do freight tricycles. Within Midtown, the median freight tricycles spend 26 percent of their travel time in stopped-time delay compared to about 40 percent for trucks. Between Midtown and the Upper East and West sides, similar ratios of 23 percent for trucks and 42 percent for truck are observed. For both trip types, very few tricycle delay to travel time ratios greater than 0.6 are observed.

For trips within the Upper East and West sides, different conditions are observed. In these neighborhoods, very similar distributions for freight tricycles and trucks are observed. The average percent of travel time spent in stopped-time delay for freight tricycles (37 percent) is actually higher than that observed for trucks (32 percent). In these neighborhoods, freight tricycles experience higher delay shares than in other neighborhoods; this is likely due to the fact that point-to-point tricycle operations within the Upper East Side are concentrated on 63rd and 64th St – Streets with relatively high intersection densities. Trucks traveling point-to-point in these neighborhoods experience fewer delays than trucks traveling elsewhere; this is likely explained both by relatively lower traffic congestion in these neighborhoods and by the concentration of truck movements on Avenues with lower intersection densities.

Interestingly, the sample standard deviations are very similar for all neighborhoods and modes (Table 12). Only freight tricycles traveling on the Upper East Side have a noticeably lower observed sample standard deviation; this result is expected because, as discussed previously, these trips are made on a very limited number of streets. In general, these values indicate that for City Harvest, expected delays are equally predictable for freight tricycles and trucks.

Although specific travel routes were not evaluated in detail for City Harvest trips, it was noted through visualization of the data that tricycles are generally able to take a shortest distance path, or close to it, when traveling between two points. Trucks, however, were observed to deviate several blocks from shortest path routes to stay on mandated local truck routes. This result was particularly evident when construction closed a crosstown truck route.

5.2.2.3 Summary of Findings

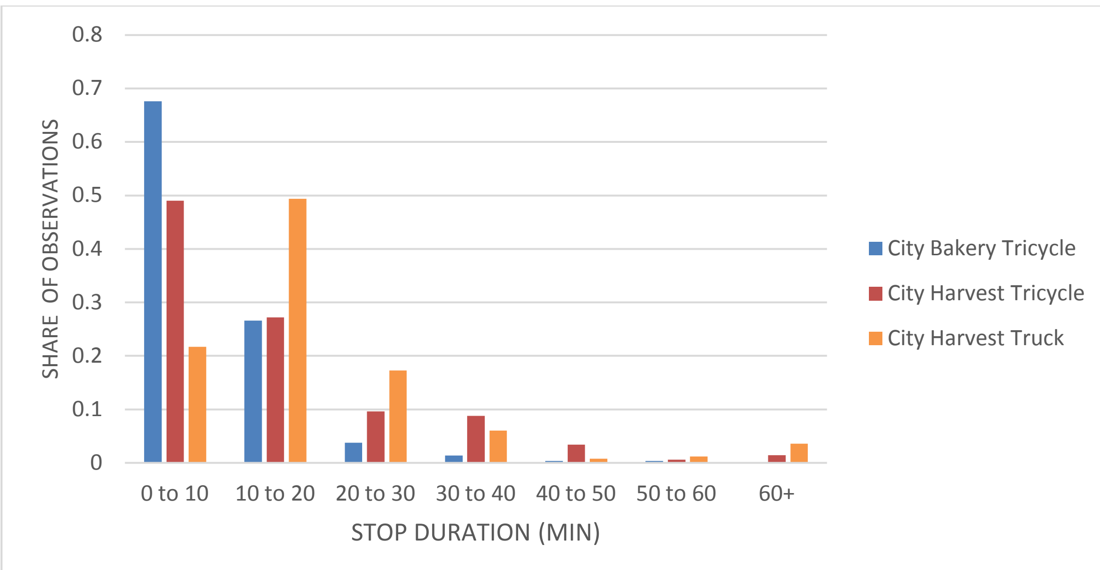
Results from both operators indicate that, in general, freight tricycles spend considerably lower shares of their travel time in stopped-time delay than trucks, although higher than average delay-to-travel time ratios are observed for freight tricycles in locations with high intersection densities. Additional stopped-time delay for trucks is likely due to traffic congestion that freight tricycles can often bypass. Considering together the median moving speeds estimated for each vehicle type and the median stopped time to moving time ratio for each vehicle type, estimated travel times for an uninterrupted one mile trip can be estimated. With a median travel speed of 3.90 mph and a median stopped time to moving time ratio of 0.36, a median City Harvest tricycle requires 20.9 minutes to travel one mile. With a median travel speed of 8.28 mph and a median stopped time to moving time ratio of 0.34, a median City Harvest truck requires 9.7 minutes to travel the same distance. A City Harvest trike, with a slightly lower median speed of 7.22 mph but a much lower stopped time to moving time ratio of 0.13, requires an even lower 9.4 minutes to travel one mile.

However, travel times are a direct function of trip distances. For tricycles, there are human limitations on travel distances; as drivers are required to travel greater distances, they will become fatigued and may begin to travel at a slower pace. While trucks are not restricted by driver limitations, they do face some policy restrictions. In Manhattan, trucks are required to travel on a limited network of local truck routes; this may increase their travel time by requiring them to deviate considerably from shortest-path routes. Trucks are also likely to be impacted more severely by network disruptions such as construction or a traffic incident than a tricycle that can generally use immediately adjacent alternatives.

5.2.3 Stop Durations

The final performance measure estimated to compare operations for trucks and freight tricycles is the stop duration at pickup and delivery locations. This measure gives some indication of how quickly pickups and deliveries can be made using different vehicles, although interpretation of the data is limited by variable operating characteristics. As demonstrated in Figure 37, very quick deliveries (less than 10 minutes) are more frequent for freight tricycles than for trucks. Regardless of parking conditions, this result is expected, as the trucks are generally carrying larger shipments than the freight tricycles, which may take additional time to unload. Detailed investigation of each mode identified some trends in stop time durations.

Figure 37. Operator Delivery Time Durations



5.2.3.1 City Bakery

City Bakery's freight tricycles make both pickups and deliveries in Manhattan. As discussed previously, goods are generally produced at their flagship bakery and two satellite locations, and are delivered to their other locations. As a result, while stops at the secondary locations can be assumed to be deliveries, stops at producer locations may be either pickups or deliveries (between producers). Table 13 shows the mean and standard deviation of observed stop times at each location; in general, producer stop times are both greater and more variable than recipient location stops. This result is expected because drivers at the producer locations may need to wait for goods to be prepared for delivery; at recipient locations, they simply need to drop-off the prepared goods. While parking regulations at City Bakery stop locations do vary (Table 13), they are not expected to have much impact on stop times, as the freight tricycles generally park on the sidewalk and are not subject to parking restrictions. The primary take-away from examining recipient stop times is that deliveries via tricycle can be completed very quickly; 68 percent of deliveries were completed in less than 10 minutes, and 94 percent were completed in less than 20 minutes.

Table 13. City Bakery Stop Time Durations

Location	Count	Stop Time (sec)		Motor Vehicle Parking Regulations
		Mean	Std. Dev.	
Pickup or Delivery	**202**	**18.8**	**13.5**	
3 W. 18th St.	71	19.1	13.7	Commercial Meters, 7 a.m. - 6 p.m. (both)
200 Church St.	57	19.4	13.9	Commercial Loading 7-10 a.m., 4-7 p.m., 1 HR Parking, 10 a.m.-4 p.m. (store side), Open Parking (opposite)
160 Prince St.	71	16.3	12.4	No Parking 8 a.m. - 6 p.m. (store side), No Stopping Anytime (opposite)
Delivery	**293**	**9.5**	**6.4**	
223 1st Ave	109	7.6	3.1	No Parking (store side), 1 HR meters 9 a.m. - 7 p.m. (opposite, few spots)
35 3rd Ave	125	11.9	8	Bus Stop outside, 1 HR Meters 8 a.m. - 7 p.m. (both sides)
Bowery Street/Prince Street	58	8	5.2	Commercial Loading, 7-10 a.m., 1 Hour Parking, 10 a.m.-7 p.m. (store side), 1 HR Parking 10 a.m. -7 p.m.(opposite side)
Unknown				
Union Square Green Market	43	13.2	9.3	N/A

5.2.3.2 City Harvest Tricycle

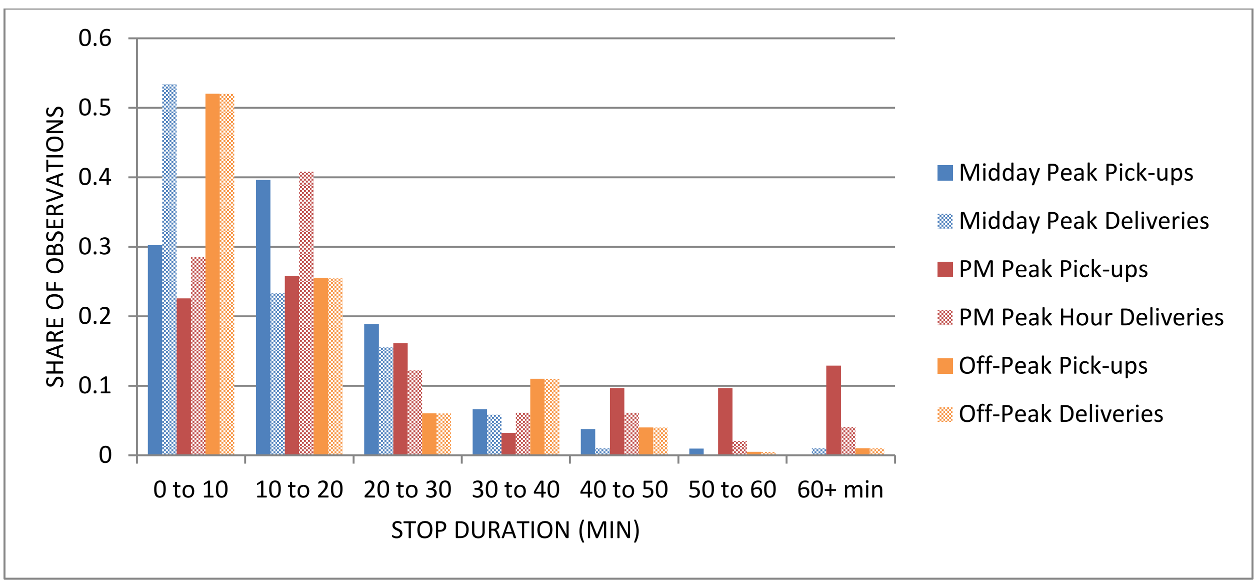
City Harvest tricycle stops were identified as pick-ups or deliveries based on proximities to donor or recipient locations; stops in locations that could not be distinguished as one or the other have not been included in the following results. As discussed in Section 4, these results include only "typical" delivery stops. Table 14 shows the mean and standard deviation of observed stop times at each location. Similarly to City Bakery, pickup stops (mean 23.4 min) are generally longer in duration than delivery stops (14.9 min). Compared to City Bakery, City Harvest's tricycle deliveries are slightly longer and more variable. This result is not surprising given the complexity of City Harvest's operations. While City Bakery delivers to its own bakeries, which have dedicated staff available to receive deliveries, City Harvest delivers to a broad range of nonprofit recipients. Nonprofits often require staff to multitask, so in many locations, the intended recipient may be otherwise occupied when the vehicle arrives, requiring the driver to wait.

Table 14. City Harvest Tricycle Stop Durations

Category	Pickup Time (min)			Delivery Time (min)		
	Count	Mean	Std. Dev.	Count	Mean	Std. Dev.
Manhattan	325	23.4	20.9	353	14.9	13.0
Area						
Downtown Manhattan	4	7.4	3.5	1	10.6	0
Midtown Manhattan	290	23.8	21.9	324	15.4	13.1
Upper East Side	31	22.4	6.7	28	9.2	9.6
Time Period						
AM Peak (6:30 to 9:30)	--	--	--	--	--	--
Midday Peak (12:00 to 14:00)	106	16.4	11.3	104	13.3	10.8
PM Peak (16:00 to 19:30)	31	29.6	25.4	49	19.4	15.3
Off-Peak Hour (other)	188	26.4	23.1	200	14.6	13.2

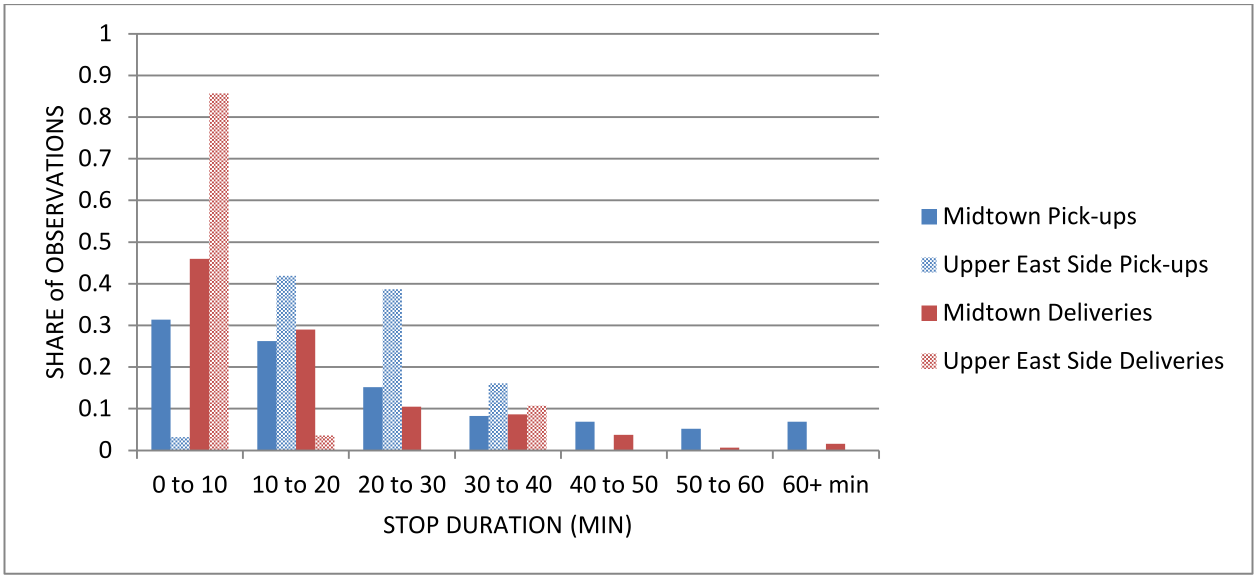
Figure 38 displays the observed likelihood of stop times by time-of-day. For pickups, the majority of off-peak stops are very short. This is expected, as donors are likely to be less preoccupied with other operations during these periods. During the midday and evening peaks, the majority of stops are still relatively short (< 20 minutes). For deliveries, the majority of stops are very short during both the midday and the off-peak. Much longer stop times are observed in the evening peak. This may be due to busy receiver operations during dinner time, or may indicate that some of these stops were not actual deliveries.

Figure 38. City Harvest Tricycle Stop Durations by Time-of-Day



As shown in Table 14, the vast majority of City Harvest stops occur in Midtown; however, Figure 39 displays the observed likelihood of stop times by neighborhood, separating out the 31 stops on the Upper East Side. With only a few delivery locations that are visited repeatedly, a trend very similar to that observed for City Bakery is observed, with very short delivery times and little variability. As noted by the standard deviation in Table 14, stop times in Midtown are much more variable.

Figure 39. City Harvest Tricycle Stop Durations by Neighborhood



5.2.3.3 City Harvest Truck

City Harvest trucks are loaded at their Long Island City warehouse; as a result, all stops made in Manhattan that are in proximity to a receiver can be assumed to be a delivery stop. While a number of stops were made in Upper Manhattan, they were excluded from this analysis, as they are not within the study area. As shown in Figure 37, very short delivery times are less likely for trucks than for freight tricycles, although the majority of deliveries are less than 20 minutes. As can be seen in Table 14 and Table 15, the average parking time for a truck is slightly higher than the average parking time for a freight tricycle. Again, this time is expected due to differing load sizes.

Table 15. City Harvest Truck Stop Durations

Category	Count	Delivery Time (min)	
		Mean	Std. Dev.
Manhattan General Summary	249	18.6	13.3
Area			
Downtown Manhattan	23	17.2	11.9
Midtown Manhattan	79	27.3	18.5
Upper East &West Sides	147	14.7	7
Time Period			
AM Peak (6:30 to 9:30)	30	14.5	9.0
Midday Peak (12:00 to 14:00)	31	14.7	9.2
PM Peak (16:00 to 19:30)	10	17.1	7.0
Off Peak	178	20.1	14.5

Comparing delivery times across times of day (Figure 40), it appears that the average delivery times increase slightly during the evening peak and the off-peak; however, the majority of deliveries are still shorter than 20 minutes. Examining delivery times by neighborhood (Figure 41), it is noticeable that there are fewer very short deliveries and more very long deliveries (> 60 min) in Midtown. These differences may be due to parking restrictions. Since double parking is illegal until 7 p.m., drivers are less likely to park in a travel lane and make a fast delivery. After 6 p.m., when commercial meters are no longer in effect, drivers have less incentive to complete their delivery quickly. Investigation of the Midtown data reveals than 9 of the 10 very long deliveries were made by trucks that arrived after 6 p.m.

Figure 40. City Harvest Truck Stop Durations by Time-of-Day

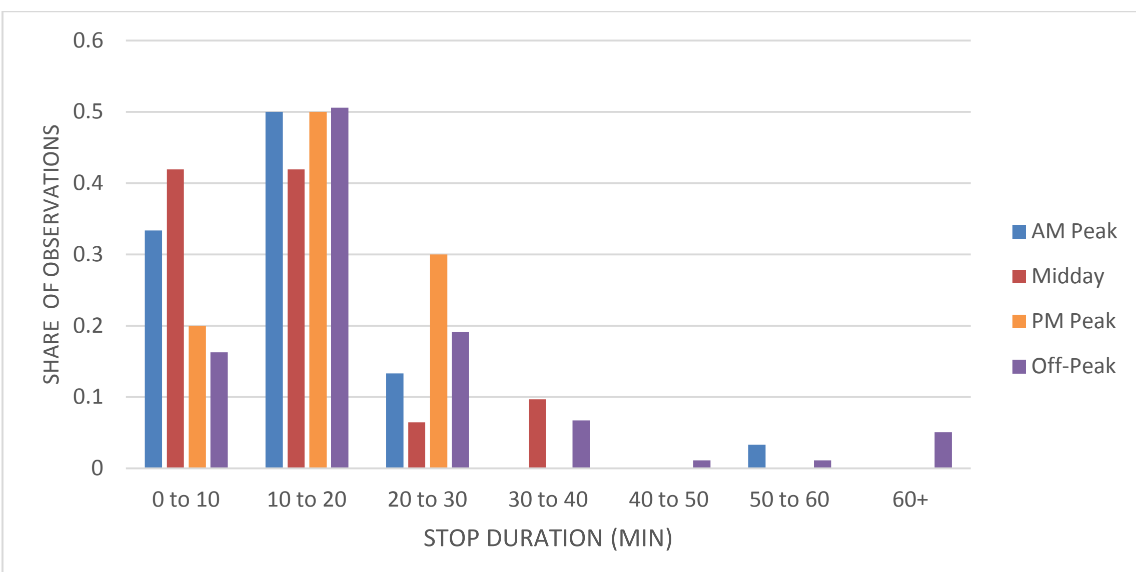
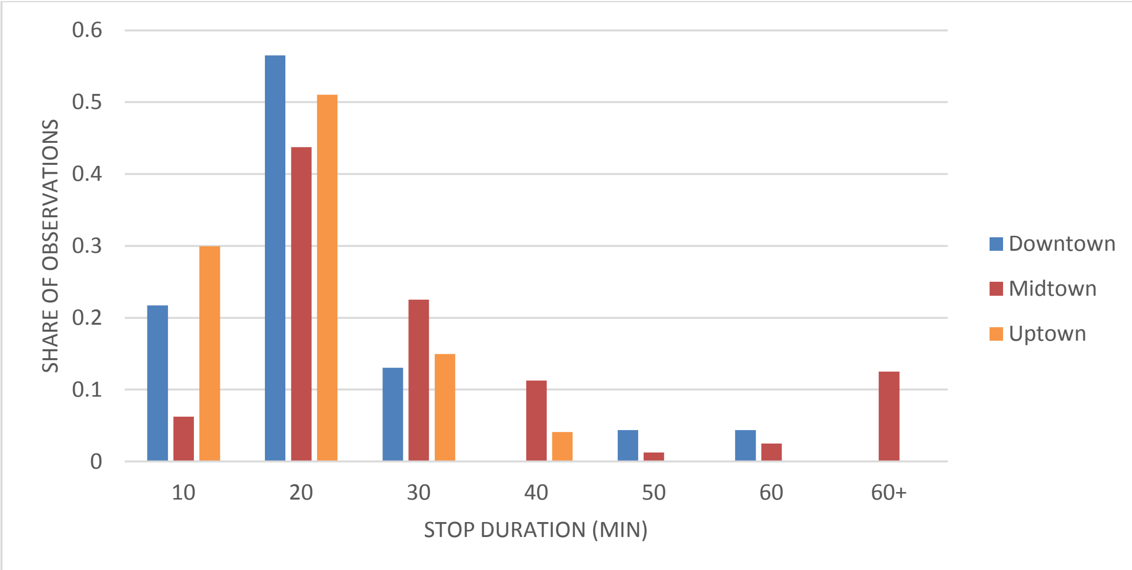


Figure 41. City Harvest Truck Stop Durations by Neighborhood



5.2.3.4 Comparative Truck Data

To understand these results in the context of broader truck operations In Manhattan as well as to further investigate the impacts of parking regulations on truck parking behavior, results from this study can be compared with estimates from data collected for the Truck/Bicycle interaction study conducted by the authors during the summer of 2012 (Conway et al. 2013). A detailed description of this study was provided in Section 4. Table 16 summarizes the truck parking observations from this study.

Table 16. Truck/Bicycle Interaction Project Vehicle Stop Durations

	Frequency	Delivery Time (min)	
		Mean	Std. Dev.
Manhattan Total	**162**	**16.8**	**13.1**
Vehicle Type			
Van	62	12.4	11.0
Truck	100	19.6	13.5
Area			
Downtown	37	16.2	12.0
Midtown	39	11.3	11.5
Upper East and West Sides	86	19.6	13.5
Time Period			
AM Peak	27	14.3	14.0
Midday	40	14.4	12.2
PM Peak	28	19.6	12.2
Off-Peak	67	18.2	13.4

To create a study dataset directly comparable with this data, delivery times observed after 5:30 p.m. (the latest arrival observed in the Truck/Bike interaction dataset) and longer than 60 minutes were removed from the City Bakery and City Harvest data sets. Figure 42 shows the parking durations by mode for the comparable datasets; City Bakery and City Harvest tricycle results were combined here to provide an aggregated modal distribution.

Figure 42. Parking Duration Comparison by Mode

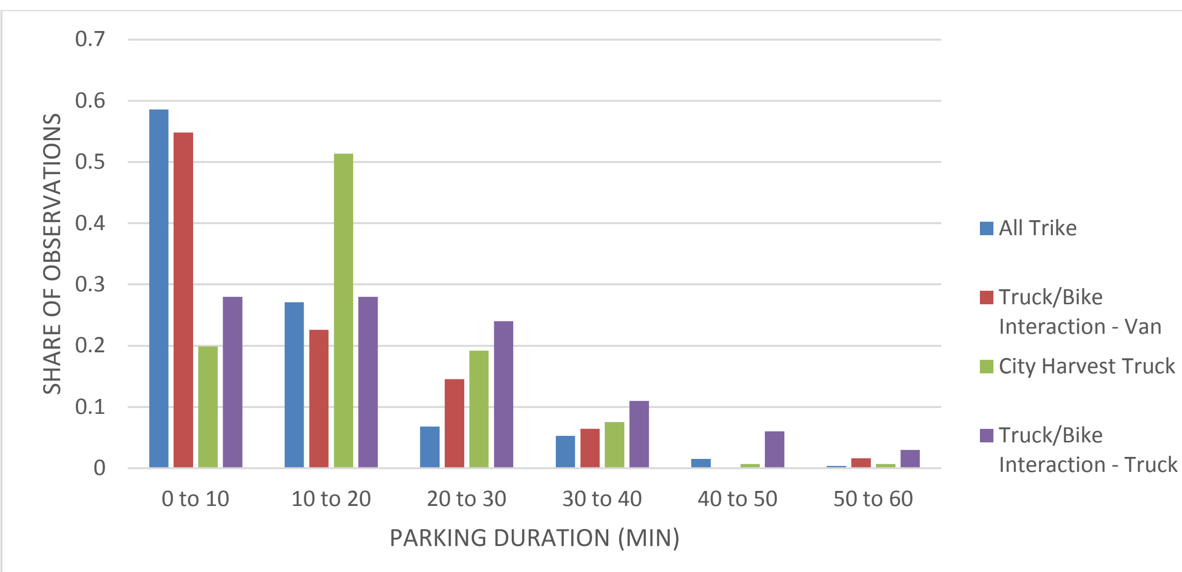


Figure 42 shows that tricycle delivery times are very comparable to those observed for vans in the truck/bike interaction study. In this limited dataset, tricycle delivery times average 12.0 minutes, compared to 12.4 minutes for vans. Also using the limited data set, the average of City Harvest truck times (17.7 min) is slightly less than that observed for all trucks (19.4 min) in the truck/bike interaction study. City Harvest trucks make a much higher share of moderately short stops (10 to 20 minutes) compared to the broader truck population.

The GPS data analysis method used in City Bakery and City Harvest case studies does not allow for evaluation of exact parking locations. Due to the existence of drift points for parked vehicles, exact locations for parking could not be determined. However, in the Truck/Bike interaction study, vehicle parking locations were directly observed. Figure 43 and Figure 44 show regulations in place where trucks and vans chose to park. For both mode types, double parking was frequent; 83 percent of trucks and 72.6 percent of vans were observed to be double-parked. Although double parking is legal in motor vehicle lanes in much of the city, a sizable share of double-parked trucks were parked illegally. Close to 40 percent of double-parked trucks obstructed bicycle lanes, and about 10 percent were located in Midtown, where double parking is prohibited. While only 13 percent of double-parked vans parked in bicycle lanes, close to a third were located in Midtown. Double parked vehicles in bicycle lanes are a particular threat to bicyclists, as they cause cyclists to have to deviate into motor vehicle lanes in locations where they might not be expected to do so. Vehicles double parked in motor vehicle lanes – legally or illegally – obstruct through traffic, contributing to congestion and emissions and presenting a risk to through travelers.

Figure 43. Observed Truck Parking Locations, Truck/Bike Interaction Study

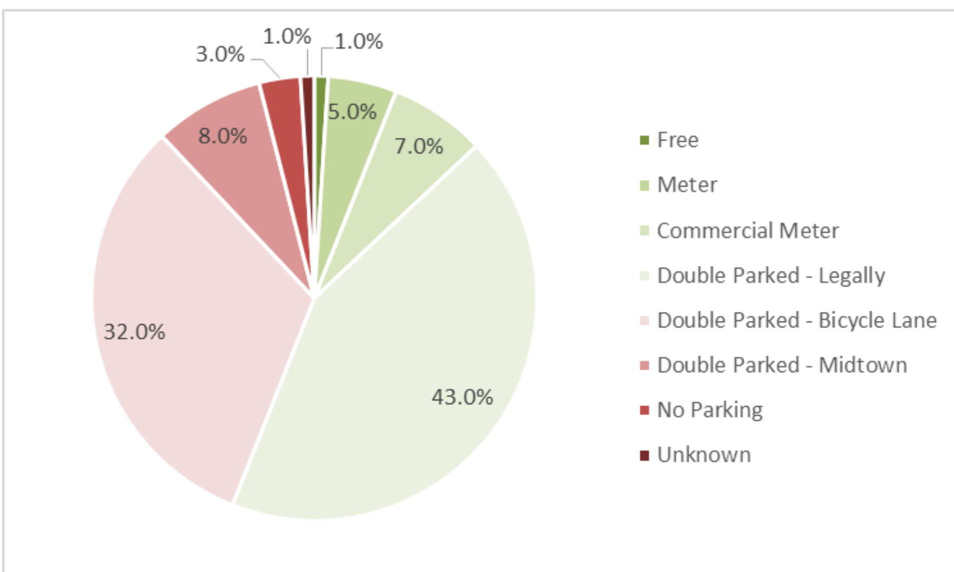
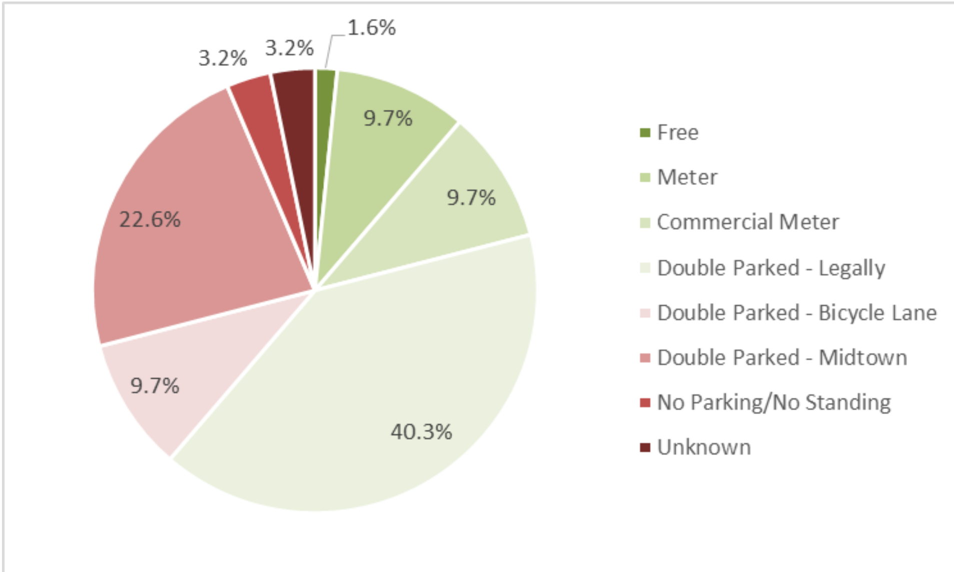


Figure 44. Observed Van Parking Locations, Truck/Bike Interaction Study



Although the small sample size does not allow for statistical validation, it appears that regulations with regards to double parking are limited in their effectiveness for at least some users. The average van parked in Midtown was found to park for nearly as long as the average legally double parked vehicle elsewhere in the city. Similarly, throughout Manhattan, the average truck double parked in a bicycle lane actually parks for longer than the average legally double parked vehicle (Table 17). For both sets of illegally parked vehicles, durations range from very short (1 min for trucks, 2 min for vans) to very long (53 min for trucks, 60 min for vans), indicating that some users aware of the restrictions likely complete deliveries as quickly as possible, while others are either unaware of or disregard them.

Table 17. Double-Parked Vehicle Stop Durations

	Count	Delivery Time (min)	
		Mean	Std. Dev.
Van	**62**	**12.4**	**11.0**
Double Parked - Legally	25	13.2	9.7
Double Parked - Bicycle Lane	6	6.8	5.0
Double Parked - Midtown	14	12.1	16.4
Truck	**100**	**19.6**	**13.5**
Double Parked - Legally	43	21.7	13.0
Double Parked - Bicycle Lane	32	22.8	15.5
Double Parked - Midtown	8	12.0	10.2

5.2.3.5 Summary of Findings

The analysis of City Bakery and City Harvest stop durations yields a number of conclusions relating to parking of freight tricycles. First, disregarding shipper and receiver constraints, deliveries by freight tricycle are generally faster than those made by trucks. In part, this difference is due to the smaller shipment sizes carried by trike. Freight tricycles also have greater flexibility in terms of parking; as a result, they can often park on a sidewalk directly in front of a pickup or delivery location. When freight tricycles park on the sidewalk, they are relatively immune to parking restrictions, and delivery time from the vehicle to an end location is reduced.

In theory, truck deliveries are much more impacted by parking restrictions. City Harvest trucks demonstrate very different behaviors in Midtown, where special parking rules apply. When double parking is banned, trucks are unable to make very quick deliveries. Similarly, when commercial meters are not enforced, delivery times increase considerably. Results from the Truck/Bike interaction study reveal additional findings. First, while tricycles are much more likely to make quick deliveries than trucks, their behavior is more similar to that of vans. Although vans cannot park on the sidewalk, they do have greater parking flexibility than trucks. However, vans often rely on illegal parking to achieve these fast deliveries; more than 35 percent of vans observed in high-demand areas with bicycle infrastructure were parked illegally. Trucks were found to be even less compliant, with more than 40 percent parked illegally. In areas outside of Midtown, both vans and trucks are heavily dependent on legal double parking, with on the order of 40 percent of each vehicle type Manhattan-wide legally double parking. Double parking – whether legal or illegal – obstructs motor vehicle traffic, contributing to traffic congestion and it related environmental externalities, and increasing potential for conflicts. These conflicts are particularly dangerous when parking obstructs a bicycle lane.

6 Impact Analysis Results

As noted in Section 4, two primary community benefits expected from cargo cycle operations are a reduction in road and parking space consumed and a reduction in air pollutant and greenhouse gas emissions from a reduced dependence on fossil fuels. To understand the reductions achievable by replacing motorized vehicles with cargo cycles, it is first necessary to understand the potential for replacement given the constraints of a specific supply chain and their associated costs.

To estimate overall space consumed and emissions generated by vehicles operated by a specific business, the space consumed by an individual vehicle, the distance over which it travels, the speed at which it moves, and the duration for which it parks must be known. A vehicle's footprint and speed can be relatively easily estimated and compared from vehicle dimensions and from local traffic data. However, the distance traveled and parking duration for different vehicle types are heavily dependent on the specific characteristics of the user's operations.

As discussed in Section 5, policy restrictions may limit operating infrastructure; when freight tricycles are permitted to operate on bicycle-only infrastructure, motor vehicles traveling even to the exact same locations may have to travel a longer distance to complete the same pickups and deliveries. Similarly, cargo cycle tours are constrained by vehicle capacities as well as by driver fatigue. A motor vehicle tour consisting of many deliveries and stops spread over a long distance may not be directly replaceable by a single cargo cycle, but many require multiple shorter tours completed in succession or using multiple vehicles. Parking behavior will also vary for different vehicles; while a cargo cycle may have access to a sidewalk, a replacement motor vehicle would need to park on-street, increasing the walking distance to make a delivery and, depending on local conditions, potentially requiring the vehicle to idle while waiting for parking.

In this study, the operators observed primarily perform local, point-to-point deliveries. City Bakery operates from a centralized location; however, with the exception of a regular morning tour to initially stock each satellite location, it performs trips on-demand, delivering small volumes of goods to stores in need of a specific product. Due to the time-sensitivity of the deliveries (and the goods themselves), the organization of deliveries is unlikely to change considerably whether deliveries are made via tricycle or via van - the mode by which goods previously moved. City Harvest moves small loads (less than 50 lbs) directly from donor to receiver. The organization has indicated that by using freight tricycles, it is able to continue to pick up these small donations from donor stores and restaurants, a service they might be unable to perform efficiently using a larger vehicle. In City Harvest operations, drivers have discretion to determine their order of pickups and deliveries, and to adjust these in real-time based on goods donated. While a larger vehicle capacity might allow for more consolidation of pickups before a delivery is made, without load data from specific donors, it is difficult to predict how pickups and deliveries might be reorganized to achieve greater efficiencies with a larger vehicle.

New York City operations differ considerably from those employed in Europe for micro-consolidation centers. For example, in the London pilot discussed in Section 2 (Browne, Allen, and Leonardi, 2011), seven long-distance van trips connecting to a distant warehouse were replaced with a single truck trip connecting to a micro-consolidation center, from which delivery tours could operate. In this study, the distances traveled locally by multiple tricycle and small electric van tours were much greater than the local distance traveled by the higher capacity cargo vans used previously. However, the distance traveled by a single truck between the warehouse and the micro-consolidation center was much lower than the sum total distance traveled by seven vans previously to connect from the warehouse to the central business district.

This section discusses the differences in vehicle footprints, traffic operating characteristics, and vehicle capacities that influence road and parking space consumption for different urban delivery vehicle types. It also discusses the factors that influence air pollutant and CO_2 emissions during vehicle movements. Finally, considering the unique constraints of each operator, City Bakery and City Harvest case studies are discussed to illustrate space and emissions savings from cargo cycle use.

6.1 Rates of Space Consumption

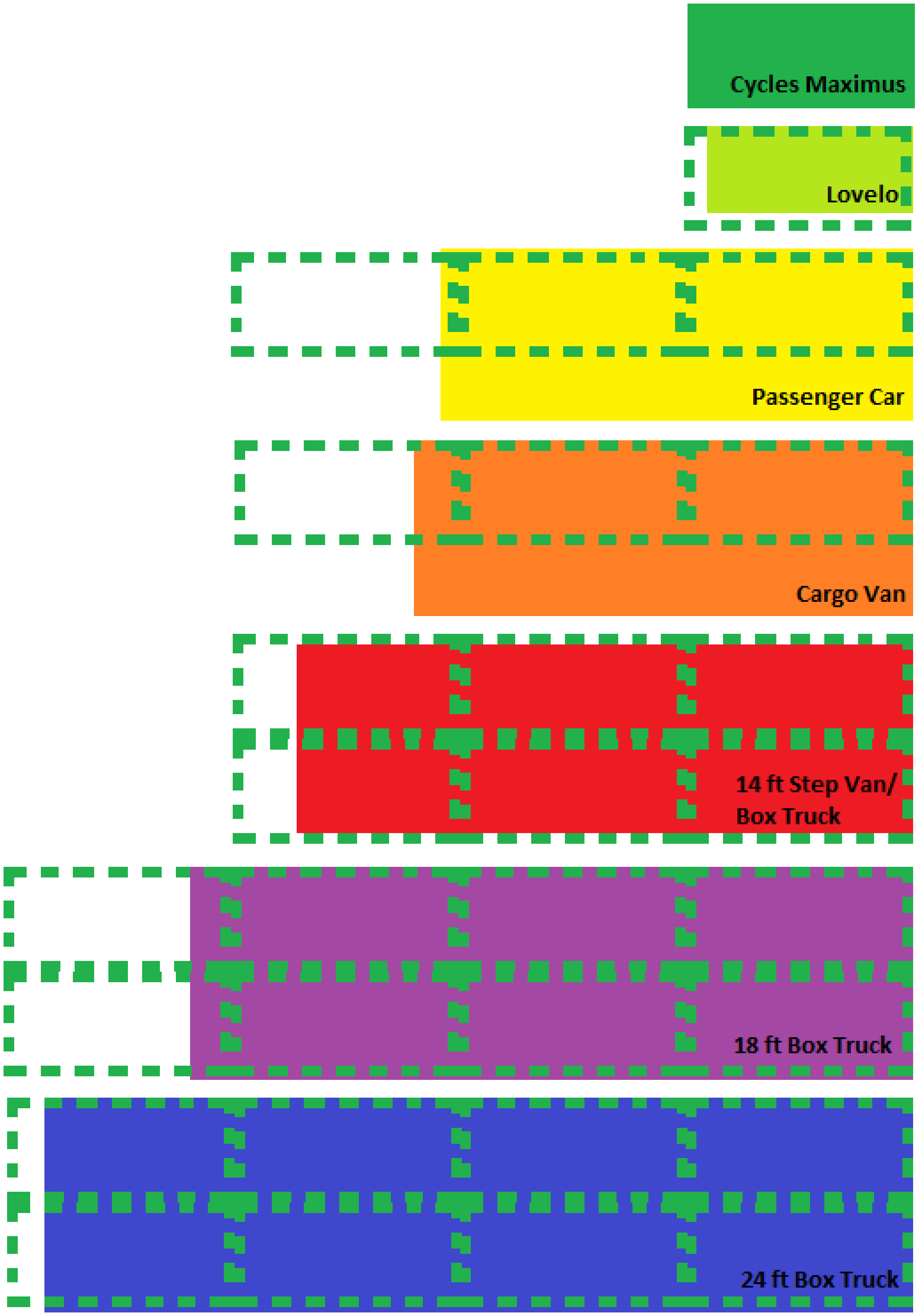
6.1.1 Vehicle Dimensions

Table 18 shows the dimensions, in feet, for the Cycles Maximus cargo cycle used by both City Bakery and City Harvest. Table 18 also gives dimensions for comparative motorized urban delivery vehicles and the Lovelo CarcoCycle used by operators in both London and Paris. To clearly illustrate how each vehicle differs from the Cycles Maximus, dimensional ratios are provided for each vehicle; these ratios were calculated by dividing the vehicle dimension by the same dimension on the Cycles Maximus trike. Figure 45 provides a to-scale visual representation of each vehicle's footprint, with the Cycles Maximus vehicle superimposed on each vehicle using a dashed green line. As can be seen, while the Cycles Maximus is slightly larger than the Lovelo vehicle, it is less than half the length of a passenger car or cargo van and about a quarter of the length of the longest (24 ft) box truck. Similarly, the Cycles Maximus is about half as wide as the step vans and box trucks, and about 60 percent of the width of a passenger car or cargo van. Multiplying these dimensions, we see that the footprints consumed by motorized vehicles range from more than three to close to eight times the area consumed by a cargo cycle.

Table 18. Freight Vehicle Dimensions

Vehicle	Length (ft)	Length Ratio	Width (ft)	Width Ratio	Area (ft^2)	Area Ratio
Cycles Maximus	8.53	1.00	3.93	1.00	33.56	1.00
Lovelo CargoCycle	7.71	0.90	3.22	0.82	24.80	0.74
Passenger Car	17.67	2.07	6.44	1.64	113.80	3.39
Cargo Van	18.68	2.19	6.60	1.68	123.26	3.67
14 ft Step Van/ Box Truck	23.20	2.72	7.00	1.78	162.40	4.83
18 ft Box Truck	27.10	3.18	8.00	2.03	216.70	6.46
24 ft Box Truck	32.60	3.82	8.04	2.04	261.76	7.80

Figure 45. Delivery Vehicle Footprints



6.1.2 Travel Lane Space

6.1.2.1 Estimated Consumption Rate

As noted in Section 4, to evaluate road space consumed by a moving vehicle in New York City, not only its footprint but also the speed at which it traverses the road should be considered. From GPS observations, overall median moving speeds for each vehicle type were estimated to be 3.90 mph for City Harvest tricycles, 7.22 mph for City Bakery tricycles, and 8.28 mph for City Harvest trucks. Applying these speeds to each of the vehicle types in Table 18 using the process described in Figure 14, the space-hours per mile of travel consumed by each vehicle type while it is moving can be estimated. To estimate space consumed while the vehicle is stopped in traffic (not parked), the stopped-time to moving-time ratio must be calculated, as defined in Equation 6. Median stopped-time to moving time ratios for each vehicle type were estimated to be .363 for City Harvest freight tricycles, .134 for City Bakery freight tricycles, and .338 for City Harvest trucks. Again, applying methods described in Figure 14, the total space-hours consumed per mile of travel for each vehicle type can be found. Results are shown in Table 19.

Table 19. Estimated Road Space Consumption by Vehicle Type

Vehicle Type	Length	Width	Space Hours Consumed per Mile of Travel						Relative Space Consumed vs. Cycles Maximus					
			Moving		Stopped		Total		Moving		Stopped		Total	
			CH	*CB*	*CH*	*CB*	*CH*	*CB*	*CH*	*CB*	*CH*	*CB*	*CH*	*CB*
	(ft)	(ft)	(ft^2*hr)						(unitless)					
Cycles Maximus	8.53	3.93	8.6	4.7	3.1	0.6	11.7	5.3	1.0	1.0	1.0	1.0	1.0	1.0
Lovelo CargoCycle	7.71	3.22	6.4	3.4	2.3	0.5	8.7	3.9	0.7	1.0	0.7	0.7	0.7	0.7
Passenger Car	17.67	6.44	13.8		4.6		18.4		1.6	3.0	1.5	7.5	1.6	3.5
Cargo Van	18.68	6.60	14.9		5.0		19.9		1.7	3.2	1.6	8.1	1.7	3.8
14 ft Box Truck/ Step Van	23.20	7.00	19.6		6.6		26.2		2.3	4.2	2.1	10.6	2.2	5.0
18 ft Box Truck	27.1	8.00	26.2		8.8		35.0		3.0	5.6	2.8	14.3	3.0	6.6
24 ft Box Truck	32.6	8.04	31.7		10.7		42.3		3.7	6.8	3.4	17.2	3.6	8.0

Taking into consideration vehicle speeds and expected delays, cargo cycles consume space at a lower rate per mile of travel than all motorized vehicles. Although motorized vehicle space consumption rates vary from about 18 to 42 ft^2*hours per mile of travel, rates for cargo cycles are much lower, regardless of whether they travel at City Harvest or City Bakery speeds. However, looking at the consumption ratios it is clear that relative space savings are dependent on vehicle speeds; City Bakery vehicles traveling at more than twice the speed of City Harvest vehicles consume space at a much lower rate. This lower rate of space consumption for faster moving vehicles should be noted by municipalities who may seek to regulate the speeds at which cargo cycles (or any urban delivery vehicles) travel.

6.1.2.2 Sensitivity Analysis

The rates of consumption estimated in the previous section for each vehicle type rely on the assumption that the vehicle is traveling at the median observed speed and at the median stopped-time to moving time ratio; however, there is considerable variability observed in the data set for each of these measures. Table 20 provides the speed observations at a number of specific cumulative observation percentiles for each vehicle type;

Figure 46 shows the estimated rates of consumption for each vehicle type when these varying percentile speeds are applied. As is expected and can be seen from the figure, while all vehicles consume more space at slower observed speeds, growth in the rate of space consumed is most extreme for the largest motor vehicles. Comparing the relative rates of space consumed for each vehicle type compared to a City Harvest tricycle at each observed moving speed percentile (Table 21), we find that relative space consumed by the motorized vehicles increases by about 70 percent for the slowest moving vehicles, and decreases by about 30 percent at the highest speeds. For City Bakery, whose observed speeds are generally higher, impacts are greater, with relative space consumed by motorized vehicles increasing by about 135 percent at the lowest speed percentiles compared to median rates, and decreasing by about 38 percent at the highest observed speeds (Table 22).

Table 20. Vehicle Type Observed Moving Speeds

Percentile	Observed Moving Speed (mph)		
	CH Trike	CB Trike	CH Trucks
10%	0.91	2.33	1.14
25%	1.94	4.63	2.46
50%	3.90	7.22	8.28
75%	6.04	9.96	17.09
90%	7.84	12.83	23.55

Figure 46. Estimated Space Consumed vs. Speed Observation Percentile

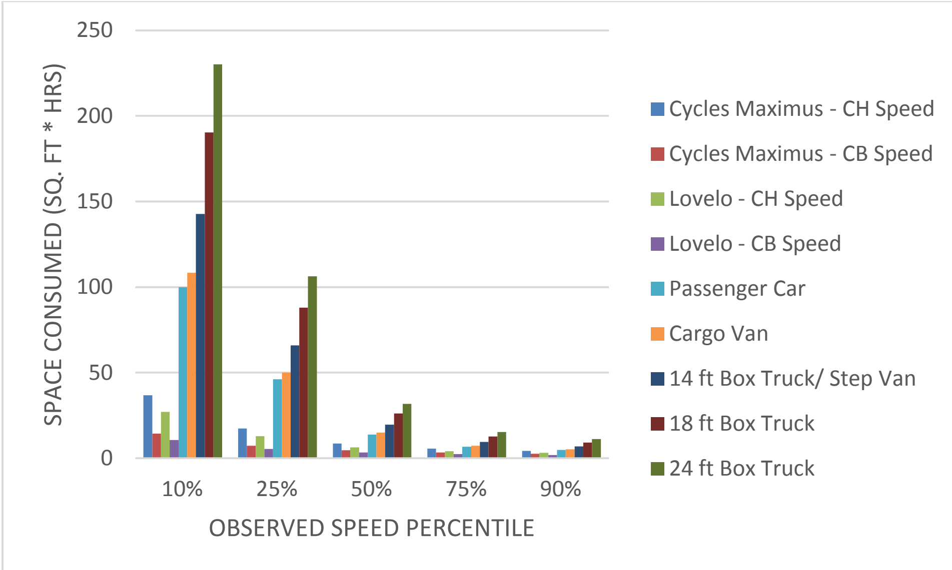


Table 21. Relative Moving Space Consumed vs. City Harvest Cycles Maximus

Vehicle Type	10%	25%	50%	75%	90%
Cycles Maximus	1.0	1.0	1.0	1.0	1.0
Lovelo CargoCycle	0.7	0.7	0.7	0.7	0.7
Passenger Car	2.7	2.7	1.6	1.2	1.1
Cargo Van	2.9	2.9	1.7	1.3	1.2
14 ft Box Truck/ Step Van	3.9	3.8	2.3	1.7	1.6
18 ft Box Truck	5.2	5.1	3.0	2.3	2.2
24 ft Box Truck	6.3	6.1	3.7	2.8	2.6

Table 22. Relative Moving Space Consumed vs. City Bakery Cycles Maximus

Vehicle Type	10%	25%	50%	75%	90%
Cycles Maximus	1.0	1.0	1.0	1.0	1.0
Lovelo CargoCycle	0.7	0.7	0.7	0.7	0.7
Passenger Car	6.9	6.4	3.0	2.0	1.8
Cargo Van	7.5	6.9	3.2	2.1	2.0
14 ft Box Truck/ Step Van	9.9	9.1	4.2	2.8	2.6
18 ft Box Truck	13.2	12.1	5.6	3.8	3.5
24 ft Box Truck	16.0	14.7	6.8	4.6	4.3

Table 23 shows the observed cumulative percentiles for ratios of stopped-time to moving-time. For both City Bakery and City Harvest freight tricycles, at the 10th percentile, the observed stopped-time was zero, resulting in a zero ratio. For City Harvest freight tricycles, a very large range was observed, with stopped-times ranging from zero to 96 percent of moving time. For City Bakery freight tricycles, much lower shares of delay were observed.

Figure 47 shows the estimated total space consumption rates for each observed ratio; results show linear growth with an increase in speed percentile for each vehicle type. The rate of consumption regularly increases when plotted against ratios observed at subsequent percentiles, with the slope increasing for larger vehicles due to their bigger footprint. For City Harvest freight tricycles, the growth is similar to that of the motor vehicles. For City Bakery freight tricycles, while linear growth is observed, consumption rates remain low at the highest percentiles due to the small delays observed for all City Bakery freight tricycles (Table 23). As can be seen in Table 24, at the highest ratio percentiles observed, City Harvest freight tricycles offer essentially no savings in stopped-time space consumption despite their smaller footprint due to greater delays observed. However, Table 25 shows that for City Bakery freight tricycles, space savings are considerable even for the vehicles facing the greatest delays. Similarly, for the lowest percentiles observed, City Bakery freight tricycles consume much less space than all motor vehicles.

Table 23. Ratio of Observed Stopped-time to Moving Time

Percentile	Ratio of Observed Stopped-Time to Moving-Time Ratio		
	CH Trike	CB Trike	CH Trucks
10%	0	0	0.12
25%	0.15	0.06	0.24
50%	0.36	0.13	0.34
75%	0.59	0.2	0.47
90%	0.96	0.27	0.58

Figure 47. Estimated Space Consumed vs. Observed Stopped-time: Moving-Time Ratio Percentile

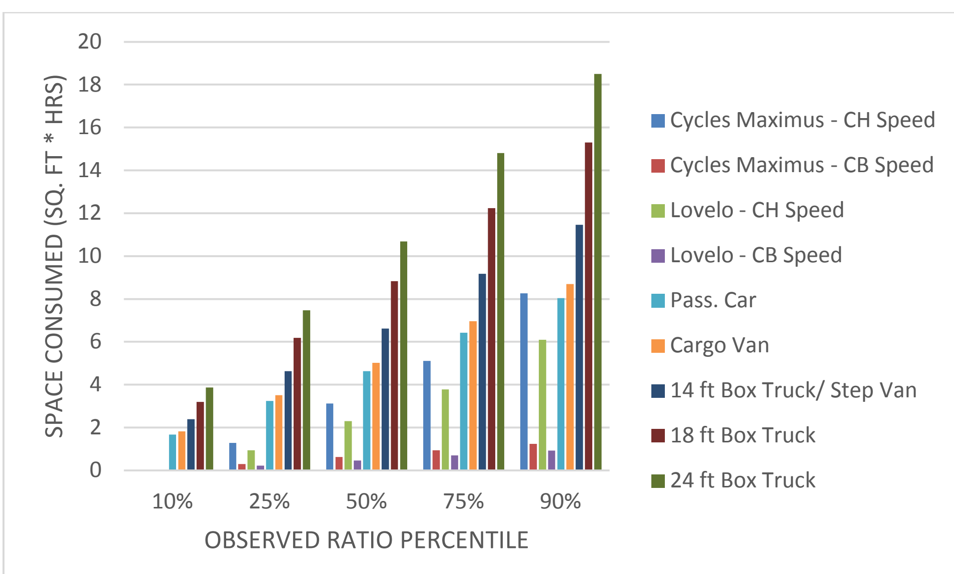


Table 24. Relative Stopped Space Consumed vs. City Harvest Cycles Maximus

Vehicle Type	10%	25%	50%	75%	90%
Cycles Maximus	---	1.0	1.0	1.0	1.0
Lovelo CargoCycle	---	0.7	0.7	0.7	0.7
Pass. Car	---	2.5	1.5	1.3	1.0
Cargo Van	---	2.7	1.6	1.3	1.0
14 ft Box Truck/ Step Van	---	3.6	2.1	1.8	1.4
18 ft Box Truck	---	4.8	2.8	2.40	1.9
24 ft Box Truck	---	5.8	3.4	2.90	2.2

Table 25. Relative Stopped Space Consumed vs. City Bakery Cycles Maximus

Vehicle Type	10%	25%	50%	75%	90%
Cycles Maximus	---	1.0	1.0	1.0	1.0
Lovelo CargoCycle	---	0.7	0.7	0.7	0.7
Pass. Car	---	10.8	7.4	6.8	6.5
Cargo Van	---	11.7	8.1	7.4	7.0
14 ft Box Truck/ Step Van	---	15.4	10.6	9.7	9.2
18 ft Box Truck	---	20.5	14.2	13.0	12.3
24 ft Box Truck	---	24.8	17.1	15.7	14.9

6.1.3 Vehicle Capacity

Although the previous section describes the rate of road space consumption for different vehicle types, these rates cannot be directly compared. The consumption rates estimated represent the space-hours consumed for one mile of vehicle travel. However, when deliveries are made using different vehicle types, delivery patterns - and the resulting distance traveled - may vary. As discussed in Section 5, travel restrictions may limit the specific routes used by different vehicles. Delivery tour patterns may also be influenced by vehicle load capacities. Vehicles can carry only as much load as their weight and volume limits allow. Table 26 provides the weight and volume capacities for each urban delivery vehicle type.

Table 26. Estimated Delivery Vehicle Capacities

Vehicle	Volume (ft^3)		Payload (lbs)	
	Maximum	Ratio	Maximum	Ratio
Cycles Maximus	35.3	1.0	551	1.0
Lovelo CargoCycle	53.0	1.5	396	0.7
Passenger Car	20.6 [a]	0.6	1,500 [b]	2.7
Cargo Van	240	6.8	2,016 [c]	3.7
14 ft Step Van	762 [d]	21.6	6,000	10.9
14 ft Box Truck	784 [d]	22.2	7,100	12.9
18 ft Box Truck	1296	36.7	8,200	14.9
24 ft Box Truck	1536 [e]	43.5	16,500	29.9

[a] From manufacturer specifications; trunk only

[b] Payload provided in manufacturer's specifications as towing weight

[c] Varies by configuration; best estimate based on online sales postings and manufacturer's specifications

[d] Payload estimates provided by City Harvest

[e] Estimate provided by vehicle rental agency - http://www.budget.ca/truck/en/fleet/

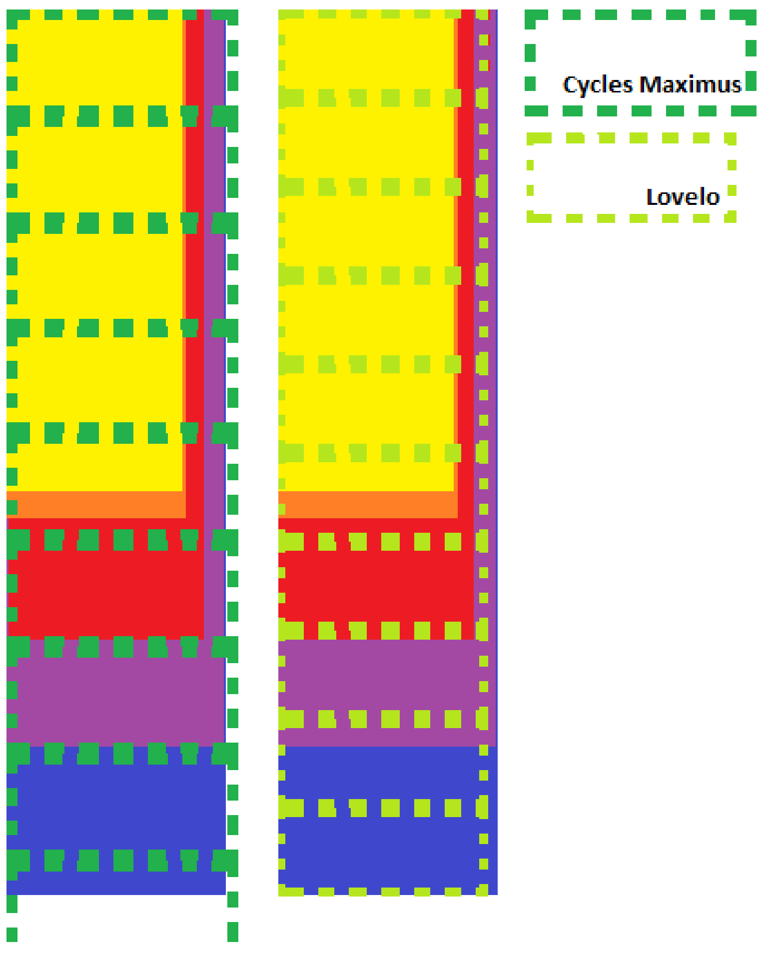
How vehicle capacity differences affect trip distances will vary for different operators. As all vehicles have capacity limits, trips cannot be infinitely chained. A vehicle with a large capacity has a greater capability to complete consecutive deliveries without returning to a production or storage facility. To complete deliveries that could be made by a single truck or van tour, an operator may need to complete multiple tours by cargo cycle from a central storage location. The London study pilot discussed previously provides an example; in that study, local vehicle travel distances increased significantly when goods were moved by cargo cycle (although long-distance travel decreased) rather than by van (Browne, Allen, and Leonardi 2011). Alternatively, when larger vehicle capacities are not being utilized, replacement with a lower capacity vehicle may have little to no impact on trip behavior. The City Bakery case study discussed in detail later in this section provides an example.

6.1.4 Parking Space

As discussed in Section 5, in general, cargo cycles park for shorter durations than motorized vehicles, as their load sizes are generally smaller. However, exact parking space consumption rates for each vehicle type are difficult to estimate given variability in load and receiver characteristics. Similarly, the flexibility of available parking space may also impact efficiencies achieved. As discussed in Section 5, freight tricycles often have the ability to park on the sidewalk, an option not available to motorized vehicles. Even when tricycle parking is confined to on-street parking space, the configuration of available space may impact the efficiency improvements achieved. As can be seen in

Table 18 and Figure 48, the Lovelo cargo cycle's length is less than the width of all of the truck configurations. The length of the Cycles Maximus is only about 6 inches wider than the truck width. If a parking lane is 9 ft or wider, cargo cycles are able to park perpendicular to the curb while remaining in the lane, which can result in more efficient use of space. For example, comparing Figure 45 to Figure 48 shows that while parking in adjacent spots parallel to the curb, (neglecting space between vehicles) six full Cycles Maximus vehicles can fit in the space occupied by an 18-ft box truck. When these vehicles park perpendicular to the curb, an additional vehicle can fit into the same length. Parking impacts under specific City Bakery and City Harvest conditions are provided in the following section.

Figure 48. Cargo Cycle Perpendicular Parking Space Consumption



6.2 Emissions Rates

As human-powered cargo cycles generate no significant pollutant or greenhouse gas emissions, savings can be quantified only by estimating the emissions of the motorized vehicle that might be replaced. As discussed, in Section 4, emissions rates vary as a function of many vehicle and environmental variables. To examine the influence of different variables on per-mile emissions rates in New York City conditions, 96 model runs were conducted for each pollutant. Each run examined a unique combination of vehicle type, fuel type, vehicle age, speed, temperature, and humidity variables. Table 27 shows the input variables evaluated. Estimated emissions rates for each individual run are provided in Appendix D.

Table 27. MOVES Model Input Variables

Variable	Values
Vehicle Type	Passenger Car, Passenger Truck (Cargo Van), Light Commercial Truck (Step Van), Small Box Truck
Fuel Type	Gasoline (Pass. Car), Diesel (All other)
Age	1 year, 5 year, 10 year
Speed	3 mph, 5 mph, 10 mph, 15 mph
Temperature	29 (Winter), 70 (Summer)
Humidity	62 (Winter), 65 (Summer)

The three pollutants examined in this study include PM 2.5, PM 10, and CO_2. As discussed previously, particulate matter is both a health and safety hazard in urban areas. Particles smaller than 10 micrometers can cause health problems, pollute water sources, and stain or damage structures (US EPA 2013). Particles smaller than 2.5 micrometers, in addition to causing health problems, can also form smog and cause visibility problems. Figure 49 and Figure 50 show the distributions of PM 2.5 and PM 10 under different variable combinations. For the gasoline-powered passenger car, both PM 10 and PM 2.5 emissions rates are much higher in the winter than in the summer. For the diesel-powered vehicles, weather factors have little influence on emissions rates. For all vehicles, emissions rates reduce exponentially as a function of speed; those vehicles traveling at the slowest speed (3 mph) generate much higher emissions even that those traveling at 5 mph. Although PM emissions rates increase with age for all vehicle types, there is a stark difference in emissions rates for all diesel-powered vehicles when comparing vehicles that are 5 years and 10 years old.

CO_2 is the greenhouse gas most commonly generated through human activities, including in motor vehicle fuel combustion.

Figure 51 and 52 show the expected CO_2 emissions generated for different variable combinations. For passenger cars, cargo vans, and step vans, emissions rates are slightly higher in the summer than in the winter. For the three smaller vehicle types, increasing fuel economy standards for vehicles less than 8,500 lbs are reflected when comparing emissions rates for vehicles 1, 5 , and 10 years old. For box trucks, rates are stagnant for vehicles of different ages, reflecting the past lack of federal fuel economy standards for heavy duty vehicles weighing more than 8,500 lbs. As with PM emissions, for all vehicle types, CO_2 emissions decrease exponentially with speed, although at slower rate for newer vehicles. Emissions estimated for City Harvest and City Bakery case studies are evaluated and discussed in the following section.

Figure 49. PM 2.5 Emissions vs. Speed by Vehicle Type

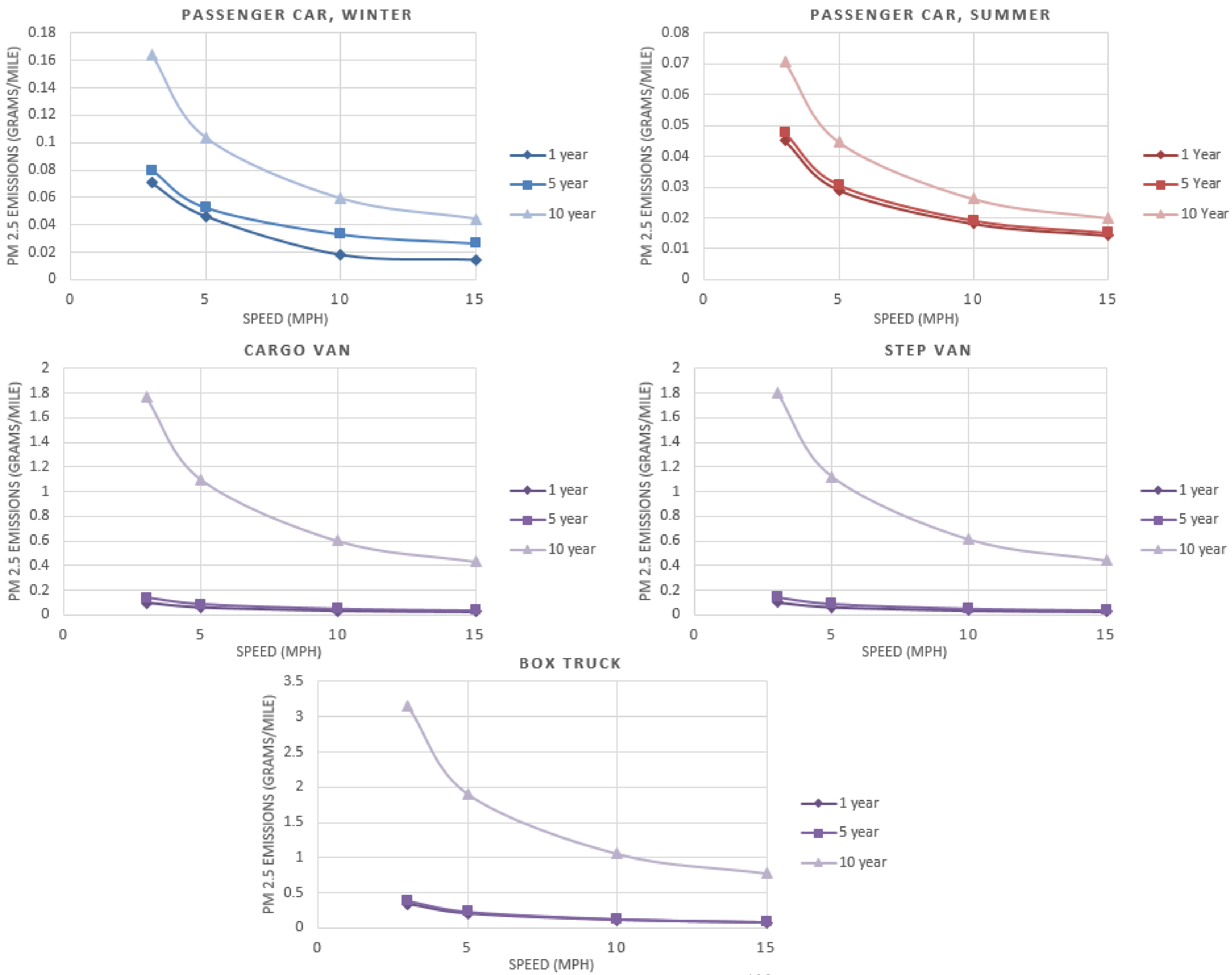


Figure 50. PM 10 Emissions vs. Speed by Vehicle Type

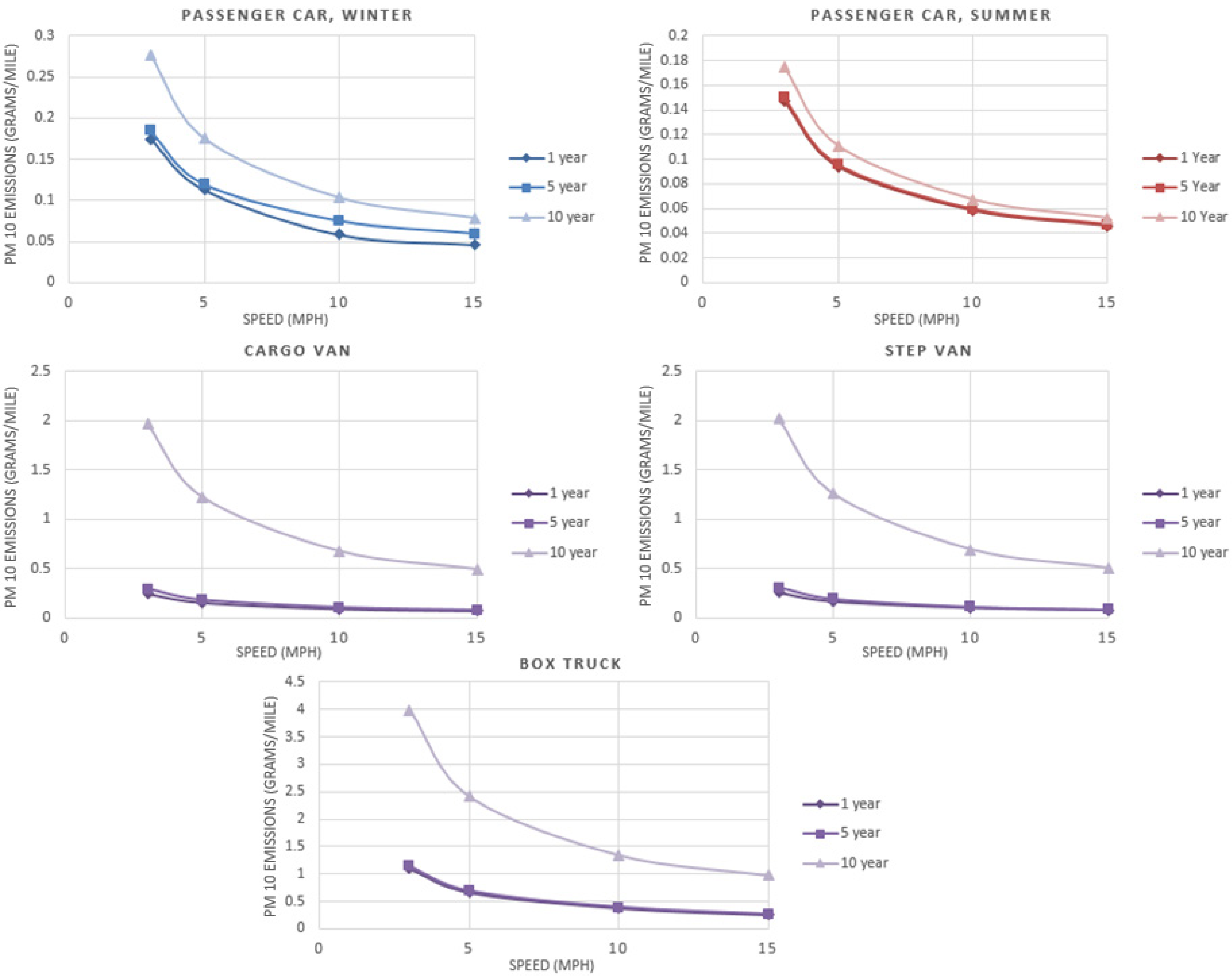


Figure 51. CO_2 Emissions vs. Speed by Vehicle Type - Small Vehicles

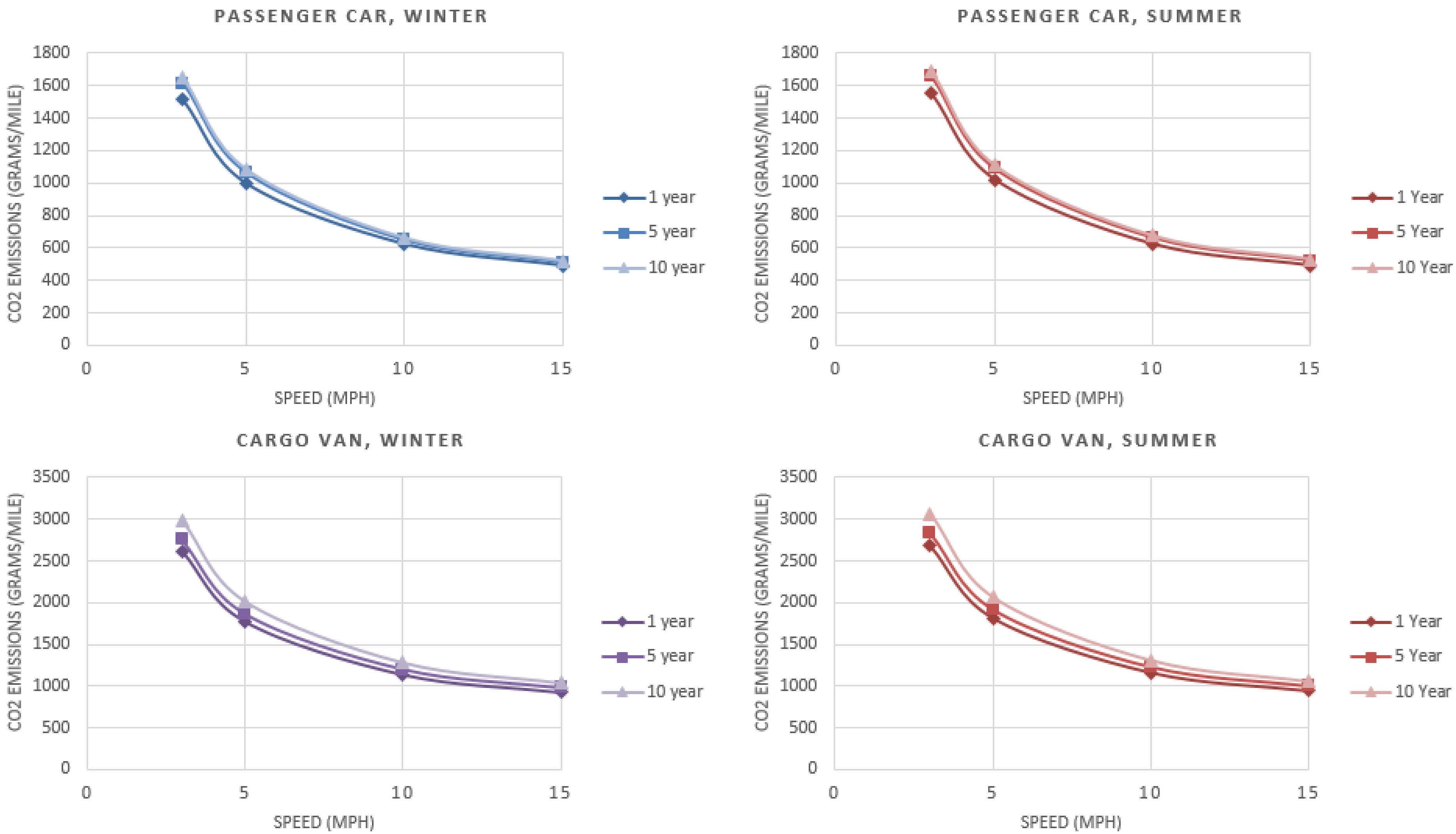
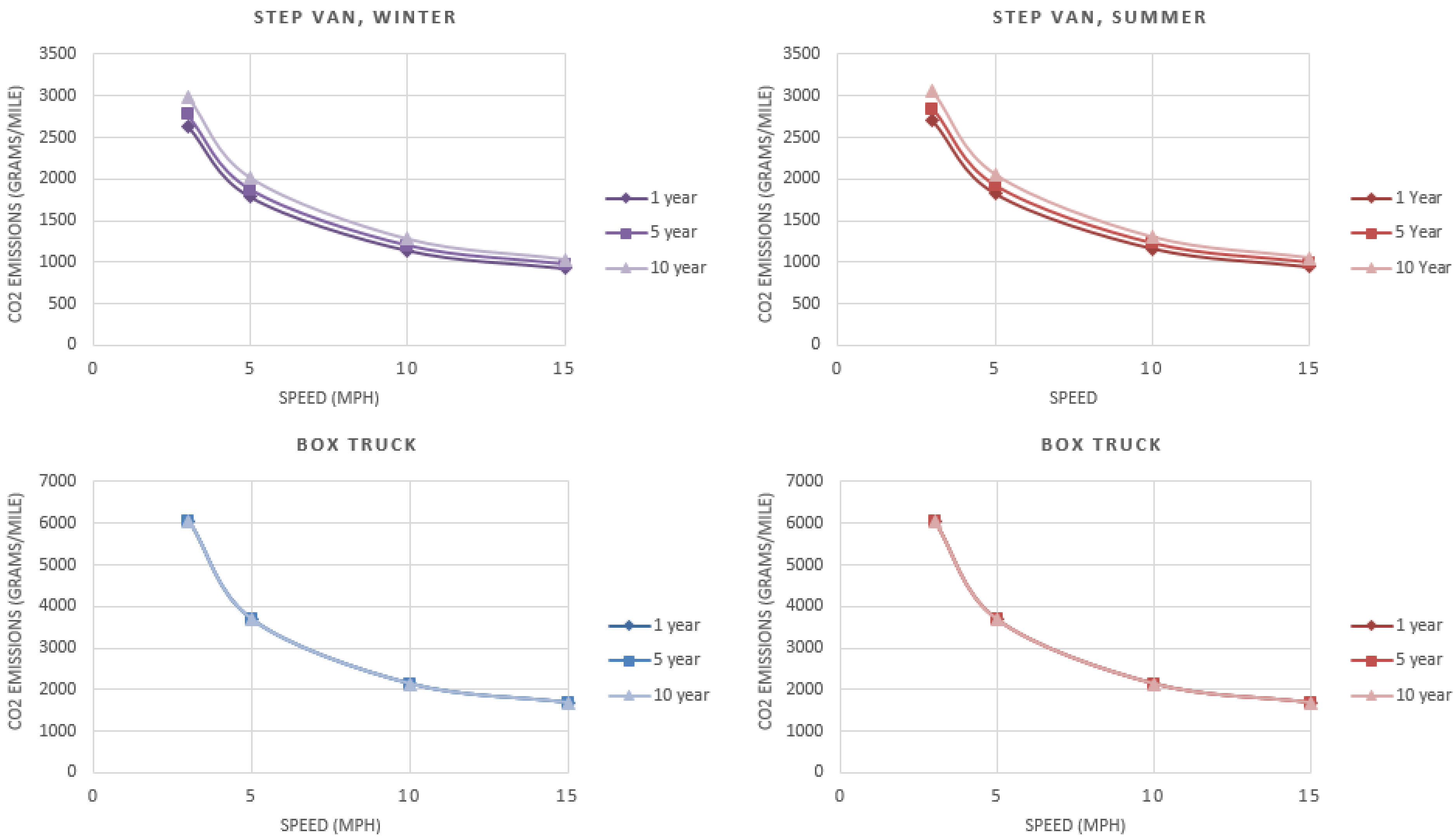


Figure 52. CO_2 Emissions vs. Speed by Vehicle Type - Large Vehicles



6.3 Case Studies

The following case studies provide estimates of road and parking space savings and emissions savings from the use of cargo cycles.

6.3.1 City Bakery

6.3.1.1 Typical Operations

As discussed previously, before implementation of cargo cycles for its daily operations, City Bakery conducted deliveries using cargo vans. Currently, freight tricycles are used to make deliveries from the City Bakery flagship location and from other "producer" locations to satellite bakery locations. In the morning, a regular tour is completed, providing each store with goods to meet expected daily demands. Throughout the remainder of the day into the early evening, additional point-to-point deliveries are made to meet additional real-time demands.

While cargo vans, like cargo cycles, can legally operate on all New York City streets, travel distances for some point-to-point trips made in this areas are expected to be higher for motor vehicles than for cargo cycles. While vans are constrained to operating in the legal direction of traffic in motor vehicle lanes, freight tricycles, irrespective of current policy restrictions, were observed to occasionally operate off-street through parks and squares and to operate in a direction opposite to motor vehicle traffic for short distances to avoid traveling a circular route. Table 28 provides the minimum observed travel distances for freight tricycles and the minimum legal travel distances by motor vehicle for trips commonly completed by City Bakery operators.

Table 28. City Bakery Minimum Point-to-Point Travel Distances by Mode

Origin	Destination	Minimum Distance (mi)	
		Tricycle	Motor Vehicle
3 West 18 St	223 1st Avenue	0.9	1.1
3 West 18 St	200 Church St	1.9	2.2
3 West 18 St	160 Prince St	1.1	1.3
3 West 18 St	35 3rd Ave	0.9	0.9
35 3rd Ave	3 West 18 St	0.9	1.2
35 3rd Ave	160 Prince St	1.0	1.2
160 Prince St	200 Church St	0.8	1.0
160 Prince St	3 West 18 St	1.1	1.3
200 Church St	160 Prince St	0.8	0.8
200 Church St	3 West 18 St	1.9	1.9
223 1st Avenue	3 West 18 St	0.9	1.2
223 1st Avenue	35 3rd Ave	0.5	0.5
223 1st Avenue	160 Prince St	1.4	1.5

6.3.1.2 Estimated Savings

To estimate total space consumption and emissions generated during daily operations, a typical daily tour was extracted from observed data. The trips made by each of City Bakery's two freight tricycles during this typical day – as well as the trips that would be made if each tricycle was replaced by a motor vehicle - are described in Table 29. In total, the freight tricycles travel 20.7 miles to complete 19 point-to-point trips. To complete the exact same deliveries, a cargo van would need to travel 23.8 miles. Scenario A assumes that motor vehicles complete the exact same deliveries as freight tricycles.

While it is unlikely that the number of on-demand point-to-point trips would be reduced for vans compared to freight tricycles, it is possible that if traffic conditions allowed, the morning tours for each tricycle could be completed by a single van tour given the higher van capacity. The trips associated with these morning tours are highlighted in gray in Table 29. Scenario B assumes that these morning tours are combined and completed by a single vehicle; the resulting tour is described in Table 30. In this scenario, the total motor vehicle travel distance would be reduced by 1.7 mi.

Table 29. City Bakery Typical Daily Tour

Origin	Destination	Distance Traveled (mi)	
Vehicle 1		**Tricycle**	**Motor Vehicle**
3 West 18 St	223 1st Avenue	0.9	1.1
223 1st Avenue	35 3rd Ave	0.5	0.5
35 3rd Ave	3 West 18 St	0.9	1.2
3 West 18 St	200 Church St	1.9	2.2
200 Church St	160 Prince St	0.8	0.8
160 Prince St	200 Church St	0.8	1.0
200 Church St	3 West 18 St	1.9	1.9
3 West 18 St	160 Prince St	1.1	1.3
160 Prince St	3 West 18 St	1.1	1.3
3 West 18 St	35 3rd Ave	0.9	0.9
35 3rd Ave	3 West 18 St	0.9	1.2
Vehicle 1 Total		**11.7**	**13.4**
Vehicle 2		**Tricycle**	**Motor Vehicle**
3 West 18 St	223 1st Avenue	0.9	1.1
223 1st Avenue	160 Prince St	1.4	1.5
160 Prince St	200 Church St	0.8	1.0
200 Church St	3 West 18 St	1.9	1.9
3 West 18 St	160 Prince St	1.1	1.3
160 Prince St	3 West 18 St	1.1	1.3
3 West 18 St	223 1st Avenue	0.9	1.1
223 1st Avenue	3 West 18 St	0.9	1.2
Vehicle 2 Total		**9.0**	**10.4**
Total		**20.7**	**23.8**

Table 30. Combined Morning Tour Trips

Combined Morning Tour		Distance Traveled
Origin	**Destination**	**(mi)**
3 West 18 St	223 1st Avenue	1.1
223 1st Avenue	35 3rd Ave	0.5
35 3rd Ave	160 Prince St	1.2
160 Prince St	200 Church St	1.0
200 Church St	3 West 18 St	1.9
Combined Morning Tour Total		5.7

Table 31 shows the tour characteristics and estimated road and parking space consumed in each scenario. As noted in Section 5, stop durations are differentiated by location type. The three City Bakery locations that produce goods typically require longer parking durations than the other locations that only receive goods. Consumption estimates assume that both types of vehicles travel at median observed speeds and park for average observed durations. Van parking durations are assumed to be identical to cargo cycle parking durations; this is a conservative estimate, as motor vehicles may require additional time to identify a parking space and cannot park on the sidewalk immediately adjacent to a delivery location. Even with this conservative assumption, it is clear that cargo vans occupy significantly more road and parking space than cargo cycles completing the same tour. Comparing current operations and Scenario A showed a nearly 397 percent increase in total space consumed, including a 434 percent increase in road space consumed and a 367 percent increase in parking space consumed. Even for Scenario B, which takes advantage of additional vehicle capacity to reduce the distance traveled and the number of stops made during the morning tour, total space consumption is 360 percent greater than current operations using a trike.

Table 31. City Bakery Space Consumption Estimates

Scenario		Current	Scenario A	Scenario B
Vehicle		Trike	Van	Van
Tour Characteristics				
Distance Traveled (mi)		20.7	23.8	22.1
"Producer" Stops[a]	**Number**	13	13	12
	Duration (min) [b]	18.8	18.8	18.8
"Receiver" Stops	**Number**	5	5	4
	Duration (min) [b]	9.5	9.5	9.5
Consumption Estimates				
Daily Road Space	**Rate (ft^2*hrs/mi)**	5.3	19.9	19.9
	Total (ft^2*hrs)	109.2	473.9	422.2
Daily Parking Space	**Rate (ft^2)**	33.6	123.3	123.3
	Total (ft^2*hrs)	136.7	502.1	463.5
Total Daily Space	**Total (ft^2*hrs)**	245.9	976.0	885.6

[a] Excludes final return trip to City Bakery

[b] Assumes van time spent searching for parking and added time due to longer delivery distance are negligible

Table 32 provides emissions estimates for each pollutant and motor vehicle scenario. These estimates assume that vans are 5 years old and travel at the median observed travel speed of 8.28 mph. Given the relatively short travel distances, net savings of particulate matter emissions are small. Slightly more than two pounds per year of particulates smaller than 10 micrometers are avoided, and about 46 percent of this mass are particulates smaller than 2.5 micrometers. CO_2 savings are more measurable, with 11-13 tons avoided annually.

Table 32. City Bakery Emissions Savings Estimates

	Pollutant			
	PM 2.5	PM 10	CO_2	
			Winter	Summer
Rate (grams/mi)	0.059	0.129	1341	1369
Estimated Daily Savings	(grams)			
Scenario A	1.4	3.1	31919.9	32580.3
Scenario B	1.3	2.7	28432.8	29021.1
Estimated Annual Savings	(lbs)		(tons)	
Scenario A	1.1	2.5	12.8	13.1
Scenario B	1.0	2.2	11.4	11.7

6.3.1.3 Summary of Findings

Overall, results from this case study analysis demonstrate that measurable space and emissions savings can be achieved when cargo cycles replace motor vehicles in delivery operations. For City Bakery, despite higher vehicle capacities, the total distance traveled is expected to increase for motor vehicle operations compared to cargo cycle operations. Assuming median speeds and excluding emissions during start-up and other emissions that occur while a vehicle is not moving, CO_2 savings of 11-13 tons/year and PM10 savings of 2-2.5 lbs per year were estimated. As shown in Figures 49-52, emissions rates are also sensitive to traffic conditions; generally emissions exponentially increase as speeds decrease. Due to changing emissions and fuel economy standards, emissions from old vehicles are much greater than from new vehicles. A 10-year old cargo van operating at 3 mph would generate 30 times as much PM2.5 emissions as the 8.28 mph, 5 year old van assumed; however, a 1-year old vehicle operating as 15 mph would generate only about half of the estimated emissions. CO_2 emissions are also variable, although less sensitive; a vehicle operating in the most polluting conditions evaluated generates a little more than twice as much CO_2 as the assumed vehicle, and the newest, fastest-traveling van generates about 70 percent less CO_2.

For median speeds and average parking durations, total space required for operations was reduced by 72-75 percent, with parking space required reduced by 70-72 percent and road space consumed dropping by 74-77 percent. As noted in Table 22, relative rates of space consumption for the different vehicle types will also vary with traffic conditions. As shown in

Figure 46, while rates of moving space consumed by cargo cycles double at the slowest evaluated speeds (10^{th} percentile), rates of consumption for motorized vehicles increase by more than a factor of six. City Bakery freight tricycles spend a notably lower share of their total travel time in delay compared to motor vehicles; at the cargo cycle 10^{th} percentile, observed stopped-times were equal to zero. The freight tricycles facing the greatest shares of delay do consume space per mile at a rate more than 160 percent greater than the average trike.

6.3.2 City Harvest

6.3.2.1 Typical Operations

As discussed in Sections 2 and 5, a typical City Harvest tricycle tour is longer than a City Bakery tricycle tour. Figure 17 describes a typical daily tour, covering 15.1 miles and 20 total stops, including 12 pickups and 8 deliveries. City Harvest vehicles do not operate from a centralized hub; rather, they perform continual point-to-point pickups and deliveries through the duration of a tour, returning to their starting point only at the end of their shift. Drivers are given the freedom to determine the order of their stops, as donation volumes will vary from day to day; this variability makes it extremely difficult to optimize stops to take advantage of larger vehicle capacities.

City Harvest has noted that tricycle operations are key to allow them to continue to make small pickups from local businesses. As noted previously, the volume of goods that City Harvest moves via tricycle is minute compared to the volumes moved through their Long Island City warehouse by truck. For movement of small delivery volumes, the freight tricycles offer a more appropriately sized vehicle than the other alternatives available in the current City Harvest fleet (box trucks ranging from 14 to 24 ft).

6.3.2.2 Estimated Savings

Given that City Harvest tricycle operations were observed almost exclusively in midtown, where the street network is a grid of parallel streets, only a single point-to-point trip was identified where the observed travel distance by tricycle was lower than the observed travel distance by car; freight tricycles traveling a single block between two locations on E. 64^{th} St. were observed to move against traffic flow rather than taking a more circuitous route. As a result, the estimated travel distance for completion of the tour by motor vehicle is only 0.4 miles longer than for a trike.

To estimate space and emissions savings from tricycle operations, two alternate scenarios were considered. Scenario C assumes that without freight tricycles, City Harvest would use the smallest vehicle available in their regular truck fleet – a 14 foot box truck – to complete operations. Recognizing that this vehicle is likely severely oversized for these small local operations, Scenario D evaluates the expected savings compared to a cargo van.

Table 33 provides road and parking space estimates for current operations and for each scenario. As in the City Bakery scenario, tricycle operations consume less space than motor vehicle operations; however, some differences can be observed. While in the City Bakery study, van road space consumption was close to 400 percent higher than tricycle consumption, for City Harvest, road space consumption increases by a much smaller 75 percent. This difference is due to two factors. First, as previously mentioned, the total travel distance by motor vehicle is only very slightly higher than by cargo cycle in the City Harvest case; for City Bakery, more than three miles of daily travel were added. Second, City Harvest freight tricycles travel at a much lower median speed (3.90 mph) than City Harvest tricycles, which at 7.22 mph are almost speed competitive with the median observed motor vehicle speed of 8.28 mph. In City Harvest operations, freight tricycles make more stops and park for longer durations, as discussed in Section 5. These longer parking times, and the much larger footprint for the 14 ft box truck, lead to considerably higher total parking space consumption. These estimates again rely on the conservative assumption that parking durations do not change by vehicle type.

Table 33. City Harvest Space Consumption Estimates

Scenario		Current	Scenario C	Scenario D
Vehicle		Trike	14 ft Box Truck	Van
Tour Characteristics				
Distance Traveled (mi)		15.1	15.5	15.5
Pickups	**Number**	12	12	12
	Duration (min) [a]	23.4	23.4	23.4
Deliveries	**Number**	8	8	8
	Duration (min) [a]	14.9	14.9	14.9
Consumption Estimates				
Daily Road Space	**Rate (ft^2*hrs/mi)**	11.7	26.2	19.9
	Total (ft^2*hrs)	176.7	406.1	308.5
Daily Parking Space	**Rate (ft^2)**	33.6	162.4	123.3
	Total (ft^2*hrs)	224.0	1082.7	822.0
Total Daily Space	**Total (ft^2*hrs)**	400.7	1488.8	1130.5

[a] Assumes motor vehicle time spent searching for parking and added time due to longer delivery distance are negligible

Table 34 provides estimated emissions savings for each scenario, again relying on a vehicle age of 5 years and an average speed of 8.28 mph. As expected, given that the vehicles are operating on identical routes, emissions are much higher for the box truck than for the cargo van. The box truck generates more and larger particulates; while for cargo vans about 45 percent of particulate emissions are smaller than 2.5 micrometers, for box trucks only about a third of the volume generated fits into that category. Overall, PM10 savings range from 1.6 to 5.72 lbs annually, and CO_2 savings are between 8.3 and 15.6 tons annually.

Table 34. City Harvest Emissions Savings Estimates

	Pollutant			
	PM 2.5	PM 10	CO_2	
			Winter	Summer
Emissions Rate	(grams/mi)			
Van	0.059	0.129	1,341	1,369
14 ft Box Truck	0.154	0.459	2,454	2,509
Estimated Daily Savings	(grams)			
Scenario C	0.9	2.0	20785.5	21,219.5
Scenario D	2.4	7.1	38037.9	38,881.8
Estimated Annual Savings	(lbs)		(tons)	
Scenario C	0.74	1.61	8.4	8.5
Scenario D	1.93	5.72	15.3	15.6

6.3.2.3 Summary of Findings

Results from this case study also identify measurable savings in air pollutant and greenhouse gas emissions; however, some differences can be observed from the previous case study. City Harvest freight tricycles operate at much slower speeds and with greater delay shares than City Bakery's; at the 90^{th} percentile, City Harvest stopped-time delays are equivalent to 96 percent of vehicle moving time, indicating that nearly half of the total travel time is spent in delay. These delay shares are higher than those observed for motor vehicles. The reason is unclear from the data; it may be due to unidentified stops, or it may reflect a need for City Harvest drivers to stop for brief periods of rest due to longer tours and potentially heavier loads. Regardless of the reason, these higher observed delays combined with slower travel speeds results in higher rates of space consumption for City Harvest freight tricycles. While the median City Bakery tricycleconsumes 5.3 ft^2*hrs of space per mile of travel, the median City Harvest tricycleconsumes more than double that amount of space, with a rate of 11.7 ft^2*hrs per mile. Although almost 90 percent of City Bakery space is consumed while a vehicle is moving, more than a quarter of the space consumed by City Harvest freight tricycles is during delay.

While speed differences limited the space savings achieved during vehicle movements, cargo cycles offer an obvious advantage in consumption of parking space. With no repeated pickups or deliveries and no clear justification for restructuring of daily operations for different vehicle types, the number and duration of stops are assumed to be the same for all vehicle types. Based solely on the footprint of the vehicle, the box truck consumes close to five times as much space for parking than a cargo cycle. While the tricyclecan park flexibly on the sidewalk or in an on-street space, the truck requires available curb space to park. This limitation is especially true in midtown, where double parking is prohibited during business hours. Space savings are likely even higer than those estimated due to additional time required for motor vehicle parking.

Results from this case highlight the difference between vehicle types when estimating emissions savings, reinforcing the discussion of emissions rate variability in the previous section. When operating on identical routes, a box truck will generate considerably higher emissions than a cargo van. Therefore, when estimating emissions savings due to cargo cycle implementation, it is necessary to understand the vehicles being replaced and how delivery tours (e.g. travel distances, number of stops) might change as a result.

7 Temperature Control Alternatives

As discussed in previous sections, a primary challenge to implementing cargo cycles in local and last-mile delivery is the vehicle's lack of mechanical temperature control. Given the mode's suitability otherwise for transporting a number of potentially temperature sensitive products – particularly food and pharmaceuticals - development of effective last-mile cold chain strategies is critical to enable use of the mode. This section describes the elements of a potential cargo cycle cold-chain, current temperature control practices in the industry, strategies and technologies available for ensuring effective operations, and basic analysis of technologies suitable for implementation.

7.1 The Cold Chain

Rodrigue and Notteboom (2013) define the cold chain as "the transportation of temperature sensitive products along a supply chain through thermal and refrigerated packaging methods and the logistical planning to protect the integrity of these shipments." This definition identifies the two key elements of any cold chain: 1) the technologies – including both vehicles and packaging – that protect goods from exposure to unsafe temperatures and humidity and 2) the processes that ensure that goods are maintained in appropriate conditions using these technologies as they are transferred from origin to destination. Depending on the scale of the supply chain and the durability of the temperature sensitive goods, products may be managed by a few or by many stakeholders for transportation and storage. In addition to handling by both the producer – who must initially prepare the goods for transportation – and the end consumer, products may be stored and sorted at multiple locations and may be transferred between multiple vehicle types. Each time goods are moved between locations, they must be loaded at the origin, carried from the origin to the destination, and unloaded at the destination. At each location and during transit, product temperatures are maintained using specific technologies; a technology breakdown can result in a cold-chain failure. However, failure can also result from lacking communications and timing in the cold chain. A delivery performed using a temperature contorolled vehicle or specialized packaging may arrive unharmed to a destination; however, if the recipient is unprepared to immediately place the goods into cold storage, it could result in goods being left in an uncontrolled environment. For example, research has found that temperature-sensitive drugs can be mishandled if staff are inadequately trained (Maggenis, Cook, and Villa 2010).

7.1.1 Temperature-Sensitive Commodities

Two primary commodity types that rely on the cold chain are perishable foods and pharmaceutical products. Both of these require goods to be maintained within a safe temperature range from the producer to the consumer; a failure in either cold chain may have serious consequences for the profits of the producer and/or the health of the end consumer. Food products - including animal products, produce, and baked goods among others - are sensitive to damage both from freezing and from overheating. Failing to maintain foods at adequate temperatures will lead to losses in product quality, reducing their value on the market. In the worst case, this deterioration may include bacterial and fungal contamination that can cause illness or even death (Rodrigue and Notteboom, 2013). In the year 2000, an estimated two-thirds of all foodborne ilnesses in the U.S. were attributed to “temperature abuse” (Reed 2005). In addition to foods, other types of plant products, such as cut flowers, may also lose their value if not maintained at the proper temperature.

Pharmaceuticals – particularly the growing market of biopharmaceuticals (Bishara 2006) – are also sensitive to variations in temperature. Many medical products composed of biological products are unstable (Reed 2005). Products such as vaccines and insulin must be maintained within strict temperature ranges; if not, they can lose their viability, rendering them valueless on the market and ineffective for treating individual patients and for maintaining public health.

Temperature control requirements are unique to the product being moved; within the food and pharmaceutical categories, ideal transit temperatures may vary considerably. Rodrigue and Notteboom (2013) define five general categories of temperature control for cold chains shown in Table 35. As can be seen, while some food products must be transported at extremely cold temperatures, others must be maintained at a much higer temperature range. A failure to stay within the prescribed range – even with slight deviation - can lead to either freezing or heat damage.

Table 35. General Cold Chain Temperature Range Classifications

Data From Rodrigue and Notteboom (2013)

Category	Temperature Range	Sample Commodities
Deep freeze	-18°F to -22°F (-28°C to -30°C)	Seafood, ice cream
Frozen	-4°F to 3°F (-16°C to -20°C)	Meat, baked goods
Chill	36°F to 39°F (2 °C to 4°C)	Many fruits and vegetables, fresh meat
Pharmaceutical	36°F to 46°F (2°C to 8°C)	Vaccines
Banana	54°F to 57°F (12°C to 14°C)	Bananas, tropical fruits, potatoes

Table 36 and Table 37 show the desired temperature ranges for a variety of food products in the United States. As can be seen, while many fruits and vegetables travel best at 32 °F, other fruits and vegetables would be damaged at this (and much higher) temperatures. Many fruits and vegetables with high water contents – e.g. cucumbers and watermelon - should be maintained at a much higher temperature. Meat, fish, and some dairy products are similarly vulnerable to freezing damage that reduces the quality of the final product. Both animal and plant products are also vulnerable to biological contamination at high temperatures, at which the bacteria with which they are all contaminated proliferates.

Table 36. Desired Transit Temperatures for Selected Fruits and Vegetables

(USDA 2008)

Commodity	Desired Transit Temperature
Apples	30°F to 32°F (–1°C to 0°C)
Apricots	32°F (0°C)
Artichokes	32°F (0°C)
Asparagus	32°F to 35°F (0°C to 2°C)
Avocados	55°F (13°C)
Bananas	56°F to 58°F (13°C to 14°C)
Blackberries	41°F to 43°F (5°C to 6°C)
Broccoli	32°F (0°C)
Brussels sprouts	32°F (0°C)
Corn	32°F (0°C)
Cantaloupes	36°F to 41°F (2°C to 5°C)
Carrots	32°F (0°C)
Cherries	32°F (0°C)
Cranberries	36°F to 40°F (2°C to 4°C)
Cucumbers	50°F to 55°F (10°C to 13°C)
Cauliflower	32°F (0°C)
Cabbage	32°F (0°C)
Eggplant	46°F to 54°F (8°C to 12°C)
Fresh lima beans	31°F to 32°F (–0.6°C to 0°C)
Grapes	32°F (0°C);
Garlic	32°F to 34°F (0°C to 1°C)
Grapefruit	58°F to 60°F (14°C to 16°C)
Kale	32°F (0°C)
Kiwi fruit	32°F (0°C)
Lemons	45°F to 55°F (7°C to 13°C)
Lettuce	32°F (0°C)
Limes	48°F to 50°F (9°C to 10°C)
Mangoes	55°F (13°C)
Melons	45°F to 50°F (7°C to 10°C)
Mushrooms	32°F (0°C)
Okra	45°F to 50°F (7°C to 10°C)
Onions	32°F (0°C)
Oranges	32°F to 34°F (0°C to 1°C)
Peaches and Nectarines	31°F to 32F (–0.6°C to 0°C)
Pears	32°F (0°C)
Peppers	45°F to 55°F (7°C to 13°C)
Pineapples	50°F to 55°F (10°C to 13°C)
Potatoes	50°F to 60F (10°C to 16°C)
Radishes	32°F (0°C)
Raspberries	32°F (0°C)
Spinach	32°F (0°C)
Squash	50°F to 55F (10°C to 13°C)
Strawberries	32°F (0°C)
Sweet potatoes	55°F to 60°F (13°C to 16°C)
Tangerines	40°F (4°C)
Tomatoes	55°F to 70°F (13°C to 21°C)
Watermelons	50°F to 60°F (10°C to 16°C)

Table 37. Desired Transit Temperatures for Selected Dairy and Animal Products
(USDA 2008)

Commodity	Desired Storage Temperature
Meat	
Beef	32°F to 34°F (0.0°C to 1.1°C)
Lamb	32°F to 34°F(0.0°C to 1.1°C)
Pork	32°F to 34°F (0.0°C to 1.1°C)
Poultry	28°F to 32°F (–2.2°C to 0.0°C)
Fish	
Halibut	31°F to 34°F (-0.6°C to 1.1°C)
Salmon	31°F to 34°F (-0.6°C to 1.1°C)
Tuna	32°F to 36°F (0.0°C to 2.2°C)
Shrimp	31°F to 34°F (-0.6°C to 1.1°C)
Lobster (American)	41°F to 50°F (5.0°C to 10.0°C)
Dairy	
Fresh Butter	39°F (3.9°C)
Frozen Butter	–10°F (–23.3°C)
Margarine	35°F (1.7°C)
Milk (whole)	32°F to 34°F (0.0 to 1.1°C)
Cheese	34°F to 40°F (1.0 to 4.0°C)
Ice Cream	–20°F to –15°F (–29 to –26°C)

Cut flowers also require careful temperature control (Van Der Hulst 2004). Their desired transit temperature is between 50 and 59 °F (10 to 15 °C). Slightly higher temperatures (up to 68 °F [20°C]) will cause or contribute to problems like uneven ripening and bent stems. Above 68 °F, the foliage will turn brown, leaving flowers valueless.

Pharmaceutical products also have unique requirements (Reed 2005). For example, the oral polio vaccine should not exceed a temperature of 46 °F (8 °C). The Bacillus Calmette–Guérin (BCG) vaccine against tuberculosis should not exceed a temperature of 86 °F (30 °C); the DPT vaccine (against diptheria, tetanus, and pertussis) must remain below the same temperature, but must also be maintained above a temperature of 28 °F (-2 °C). The hepatitis B vaccine, which is only sensitive to freezing damage, only requires maintainence above a temperature of 28 °F (-2 °C). These requirements also vary according to travel time and surrounding ambient temperatures. While some products can withstand temperature deviations of several days, other goods can be damaged or destroyed within hours.

7.1.2 Regulatory and Industry Controls

Given both the economic and public health interests in maintaining product integrity for these commodities, regulations have been put in place and specialized technologies and management practices have been developed to maintain required temperatures during transportation and storage. Regulatory enforcement is challenging given the complexity of the supply chains through which these products move; as a result, ensuring compliance requires not only good practice by individual actors, but also effective communications between actors. To achieve these aims, management practices and methods of management have been developed and employed in both the food and pharmaceutical industries.

Under the Sanitary Food Transportation Act of 2005, the U.S. Food and Drug Adminstration (FDA) is required to "prescribe sanitary transportation practices to ensure that food (including animal feed) transported by motor vehicle or rail is not transported under conditions that may adulterate the food (U.S. FDA 2014a)." The agency has published guidance on the safe transportation of fruits and vegetables, milk, and eggs, among other products. In January 2014, a rule – the Food Safety Modernization Act (FMSA) – was proposed that would require shippers, receivers, and carriers to use sanitary transportation practices to ensure the safety of food (U.S. FDA 2014b). If passed into law, this rule would regulate vehicles, operations, and communications between stakeholders.

Historically, the FDA has issued guidelines for specific operations, such as its *Good Manufacturing Practices,* that ensure compliance from individual actors (USDA, 1997*)*. Building on these, in 1997, the FDA introduced the Hazard Analysis and Critical Control Point (HAACP) approach. While initially introduced to address challenges in the meat industry, this approach has been widely adopted across supply chains – from manufacturers to retail establishments - for all types of food. Developed as a rational means by which to ensure safety in the food industry, HAACP consists of seven principles, as listed in the Table 38 (USDA 1997). To implement these principles, stakeholders employing a HAACP approach develop a detailed plan defining specific actions for implementation of these principles to meet the requirements of their operations.

Table 38. HAACP Principles

1. Conduct a hazard analysis.
2. Determine the critical control points (CCPs).
3. Establish critical limits.
4. Establish monitoring procedures.
5. Establish corrective actions.
6. Establish verification procedures.
7. Establish record-keeping and documentation procedures.

To ensure adequate temperature control in transit and storage, stakeholders must first understand the specific requirements of a product being moved. Once requirements are understood, hazards that may threaten the integrity of the product during specific operations of the stakeholder (e.g. loading, in-transit) can be identified. Once hazards are identified, the critical control points at which the hazard can be prevented or mitigated can be determined. Specific testing procedures or actions to be applied at the control point can then be identified, and a monitoring system to observe and record performance can also be developed and employed. For example, if potential exposure during loading can produce a threat, a new loading bay with better temperature control might be required. Product temperatures might then be tested after loading to ensure compliance. Finally, in case of deviation from required performance, corrective actions should be determined. For example, if temperatures have exceeded a safe value, a cooling technology might be applied or, if the temperature deviation has persisted for an unacceptable duration, the shipper or receiver might be notified. To ensure that the system is working, ongoing testing should be conducted and feedback from downstream recipients should be sought. Operations, monitoring, and testing activities should be well documented.

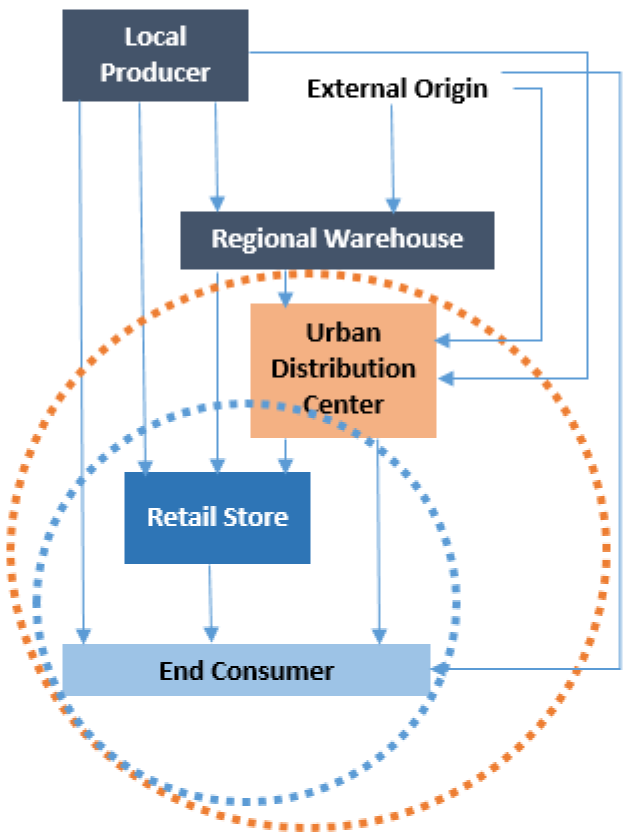
The FDA also defines good practices for pharmaceuticals, including temperature and humidity requirements for storage (Magennis, Cook, and Villa 2010). Additional regulations for international distribution of pharmaceuticals have been issued by the World Health Organization (WHO) (Bishara 2006). The United States Pharmacopeia develops guidelines for temperature control; once approved, these are mandated by the FDA (USP 2013) . The Parenteral Drug Association (PDA 2007) has also published industry guidance for managing pharmaceutical cold chains. Bishara (2006) identifies two critical requirements for management of pharmeceutical supply chains: quality management and risk assessment. A quality management system should include include all aspects of planning, organization, implementation and control, performance measurement, and stakeholder communications before and after a shipment. Ongoing risk assement should establish procedures to monitor compliance with regulations and industry guidelines, recognize factors that impact the stability of products, and identify and respond to environmental and human impacts.

As noted previously, succesful implementation of a comprehensive management and response plan requires cooperation from multiple stakeholders. In general, producers and manufacturers are responsible for the quality of their product until it reaches an end consumer (Bishara 2006); however, maintenance of that quality relies on shippers, carriers, forwarders, and staff at a recipient location. Manufacturers must empower these stakeholders to properly maintain the product by first properly packaging and labeling goods for shipment. Once requirements are properly identified and communicated, downstream stakeholders must employ adequate processes and technologies to maintain the product.

7.2 The Cold Chain Last Mile

For both food and pharmaceutical transportation, the "last-mile" is commonly recognized as a weak link in the cold chain. For long-distance movements bulk goods can be moved by ship, rail, and truck in sealed reefers. Similarly, major producers can store large quantities of a single product in a specific temperature-controlled environment. Alternatively, local and last-mile movements – generally of smaller quantities - rely on the less controlled environments of local delivery vehicles. Both carriers and local warehousing facilities often handle a variety of products with varying temperature-control requirements. Figure 53 shows a variety of goods movements that may be performed locally, whether for locally or globally sourced products. Failures occur when vehicles and packaging are inadequate to protect goods from the surrounding environment and when miscommunications and poor timing of deliveries leave goods exposed.

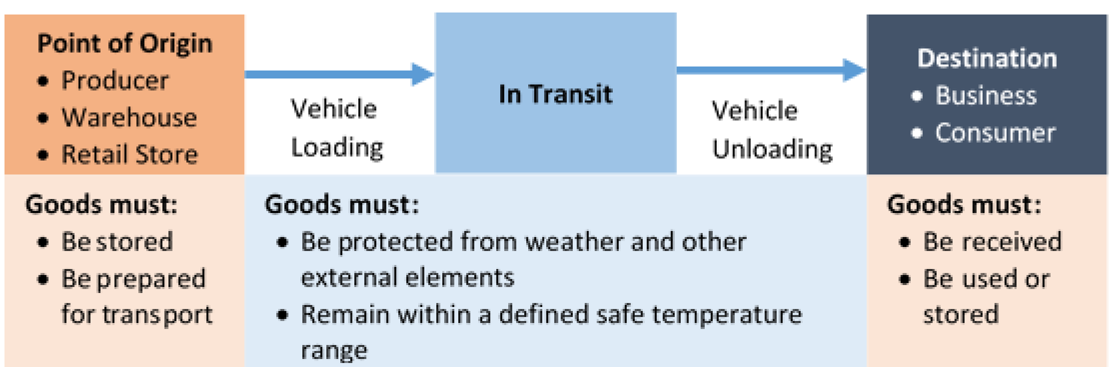
Figure 53. Local Supply Chains



The circles in Figure 53 identify two specific types of local movements likely to be made by cargo cycles. The orange circle highlights movement from a local distribution center either to a retail outlet or directly to an end consumer. Microdistribution centers in Paris and London utliize cargo cycles for these types of deliveries. The blue circle higlights direct retail store to consumer movements; grocery stores currently utilizing cargo cycles in New York (and elsewhere) conduct this type of delivery. A third type of movement not shown in this figure but currently made by City Bakery is movement between different retail locations.

Figure 54 summarizes the basic activities that occur at each point in cargo cycle operations. To maintain an adequate cold chain, the operator must implement controls during storage, loading, transit, and unloading. In general, cargo cycle operators will not hold goods for longer than a few hours. Distribution centers may transfer goods directly from a delivery truck to the cycles or may unload them to on-site storage space for sorting before tricycleloading. This offloading provides the first critical point at which goods might be subjected to a temperature risk. If loaded directly from truck to cycle, the truck itself may provide temperature control. If goods are offloaded to on-site storage, temperature control must be provided either through control of ambient temperatures in the warehouse or through careful packaging of the goods. Whether from a distribution center, producer, or retail store, cargo cyle loading presents a second point at which goods may be exposed. During transit, product temperatures must be controlled with direct packaging or through temperature control of the vehicle's cargo box; the next section describes current and potential technology options in detail. At the point of delivery, goods are transferred from the vehicle to the receiver; again at this point, maintenance of the cold chain requires an efficient transfer of goods. Product temperatures are best maintained during loading and unloading when exposure to the uncontrolled surrounding environment is limited. This exposure can be limited by ensuring a quick transfer or by packaging goods in a manner that protects the goods from surrounding heat, cold, or humidity. During all stages of the cold chain, ambient temperatures in a container should be monitored using a variety temperature gauges.

Figure 54. Local Cold Chain Operations



7.3 Temperature Control Technologies and Applicability for TricycleOperations

During storage and transportation, a number of technologies can be used for temperature control; in the global supply chain, solutions range from simple products such as insulation blankets and plain ice to complex mechanical systems. Although they often carry temperature-sensitive goods, no cargo cycle specifically designed to provide temperature control could be identified on the current market. One Parisian manufacturer, Lovelo, previously produced a vehicle – the Frigocycle – which was insulated. This vehicle was designed specifically for a pilot study moving dairy products for a specific customer. However, the operator no longer serves this customer, and the vehicle is no longer produced. The same operator does continue to perform temperature-sensitive deliveries for a grocery store using gel packs, as discussed in detail below (personal communications with La Petite Reine).

The survey of North American cargo cycle operators discussed in detail in Section 3 found little uniformity in temperature control operations (Table 39); only a single approach – box insulation – was in use by more than one of the six carriers who answered questions relating to temperature control. One of these specified that fiberglass insulation was used. Although most carriers recognized that temperature control is critical to protect foods and other sensitive products, many noted that with short trip distances and travel times, goods receive little exposure during transit. As a result, their investment in and application of temperature control technologies has been minimal. Discussions with existing operators also revealed very little use of temperature monitoring technologies. Although none of the North American carriers surveyed was found to be monitoring temperatures during delivery, a shipper employing La Petite Reine in Paris was noted to randomly test the temperature of its cold shipping boxes, and City Harvest noted that they do test foods temperatures at the point of delivery to ensure product safety.

Table 39. Control Technologies in Use by North American Operators

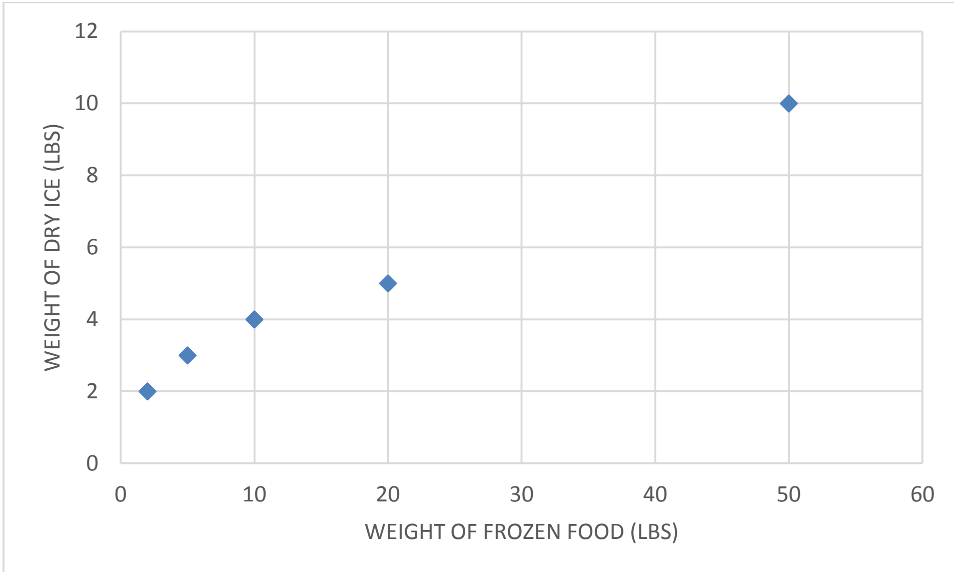
Control Technology	Number of Users
Insulated Container	1
Cooler	1
Box Insulation	2
Hot plates	1
Cold plates	1
Ice packs	1
Dry Ice	1

Table 40 summarizes a variety of technologies used in global supply chains for temperature control. Products fall into three general categories: insulation, passive cooling, and mechanical cooling. Insulating products do not provide cooling or heating; rather, they simply protect goods being shipped from external ambient temperatures. Insulation is generally very lightweight and relatively inexpensive; however, insulation is of little value if used on an inproperly sealed box. Of the three products identified, plastic foam likely provides the best option for use on cargo cycles, as it is weather-proof and poses little risk to the driver and to the commodities being moved (USDA 2008). Blankets could be used, but would likely need to be repositioned after each stop. Fiberglass may be less expensive; however, if not installed in a manner that completely isolates it from the goods and the driver, it could pose a risk to both. Although not an insulator, reflective paint may also be used on the vehicle's outer surface to prevent the cargo box from absorbing solar energy and heat.

A variety of "passive" systems are in use for shipping of chilled and frozen goods. These products do provide cooling to prevent temperatures from rising as the goods absorb energy in transit. The suitability of each product for use on cargo cycles depends on the commodities being shipped. For goods that must be maintained at very low temperatures, dry ice is more suitable than ice and gel packs alone. Dry ice, the solid form of carbon dioxide (CO_2) is easy to obtain, although it is not reusable and must be replaced regularly. Unlike ice, it is capable of maintaining very low temperatures over relatively long durations; this characteristic is desirable for moving frozen goods such as meats and ice cream (Rodrigue and Notteboom 2013).

Dry ice is heavy, weighing about 40% greater than the same volume of ice. While exact volumes required vary, Figure 55 shows manufacturer recommended volumes of dry ice required for a 4-hour long shipment of frozen food (dryiceinfo.com 2013). At normal atmospheric pressure, it sublimates (transitioning directly from solid to gas) at about -112 °Fahrenheit; this extremely low temperature does pose a risk to the handler, who if not wearing gloves or other protective clothing could be subject to frostbite. Also, as dry ice sublimates, CO_2 gas will build up, creating a potential explosion risk (Langford 2013). While exact prices vary, dry ice is very inexpensive and costs on the same order as commercially available ice. While the table also notes the existence of cryogenic freezing to move frozen goods (Pedolsky and Bau 2010), this option is more suitable for higher-volume, long-distance transportation and is likely financially infeasible for cargo cycle operations.

Figure 55. Manufacturer Recommended Dry Ice Shipping Volumes, 4-Hour Shipment



For goods that can withstand slightly higher and potentially more variable temperatures, ice and gel packs provide some advantages. Both ice and gel packs are generally lighter than dry ice. Gel packs can be frozen or refrigerated (Rodrigue and Notteboom 2013). Although they have a slightly higher purchase cost than ice and dry ice, gel packs are reusable. Neither ice nor gel packs pose the same explosion risk or level of frostbite risk as dry ice. If a humid environment is preferred, ice melting then evaporating maintains moisture in the air (Langford 2013). However, ice melts more quickly than dry ice – providing a shorter duration of cooling – and direct contact with water can also potentially damage goods. La Petite Reine, the French operator previously employing the Frigocycle, currently cools food deliveries requiring temperature control using gel packs. When boxes received from the shipper are labeled as requiring temperature control, they are shipped in a 24.4 in × 16.5 in × 11.8 in (62 cm × 42 cm × 30 cm) cold box, into which gel packs are inserted. The food products are placed in slightly smaller coolers (23.6 in x 15.7 in x 11.8 in or 60 cm × 40 cm × 30 cm), which are then inserted into the cold box. Goods are maintained at a temperature of 41°F (5 °C).

The most flexible product that can be used for frozen, chilled, and heated shipping, and that can better maintain a constant temperature than ice and gel packs, is the eutectic plate. Eutectic plates are thin plastic plates filled with liquids; by varying the chemical composition of the liquids, these plates have the capability to be cooled to specific temperature settings. Using phase-changing materials, plates can also be manufactrured to provide heating. One manufacturer offers products ranging in temperature from -80 °F (-100°C) to 192 °F (89°C) (PMA 2014). The plates must be frozen, cooled, or heated overnight before being inserted into a box for delivery. Revolution Rickshaws requested specifications from one European manufacturer for a custom trike-specific box cooled by eutectic plates (personal communications with Gregg Zuman). The estimated cost for this product was about $2,700 for the box and about $105 for each plate. With frequent opening for deliveries, the box was expected to maintain its stated temperature for approximately two hours; with no box openings, much longer durations can be maintained. Although their purchase cost is much higher than alternatives, eutectic plates have a much greater capability to maintain temperatures within a specific range – a quality desirable for the movement of goods such a foods and pharmaceuticals with a small desired temperature windows These plates also have the capability to reach temperatures near that of dry ice without its heavy weight and frostbite and explosions risks.

A mechanical cooling system using diesel/gasoline combustion would provide better temperature control than passive systems, as trip durations would not be not limited by product limitations. A battery powered system would have a limited life, put like a diesel-powered system would be generally reliable, and could maintain a constant temperature, provide rapid temperature changes, and be adjusted to different conditions for variable products. However, these sytems also offer a number of disadvantages compared to passive alternatives. Purchase and maintenance costs for active systems would be high (Langford 2013). In addition, as noted in Section 2, a battery-powered electric-assist system adds more than 120 lbs of weight to a trike; a battery providing refrigeration would likely be even heavier. Systems reliant on fuel combustion to power a battery might be slightly lighter and provide greater autonomy than a battery-powered system; however, cargo cycles reliant on fossil fuels for temperature control would no longer be zero-emissions vehicles, and combustible fuels would present a risk to the driver.

Solar and pedal-powered systems are more environmentally friendly; however, both currently produce low, unreliable power outputs. Solar systems rely on potentially volatile weather conditions; in major cities like New York, direct sunlight might also be limited by urban canyons. Pedal-powered systems would require significant energy inputs from drivers for minimal power output. Given the relatively short trip distances required, the energy required for drivers to move heavy loads, and the low cost margins at which carriers operate, for most cargo cycle applications, passive methods of temperature control are likely preferable to mechanical systems.

Table 40. Temperature Control Technologies

Data from USDA 2008, Pedolsky and Bau 201,; Langford 2013, Rodrigue and Notteboom 2013.

Technology	Power During Transit	Weight	Purchase Cost	Operating Cost	Other Benefits	Other Drawbacks
Insulation						
Blankets	None	Low	Low	Very low		Water permeability varies with material.
Fiberglass	None	Low	Very low	Low		Direct exposure can contaminate goods, pose a health risk to driver; subject to water damage.
Plastic Foam	None	Low	Low	Very low	Waterproof and noncorrosive.	
Reflective paint	None	Low	Low	Low		
Passive Cooling						
Ice	None	Low	Very low	Very low	Maintains humidity; no pollutant emissions	Direct contact may damage goods; requires well-insulated container and water resistant packaging; limited life/non-reusable.
Dry Ice	None	Moderate	Low	Very low	Provides rapid cooling/recovery after stop; has longer durability and maintains lower temperature than ice.	Limited life/non-reusable; CO_2 gas may dehydrate fresh products; temperature difficult to regulate - if too cold, might freeze cargo; Must be used quickly after purchase to prevent volatilization; difficult to store.
Gel Packs	None	Low	Low	Low	Reusable	Requires power for re-freezing
Eutectic Plates	None	Low	Moderate	Low	Can be used for frozen, cooled, or heated goods; can reliably maintain constant temperature for a specific duration of time; operates silently; provides rapid cooling.	Requires power for re-cooling or heating, which may require 12+ hours.

Table 40 continued

Technology	Power During Transit	Weight	Purchase Cost	Operating Cost	Other Benefits	Other Drawbacks
Cryogenic Cooling (Liquid nitrogen or liquid carbon dioxide [CO_2])	None	Moderate	Very high	High	No noise; provides rapid cooling/recovery after stop.	Suitable only for movement of frozen goods; fuel difficult and expensive to obtain; requires fuel delivery system; requires frequent refueling.
Mechanical Cooling						
Mechanical Refrigeration	Electric Battery	Heavy	High	Moderate	Low recharge cost.	May require complicated maintenance.
	Diesel/ Gas Combustion	Heavy	High	High	Low fuel cost.	May require complicated maintenance; potential safety risk.
	Solar	Heavy	High	Moderate	Renewable energy source.	Unpredictable power source; may become very hot.
	Pedal	Heavy	High	Moderate	Renewable energy source.	High burden on driver; low, unpredictable power

7.4 Summary of Findings

From this review of temperature requirements and available temperature control technologies, it is clear that systems do exist that would enable cargo cycles to be employed in the shipping of temperature sensitive goods; however these systems must be employed in a well-structured supply chain with effective communications between shippers, carriers, and receivers. Tricycle operators must first be aware of the specific temperature-control requirements of the goods that that carry, understanding the temperatures at which goods will lose quality or become damaged beyond repair. This information must be communicated to the tricycle operator by the producer or manufacturer, likely through clear labeling of the product. Transfers of goods between vehicles or between vehicles and storage areas must be completed efficiently, limiting the exposure of goods to uncontrolled environments. This efficiency can be enhanced by the use of well-structured loading and unloading processes and the use of modular containers or specialized loading equipment.

A number of technologies are available to maintain goods in transit. Insulation methods – including plastic foam, blankets, and fiberglass - can be employed to limit the exposure of goods enclosed in a container to outside ambient temperatures. Reflective paint can be used to limit the solar energy absorbed. However, these products do not provide cooling to counteract the heat generated by energy that does penetrate the insulation. Mechanical cooling systems can provide reliable temperature control; however their weight and cost make them difficult to implement in tricycle operations.

Passive cooling systems have the greatest potential for application in tricycle operations. Dry ice provides a very inexpensive method to transport frozen and chilled goods; at adequate volumes, it can provide sub-freezing temperatures for many hours before sublimating. However, it also has some drawbacks; it is very heavy, generates CO_2 gas, and may freeze goods that should not be frozen. For transport of goods at chilled but not frozen temperatures, both ice and gel packs can be used. Like dry ice, ice must be replaced after each use. While generally lighter than dry ice, it melts at a faster rate; as a liquid, it can damage unprotected goods. Unlike ice or dry ice, gel packs are reusable; however, like ice, they provide only a limited life before re-liquefying. Both gel packs and ice can be used to maintain chilled temperatures above freezing; however, their ability to maintain a constant temperature is limited by their melting temperatures. Eutectic plates likely provide the most versatile solution for application in tricycle operations, as they are lightweight and reusable. Different plates can be purchased and used to maintain varying temperatures, ranging from the very cold temperatures achieved by dry ice to chilled temperatures more commonly provided by ice and gel packs, and even to heated temperatures for delivery of cooked foods.

8 Conclusions

As stated in Section 1, the aim of this project was to investigate the potential for use of freight tricycles (or more generally, cargo cycles) for local and last-mile delivery in New York City. A desire to further investigate this mode was prompted by a number of political and operational realities. Currently, in New York City, urban delivery vehicles face very difficult conditions, including heavy congestion and inadequate space available for legal parking. These conditions result in late deliveries, heavy parking fines, wasted time and fuel, and associated greenhouse gas and air pollutant emissions. In recent years, the city's urban streets have been transforming to better accommodate more sustainable passenger modes; space already inadequate to accommodate truck traffic is becoming increasingly dedicated for transit and non-motorized use. Cargo cycles offer an opportunity to safely provide reliable goods movements on shared-multimodal infrastructure with little to none of the emissions resulting from the fuel combustion required for more traditional motorized modes.

To gain a broad understanding of this mode, four specific goals were sought:

1. To understand the potential commodities moved and sectors served by cargo cycles.
2. To identify the expected benefits, challenges, and barriers to operation.
3. To understand freight tricycle traffic performance in NYC conditions.
4. To understand the capability of cargo cycles for use in cold chains – such as food and pharmaceutical delivery – that require temperature control.

8.1 Commodities and Sectors

To complete goals one and two, an extensive literature review of experience – primarily from Europe – was undertaken. In addition, interviews were conducted with operators in New York City and throughout North America. The literature review revealed that cargo cycles are currently being used in a broad range of sectors; however, despite relatively recent adoption of the mode in both Europe and the U.S., stark differences exist between operations on the two continents. In general, freight tricycles or cargo cycles are used in both business-to-business and business-to-customer operations. In North America, the dominant commodity moved by cargo cycle is food; nearly all operators identified some type of food as a primary product moved. The only other commodity common to multiple North American carriers was garbage/recycling/compost. In Europe, cargo cycles are becoming increasingly common as a final link in parcel transportation. In a number of European cities – including London, Paris, and Brussels – small distribution centers where goods are transferred from trucks to cargo cycles have been established or tested. In Germany, a large national study is investigating the potential of the mode for courier services. In addition to parcels, European operators were also found to be moving food, pharmaceuticals, office supplies, and garbage and recycling.

Differences in U.S. and European operations may be due to a number of factors. In general, European cities are generally much older, with dense land developments and narrow streets built before the advent of the automobile. In recent decades, the critical urban delivery challenges faced by these cities have led to the development of a new field of study – city logistics. With a growing interest in city logistics solutions, European operations have received funding through EU and local government investment. While only a few companies receive subsidy for their daily operations (primarily in the form of reduced-cost space), public sector investment has given many companies the opportunity to assume lower risk in testing of new operations and technologies and to receive public recognition. Many of these EU-funded pilots have also included major corporate shipping partners that provide a critical volume of deliveries in relatively small delivery areas suitable for tricycle operations. This provides a contrast to operations in New York City (and North America generally) where partner shippers are almost exclusively small, local businesses.

8.2 Benefits, Challenges, and Barriers to Operation

The review of European experience and survey of North American operators revealed a number of benefits, challenges, and barriers to operation for cargo cycle operators, which are summarized as follows.

8.2.1 Potential Benefits

- Cargo cycles may offer faster speeds and more reliable travel times in congested traffic conditions or where regulations limit motor vehicle operations.
- Where regulations allow, cargo cycles can often park closer to a delivery destination – even on the sidewalk directly adjacent to a delivery location.
- Cargo cycles are much smaller than motor vehicles; as a result they consume less road and parking space.
- Human-powered cargo cycles consume no fossil fuels and generate no pollutants from fuel combustion. They also produce considerably less noise pollution than motor vehicles.
- Costs for vehicle purchase, parking, maintenance, and vehicle insurance are likely to be much lower for a cargo cycle than for a motorized vehicle.
- While truck drivers face health challenges from idle behavior, cargo cycle operators improve their health through active operation of the vehicle.
- Cargo cycles do not require a specialized license or significant training to operate; as a result, cargo cycle operations provide low-barrier-to-entry jobs in a local community.

8.2.2 Potential Challenges and Barriers to Implementation

- Cargo cycles carry only limited quantities of goods due to vehicle load capacities and human operator limitations; as a result, they cannot provide the same economies of scale that might be achieved using a larger vehicle.
- The availability of affordable space in an urban area is a challenge to cargo cycle operations. Whether space is needed for storage and transloading of goods or simply for vehicle storage, it can be prohibitively expensive in the dense urban areas best served by cargo cycles.

- Labor costs for cargo cycle operators can also be expensive. Cargo cycle operators need to be compensated for the energy that they expend in their daily operations. Multiple drivers may also be required to complete the number of deliveries carried by a single driver on a motor vehicle. In New York City, cargo cycle operators must also be covered by workman's compensation insurance; without a mature pool of cycle operators, this insurance is extremely expensive, as drivers must pay the same rates as the bicycle messengers who operate at much higher speeds and in riskier conditions.
- Cargo cycle operations can be inhibited (or enhanced) by local regulations. In cities where roadway restrictions and emissions policies restrict motor vehicle movements, cargo cycles might have a competitive advantage. However, when cargo cycle use of flexible infrastructure is limited or when use of an electric-assist is prohibited, operations may be impacted negatively by local policies.

8.2.3 Uncertain Impacts

- Overall safety impacts from cargo cycle operations are uncertain. It is expected that shifting goods from truck to cargo cycle would have overall positive impacts on safety by reducing the likelihood of very dangerous truck-non-motorized accidents. However, results from the London pilot study indicate that overall mileage traveled locally increased for cargo cycles compared to cargo vans; as a result, gains in accident severity could be offset by increased exposure to freight-carrying vehicles.
- The security performance of cargo cycles is also uncertain. Goods appear to be at higher risk on a cargo cycle than on a locked motor vehicle; however, neither the literature review nor the survey of North American operators identified cargo security as a major challenge for operators.

8.3 Traffic Performance in NYC Conditions

Most previous studies of this mode have been conducted primarily to compare the costs of cargo cycle operations with those of the motorized vehicle operations required to complete the same deliveries. The focus of this study is not on operating costs, but rather on the traffic performance of these modes of urban delivery in New York City conditions. To examine cargo cycle operations in detail, case studies were conducted with two local businesses currently employing freight tricycles in their daily operations. Freight tricycles operated by City Bakery, which operates a number of local green bakeries, and City Harvest, a nonprofit food rescue organization, were equipped with GPS tracking devices. Three City Harvest trucks were also equipped with these devices. Using the collected data, performance measures – including travel speeds, travel times and delays, and stop durations – were developed for each mode. Major findings from this evaluation are summarized as follows.

8.3.1 Travel Speed

- City Bakery and City Harvest freight tricycles exhibited very different speed behaviors. While City Bakery freight tricycles traveled at a median speed of 7.2 mph, the median for City Harvest freight tricycles was only 3.9 mph. While City Bakery freight tricycles regularly exhibit speeds up to 15 mph, City Harvest freight tricycles typically maxed out around 9 mph. Some potential reasons for these differences include the longer tour durations conducted by City Harvest, relatively heavier loads carried by City Harvest drivers, and the differing nature of the delivery types, which for City Bakery include on-demand deliveries between store locations.

- Cargo cycle speeds vary very little as a function of infrastructure characteristics, although median speed values do appear to increase somewhat on roads where freight tricycles have adequate space to maneuver, including on wide avenues, on major cross-town truck routes, and on routes with Class 1 bicycle infrastructure.
- For trucks, travel speeds on crosstown "Streets" are considerably slower than on north-south "Avenues," and slower speeds are observed during the morning peak hour. For deliveries of relatively light goods during morning peak hours or traveling crosstown, tricycles may offer a more reliable, if not faster, option.
- A considerable proportion of truck speeds are feasibly replicable by tricycle. About one-third of observed truck speeds were below the median travel speed for City Harvest freight tricycles, and nearly 47 percent below the median speed for City Bakery. About 60 percent of trucks speeds are below the 99th percentile speed for City Harvest freight tricycles, and about 78 percent are below the 99th percentile speed for City Bakery freight tricycles.

8.3.2 Travel Times and Stopped-Time Delays

- Freight tricycles spend considerably lower shares of their travel time in stopped-time delay than trucks, which is likely due to their ability to bypass traffic congestion.
- Higher than average delay-to-travel time ratios are observed for freight tricycles in locations with high intersection densities, which reflects time spent stopped at traffic lights.
- Average travel speeds are a direct function of trip distances; as drivers are required to travel greater distances, they become fatigued and begin to travel at a slower pace.
- In Manhattan, trucks are required to travel on a limited network of local truck routes; this may increase their travel time by requiring them to deviate considerably from shortest-path routes. These restrictions may be most critical when the network is obstructed by a traffic incident or construction.

8.3.3 Stop Durations

- Deliveries by freight tricycle are generally faster than those made by truck; this is due to smaller shipment sizes as well as parking flexibility.
- Tricycle parking times for City Harvest were observed to be erratic with some very long parking times. Uncertainty is inherent in the organization's business model. When a driver arrives to either a pickup or delivery location, he made need to wait for a long duration for goods to be prepared or received. Freight tricycles, which can generally park off-street for long durations without being subject to parking fines, are better suited to this type of operation than motor vehicles that would face stricter time limitations and heavy fines.
- While tricycle operations are relatively immune to parking restrictions, results from the City Harvest case study indicate that commercial vehicle parking behavior is impacted by parking restrictions. In midtown, City Harvest trucks park for long durations when meters are not in operation. In other parts of the City, where double parking is legal, average deliveries are much faster than in Midtown.
- Results from a study of truck and van parking behavior in high bicycle demand areas of Manhattan found that 35 percent of vans and more than 40 percent of trucks parked illegally while making deliveries; another 40 percent of each vehicle type were found to be legally double parked in areas outside of Midtown.

8.4 Impacts of Tricycle Operations

As previously noted, past studies have recognized that replacing motorized vehicles with cargo cycles can also reduce the negative externalities generated by local delivery operations. Two of the primary benefits noted include a reduction in space consumed and a reduction in vehicle emissions. To evaluate these impacts in New York City conditions, analyses of both space consumption and vehicle emissions were conducted.

8.4.1 Space Consumption

To evaluate space consumed, freight tricycle dimensions were compared with those of other common urban delivery vehicles, including a passenger car, cargo van, step van, and box trucks. Integrating speed estimates from the GPS analysis previously described, road and parking space consumption rates could be estimated. Case study analyses for both City Bakery and City Harvest were also conducted. Major findings from this space analysis include:

- The Cycles Maximus freight tricycle consumes less than a third of the footprint of a passenger car, and close to an eighth of the footprint of a 24-ft box truck. In many locations, freight tricycles can park perpendicular to the curb, allowing for more efficient use of available parking space.
- Even considering observed vehicle travel speeds, cargo cycles consume space at a lower rate per mile of travel than motorized vehicles. A City Bakery tricycle consumes road space at a median rate of 5.3 ft^2*hours per mile of travel, while a City Harvest tricycle consumes space at more than double that rate - 11.7 ft^2*hours per mile. The difference in these rates reflects the impact of vehicle speeds on road consumption rates. Median motor vehicle space consumption rates vary from about 18 to 42 ft^2*hours per mile of travel.
- Freight tricycles can carry a comparable volume of goods to a passenger car, but considerably less than all other urban delivery vehicles. Due to human and vehicle limitations, cargo cycle payloads are considerably smaller than all motorized vehicles. Cargo cycle payloads also vary as a function of vehicle design; while carrying less volume, the lower, wider Cycles Maximus can carry a heavier payload than the Lovelo CargoCycle.
- Cargo cycles can carry significantly heavier loads when the use of electric-assist is permitted.

- For the City Bakery case study, assuming that freight tricycles replace cargo vans and that both vehicle types travel at median speeds and park for median durations:
  - The total distance traveled is expected to be less for freight tricycles than for motor vehicles, even if some trips are combined.
  - Total space required for operations is reduced by 72-75 percent, with parking space required reduced by 70-72 percent and road space consumed dropping by 74-77 percent.
  - Rates of moving space consumed by cargo cycles double at the slowest evaluated speeds; freight tricycles facing the greatest shares of delay consume space per mile of travel at a rate more than 160 percent greater than the average trike.
- For the City Harvest case study, comparison with both a cargo van and City Harvest's smallest 14-ft box truck were performed. Assuming again that all vehicle types travel at median speeds and park for median durations:

- City Harvest's smallest truck consumes road space at a rate 130 percent greater than a trike; a cargo van consumes road space at a 75 percent higher rate.
- While almost 90 percent of City Bakery's space consumed is while a vehicle is moving, more than a quarter of the space consumed by City Harvest freight tricycles is during delay.
- Assuming the number and duration of stops are the same for all vehicle types, the cargo van consumes more than three and a half times as much space for parking than a cargo cycle. The box truck consumes close to five times as much parking space.

8.4.2 Emissions

Emissions analyses were conducted using the EPA's MOVES model. Because the Cycles Maximus vehicles in use by the case study operators are fully human-powered, emissions savings were evaluated by estimating emissions rates for the comparative motorized urban delivery vehicles. CO_2, PM2.5, and PM10 estimates were calculated for each vehicle type. CO_2 is the greenhouse gas most commonly produced by human activity, including vehicle fuel combustion; PM is also generated primarily through fuel combustion, and poses both a health risk and visibility challenges. Emissions vary as a function of vehicle type, speed, age, and fuel type and of local weather condition; as a result, 96 runs were conducted for each pollutant to examine the impacts of these variables on emissions rates. Additional runs were conducted to estimate emissions rates at median observed vehicle speeds. Major findings from these analyses include:

- Both CO_2 and particulate matter emissions rates decrease exponentially as speeds increase.
- Particulate matter emissions rates are considerably lower for one and five year old vehicles than for 10- year-old vehicles due to changes vehicle emissions standards; while CO_2 emissions rates have also improved over time, no drastic change has been observed.
- For the City Bakery case study, assuming that cargo cycles replaced daily operation of a five-year-old cargo van traveling at a speed of 8.28 mph:
    - An estimated 11-13 tons/year of CO_2 and 2-2.5 lbs/year of PM10 are saved during vehicle movement.
    - A 10-year old cargo van operating at 3 mph would generate 30 times as much PM 2.5 emissions as the speed and age assumed; however, a 1-year-old vehicle operating as 15 mph would generate only about half of the estimated emissions.
    - A vehicle operating in the most polluting conditions evaluated generates a little more than twice as much CO_2 as the assumed vehicle, and the newest, fastest-traveling van generates about 70 percent less CO_2.
- For the City Harvest case study, assuming that all three vehicle types operate on identical routes:
    - Total annual CO_2 savings are between 8.3 tons for freight tricycles replacing a cargo van and 15.6 tons for freight tricycles replacing a box truck; yearly PM10 savings range from 1.6 lbs for a cargo van to 5.72 lbs for a box truck.
    - Particulates generated by a box truck include larger particles than those generated by the cargo van; while 45 percent of cargo van particulate emissions are smaller than 2.5 micrometers, only about a third of box truck particulates are as small.

8.5 Temperature Control Alternatives

Maintaining a cold chain requires implementation of processes that ensure efficient movement of freight between stakeholders and of technologies that provide adequate temperature control during goods movement and storage. Two types of commodities that are currently moved by cargo cycle – food and pharmaceuticals – rely on the cold chain. Different foods require varying ideal shipping temperatures, ranging from “deep freeze” temperatures required for some seafood to relatively warm temperatures required for bananas and some tropical fruits. Pharmaceutical ranges also vary, although they generally move at chilled rather than frozen temperatures. If these types of goods are not maintained at a proper temperature range, they can be damaged, initially losing quality and ultimately becoming useless and valueless. Although both types of goods are currently being moved by cargo cycle, few cargo cycle operators have developed comprehensive temperature management strategies. Because cargo cycles generally move goods over short distances during tours with short durations, goods receive little exposure to ambient conditions; as a result, damage is minimal, even when temperature control is inadequate.

Tricycle and truck operators currently use a variety of technologies for temperature control. Three main approaches to temperature control include insulation, passive temperature control, and mechanical temperature control. Insulation – including plastic foam, fiberglass, and blankets – protects goods from external elements but does not provide cooling. Of these, plastic foam is likely a preferred method, as fiberglass poses a risk to both goods and drivers if not properly isolated and blankets would likely require additional handling at each stop location. Mechanical systems offer the highest level of control; temperatures can be carefully managed using variable settings. However the weight and expense of an electric battery operated system make it unsuitable for tricycle operations; diesel-powered systems are additionally dangerous to operate and pollutant-producing. Alternative power systems – including solar and pedal-powered – may offer another alternative, but currently, these technologies produce low, unreliable power outputs.

Although they can only be used for limited durations, passive temperature control technologies are most commonly used in tricycle transportation and are likely most suited to this use. Ice, dry ice, gel packs, and eutectic plates are all feasible options depending on the goods to be transported via trike. For transportation of frozen goods, dry ice offers cooling to very low temperatures; however, for goods to be transported at higher-than-freezing temperatures ice or gel packs may offer a better option. Eutectic plates provide the most flexible system for temperature control; plates containing different liquids can be frozen to consistently maintain temperatures ranging from extreme cold to chilled. Both dry ice and ice must be replenished after each use. Dry ice can cause frostbite when touched and generates CO_2 that can pose an explosion risk, and melted ice can damage goods or packaging if not properly isolated. Gel packs and eutectic plates can be reused, and eutectic plates can be handled without protection.

8.6 Potential for Freight Tricycles in New York City

Results from this study indicate that freight tricycles offer a feasible alternative to motorized vehicle operations for local and last-mile deliveries in New York City, even for transportation of temperature-sensitive goods. Despite the relative infancy of the sector in North America and a recent history of frequent business turnover in New York City, European experience has demonstrated that cargo cycles can be successful and even cost-competitive with other modes if a sufficient volume of customers can be identified in a concentrated delivery area. Given the short trip distances and durations required for delivery via cargo cycle, needed temperature control is very feasible with existing passive technologies, including ice, dry ice, gel packs, and eutectic plates; however, maintaining a cold chain requires not only implementation of these technologies, but also effective management of loading, unloading, storage, and transportation processes to ensure that goods are not over-exposed to uncontrolled conditions.

Cargo cycles offer a tremendous advantage over motor vehicles in parking flexibility; with the ability to park both on- and off-street, cargo cycles can generally be parked much closer to delivery locations and are largely immune to the parking fines that plague New York's commercial vehicle operators. The city's street infrastructure also currently offers advantages to cargo cycles compared to motorized vehicles, especially trucks. As noted in the case studies, for a number of trips, freight tricycles were able to travel on routes shorter than the minimum motor vehicle travel distance. Although smaller vehicles such as cargo vans can travel relatively unrestricted on the city's road networks, larger trucks are required to stay on local truck routes, deviating from defined routes only to take a shortest path to a final delivery location. Travel speeds can be competitive between modes; while variations were noted between the two tricycle operating companies, City Bakery freight tricycles consistently achieved speeds that were close to those achieved by City Harvest trucks. While the estimated median truck moving speed was slightly higher than that estimated for City Bakery freight tricycles, trucks also generally spent more time in stopped-time delay. As demonstrated by City Harvest's slower moving speeds, tricycle speeds are sensitive to load sizes, trip distances, and tour durations. When operators are tired – whether from heavy loads or long trips or tours – they will travel at slower speeds. This difference could be mitigated through the use of an electric-assist. As cargo cycles have been demonstrated to offer competitive speeds, relatively reliable travel times, and clear benefits in parking flexibility, companies performing local delivery of relatively small modes should consider a direct mode switch. Even for operators moving larger volumes of goods, delivery via cargo cycle from a micro-distribution center may be feasible.

Cargo cycle implementation also has the potential to produce measurable social and environmental benefits locally. In general, results from this study indicate that considering dimensions of time and space, freight tricycles consume both road and parking space at a much lower rate than motorized vehicles, even when they travel at significantly lower median speeds. It should be noted, however, that space savings for cargo cycles compared to motorized vehicles are highly variable depending on the exact vehicle configurations, utilization of space on small and large vehicles, and vehicle speeds. If space in a cargo van is underutilized, a single cargo van tour might be replaced with a single freight tricycle tour; however, if space in a larger vehicle is used efficiently, and its routes are optimized, many tricycle tours may be required to replace a single motor vehicle tour. Results from this study also indicate that both air pollutant and greenhouse gas emissions can be reduced through cargo cycle implementation, although emissions savings during vehicle movement are also highly variable depending on vehicle type, age, speed, and fuel type. The results estimated in this study consider only moving activity, and do not include additional savings achieved during vehicle start-up and other idling activity. While savings from replacing one or a few vehicles is relatively small, a mode shift of only a small percentage of the city's delivery fleet would produce measurable savings.

A few local conditions – including high costs for workmen's compensation insurance and restrictions that prohibit bridge crossings and the use of electric-assists – do pose unique challenges that must be overcome in New York; while insurance costs could be reduced with significant growth in use of cargo cycles, the other challenges would require changes to existing policy. As this mode provides clear benefits for the public in terms of emissions and especially space savings, public agencies should explore methods to promote increased implementation. The New York State Department of Transportation, the New Jersey Department of Transportation, and the Port Authority of New York/New Jersey recently released a long-range, comprehensive framework for improving freight movement in the New York City region – the Goods Movement Action Program (G-MAP). Two of the program's six primary goals are to improve supply chain performance and reliability in the region and to better align freight operations with broader social and environmental needs. To achieve these aims, the agencies have identified a number of strategies. One strategy is to reduce freight use of limited road capacity during peak hours. Whether implemented for local deliveries or as part of a consolidation center, cargo cycles have the potential to reduce demand for limited road and parking space. When cargo cycles are used as part of a consolidation scheme, they can enable off-peak delivery to a central business district via truck despite inflexible receiver delivery times.

Other relevant strategies identified in the G-MAP include preserving industrial land for freight activities, fostering new business models for distribution and consolidation, and incentivizing low-carbon vehicles and land development patterns that encourage sustainable freight operations. These strategies are all critical to promote the use of cargo cycles. Provision of affordable space in dense, centrally located areas for sorting and loading has been a critical component of successful micro-consolidation centers utilizing cargo cycles in Europe. These consolidation activities require cooperation between government and multiple private sector stakeholders. Policies that improve the competitiveness of cargo cycle operations compared to other modes may be implemented to induce a mode switch; alternatives include legalizing electric-assist motors as well as imposing access restrictions – e.g. low emissions zones or congestion charges – for motorized vehicles. Proactive incentives could also be provided in the form of recognition schemes, direct subsidies for operations, or access to affordable space. Regardless of which strategies are employed, cargo cycle operators will rely on supportive local policies to enable their operations.

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Appendix A: Survey Questions

A.1. Questions for North American Freight Operators

1. How long has your company been operating?
2. What types of goods do you deliver?
3. What services do you provide? (e.g. delivery services for commercial customers, delivery for private customers, vehicle sales, vehicle maintenance, etc.)
4. What types of vehicles do you operate? (e.g. cargo tricycle, bicycle w/ trailer, specific model)
5. What is your approximate delivery range? What is the maximum distance you would bike to make a delivery?
6. Do you have a standard rates for delivery services? Are rates variable by weight and/or volume?
7. Do you offer any value added services?
8. Is your company a nonprofit?
9. Has your company received any support from the local government?
10. Has your company received support (or faced opposition) from the local cycling community?
11. Have your "drivers" faced any safety concerns in interacting with vehicles, bicycles, or pedestrians while making a delivery?
12. Has your company had any problems with cargo security?

A.2. Questions for Case Study Partners

1. How long have you been in operation?
2. What types of products (foods) do you move?
3. How often do you make deliveries?
4. What is the size of a typical delivery (or range)?
5. What is typical delivery distance and service area?
6. Do you serve areas outside of Manhattan?
7. Currently, what method of transportation do you use?
8. How many vehicles do you use?
9. What type of vehicle? (passenger car or truck?)
10. Is (are) the vehicle(s) used for multi-functions or only for deliveries?
11. Do you employ personnel dedicated for delivery? If yes how many?
12. Do you have a designated space to receive deliveries? Is your available space adequate?
13. Do you have a designated parking place for your existing delivery vehicles?
14. Do you ever receive parking tickets in Manhattan?
15. Why were you initially interested in using freight tricycles?
16. Other than environmental benefits, are there other benefits that you expect from using freight tricycles?
17. Were you looking to own a trike(s) or use a third-party service?
18. How do expect the cost of operating a tricycle compares with that of operating other modes?

- Operations
- Maintenance
- Driver
- Insurance

19. Are any of the following major concerns that have prevented you from using freight tricycles?

- Lack of service area flexibility?
- Security of goods?
- Lack of temperature control?
- Other product integrity issues (e.g. jostling of food due to lack of suspension system)? Insurance/liability issues?

20. Are there any other specific concerns that you see to freight tricycle implementation?
21. Are there any specific services, vehicle attributes, or container attributes that you think would solve your existing concerns?

Appendix B: Corridor Speed Distributions

Figure B1. City Bakery, Numbered "Avenue" Corridor Speed Distributions

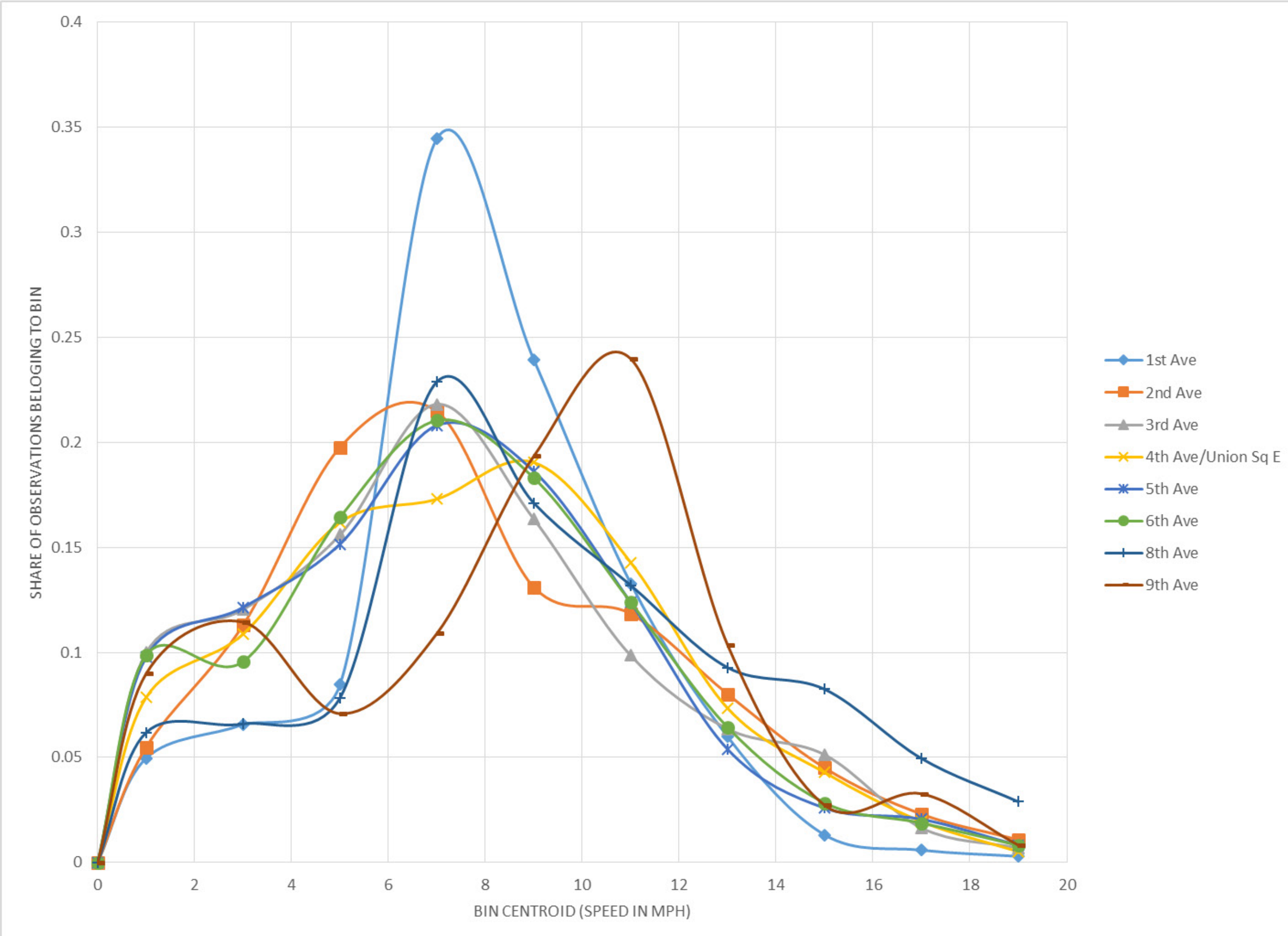


Figure B2. City Bakery, Other "Avenue" Corridor Speed Distributions

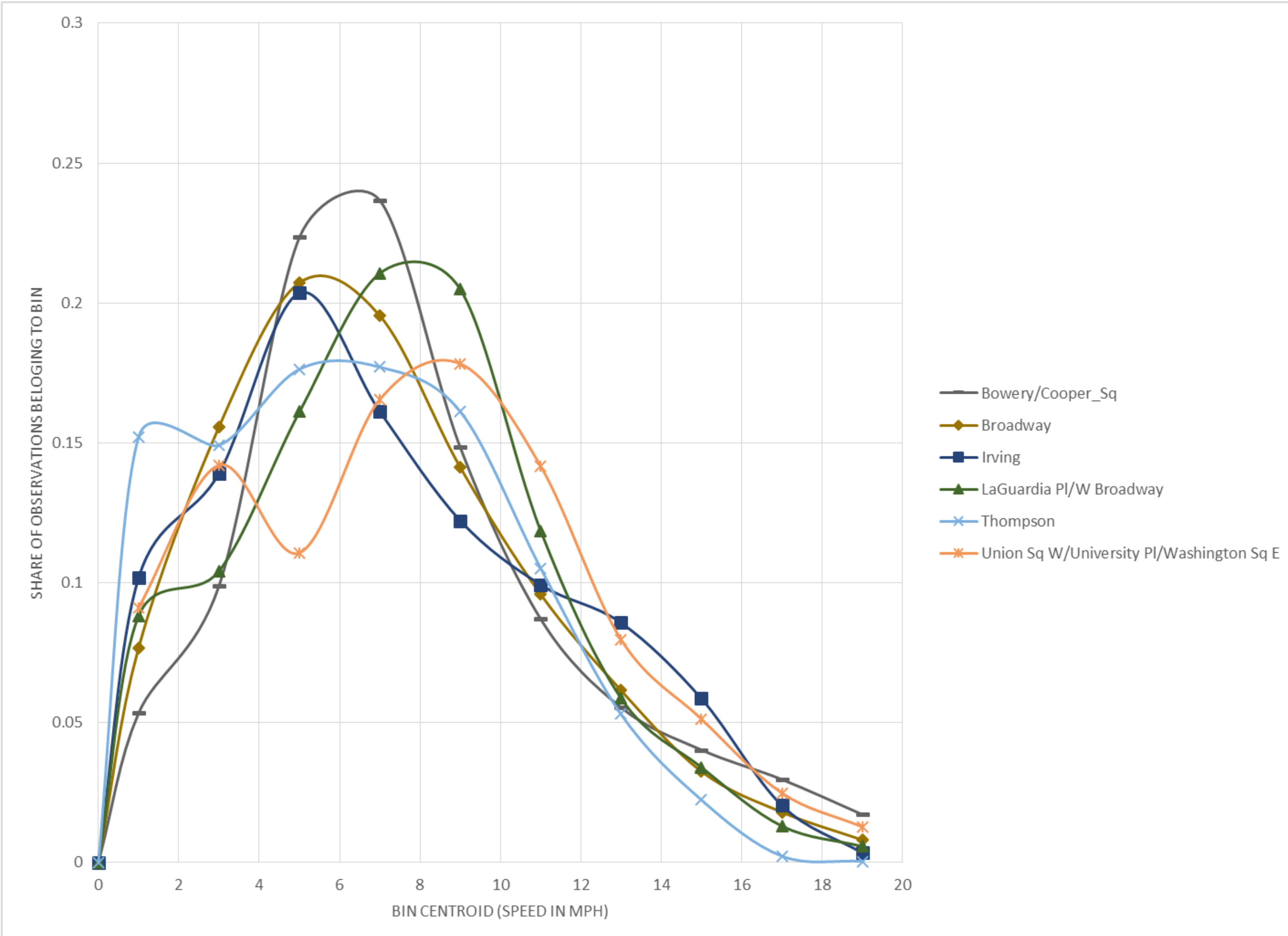


Figure B3. City Bakery, Southern "Street" Corridor Speed Distributions

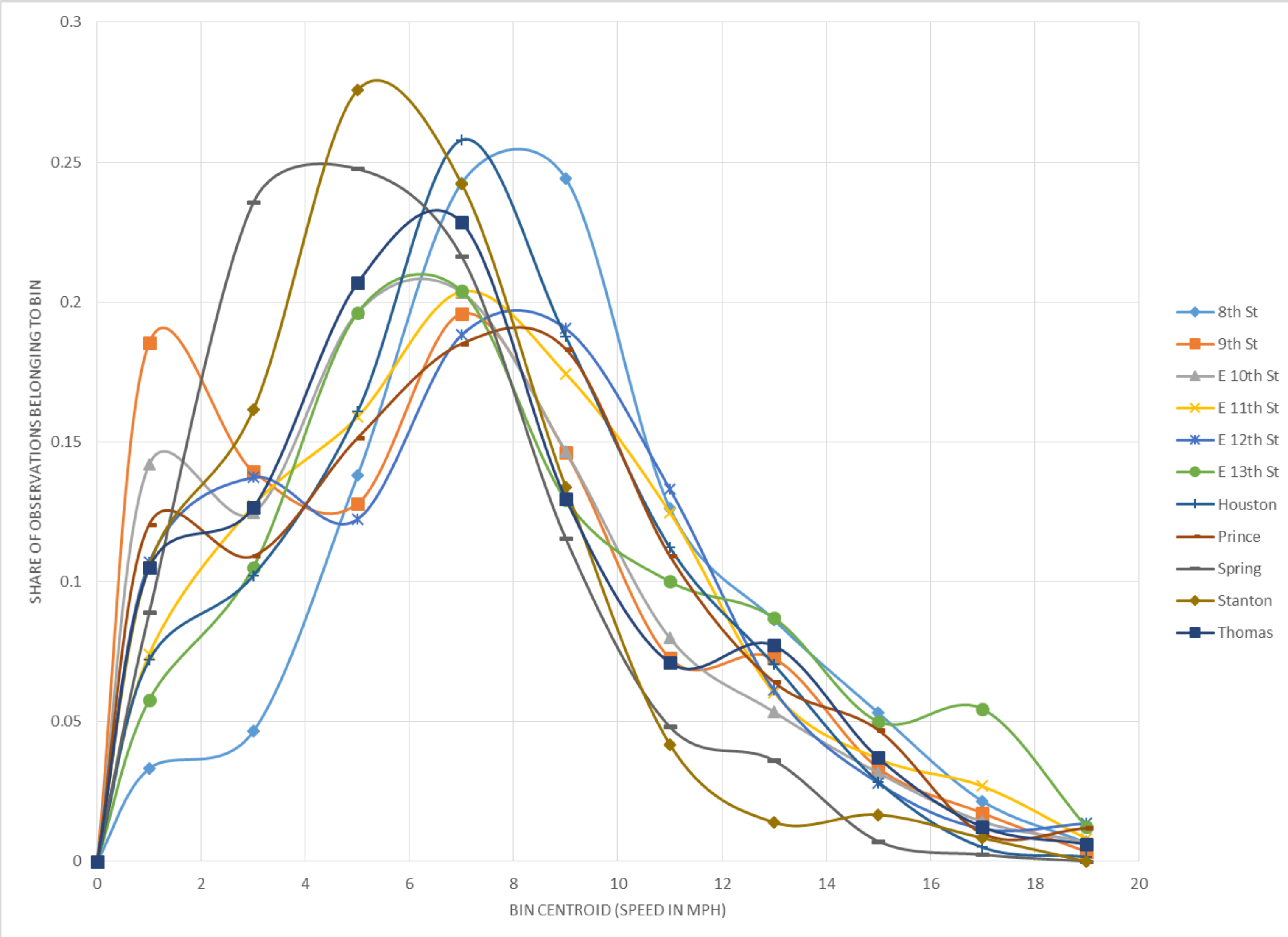


Figure B4. City Bakery, Northern "Street" Corridor Speed Distributions

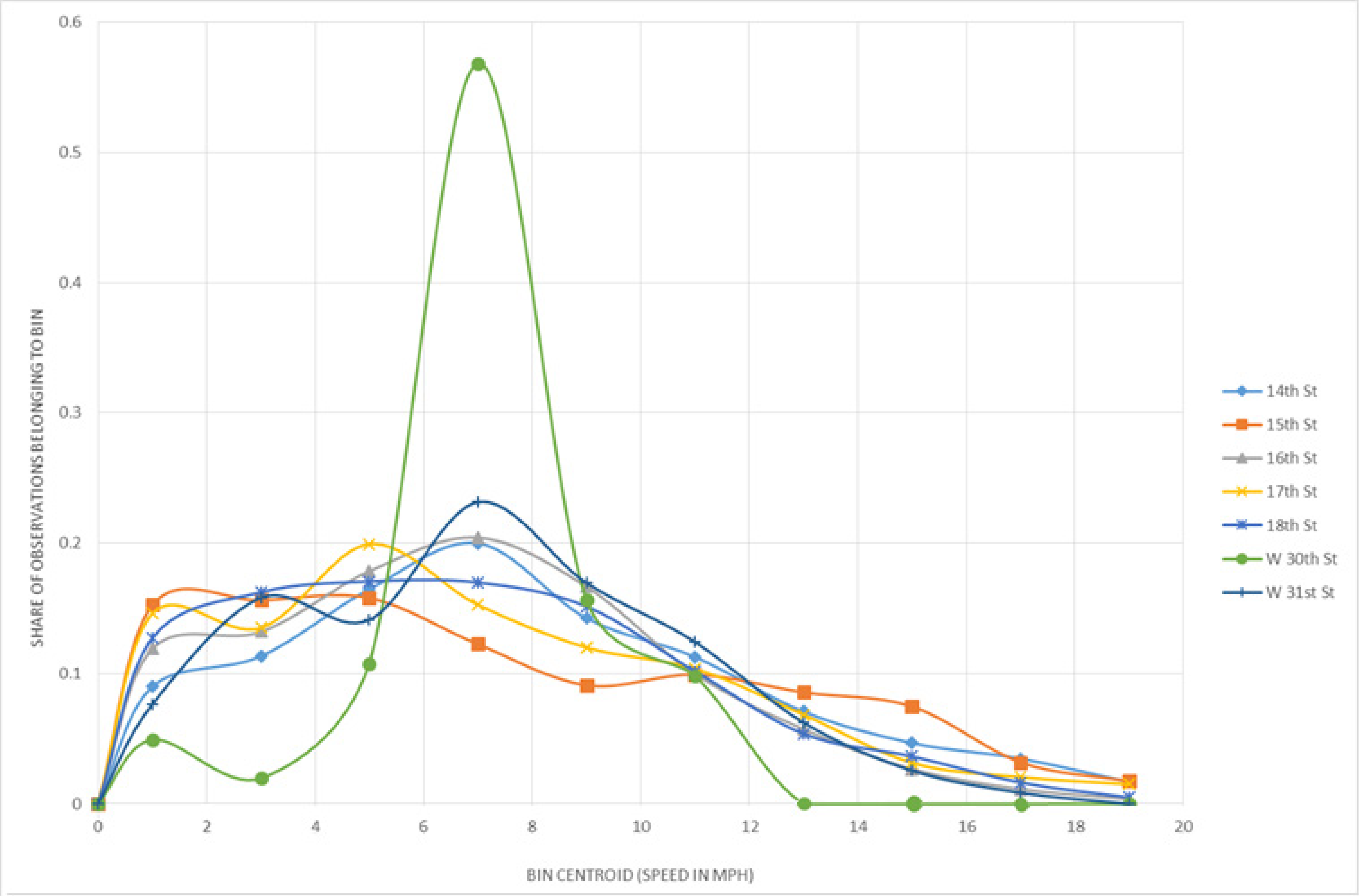


Figure B5. City Harvest, West Side "Avenue" Corridor Speed Distributions - Tricycles

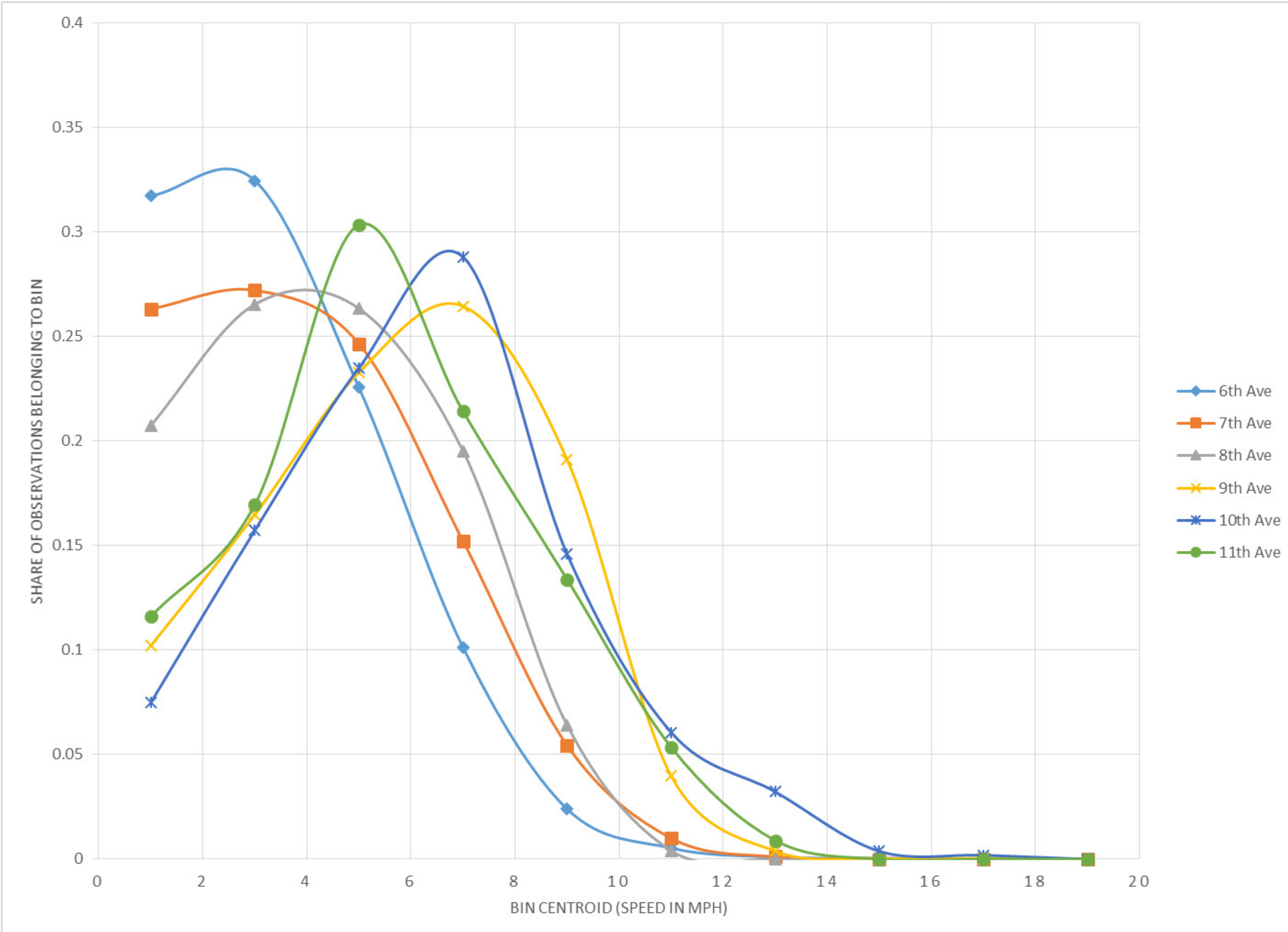


Figure B6. City Harvest, East Side "Avenue" Corridor Speed Distributions - Tricycles

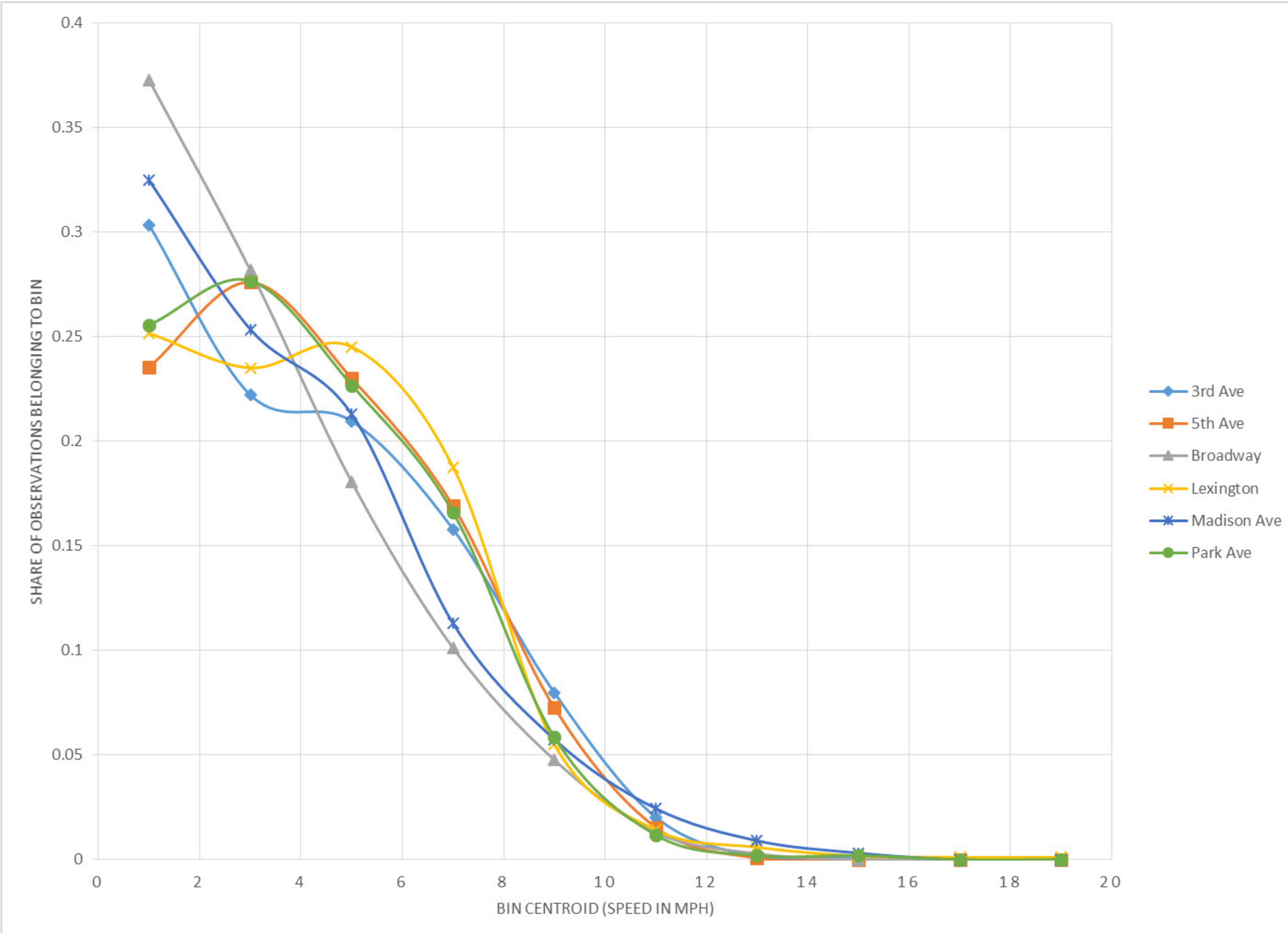


Figure B7. City Harvest, Southern "Street" Corridor Speed Distributions - Tricycles

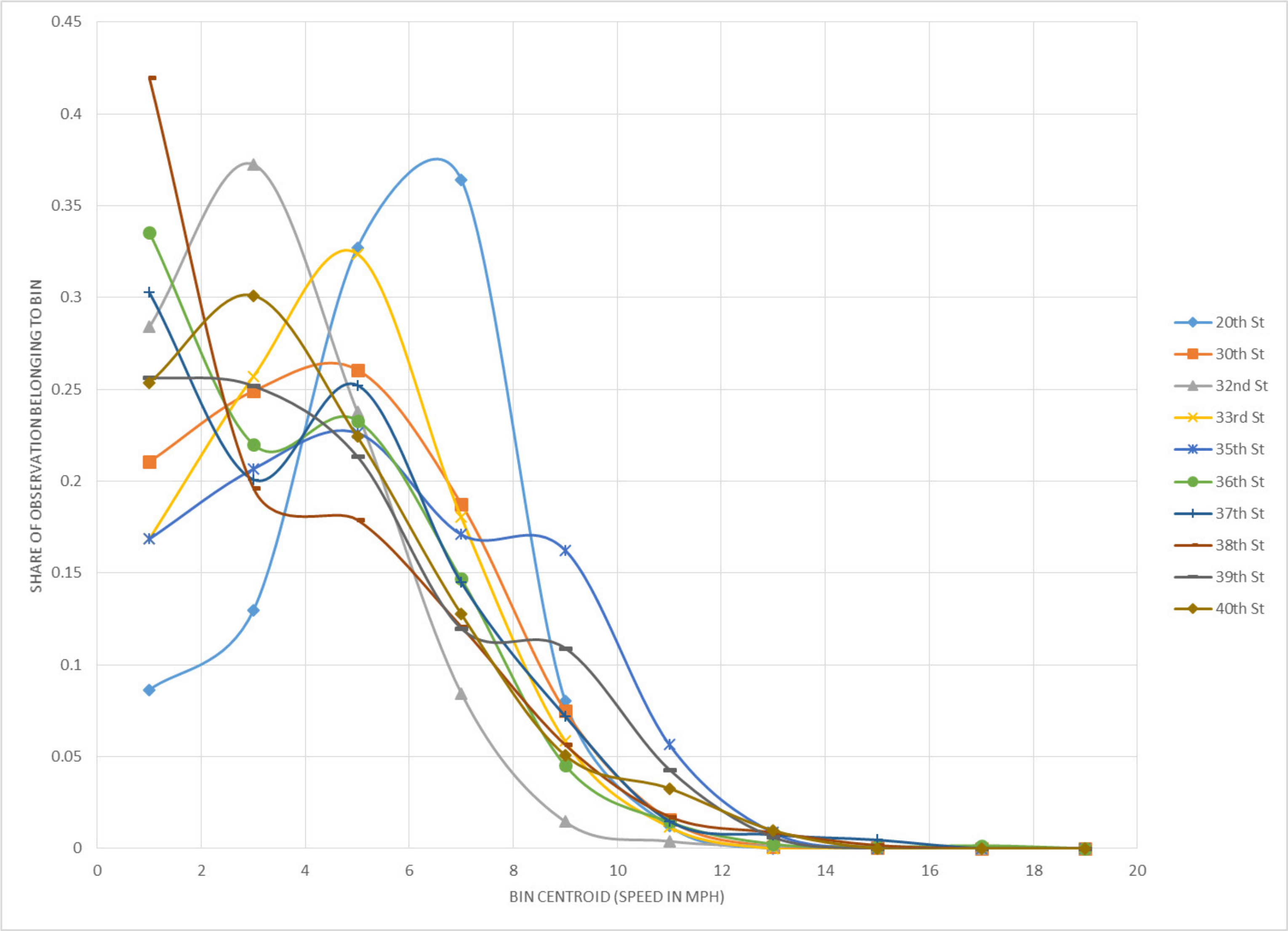


Figure B8. City Harvest, Northern “Street” Corridor Speed Distributions - Tricycles

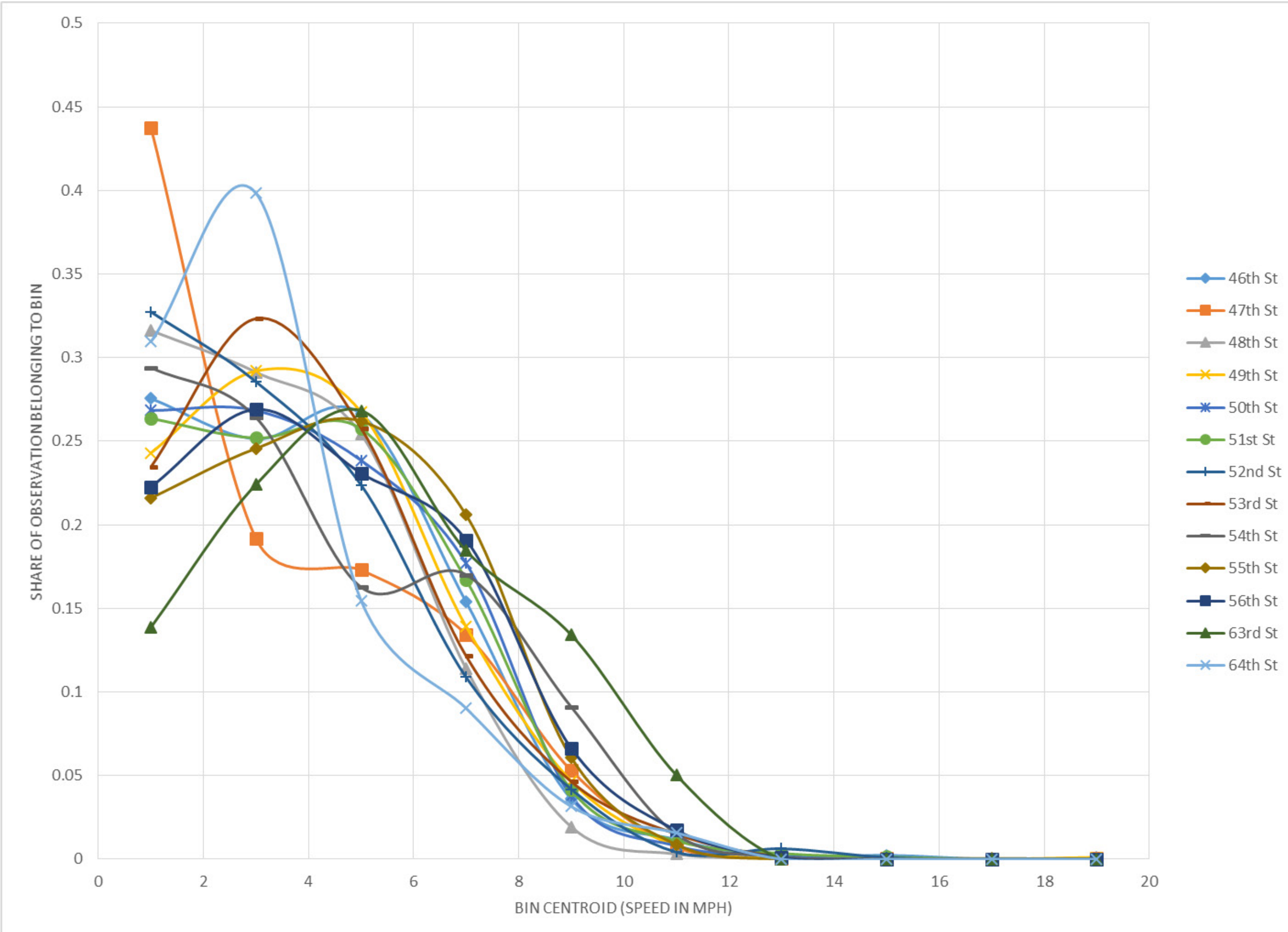


Figure B9. City Harvest, Downtown “Avenue” Corridor Speed Distributions - Trucks

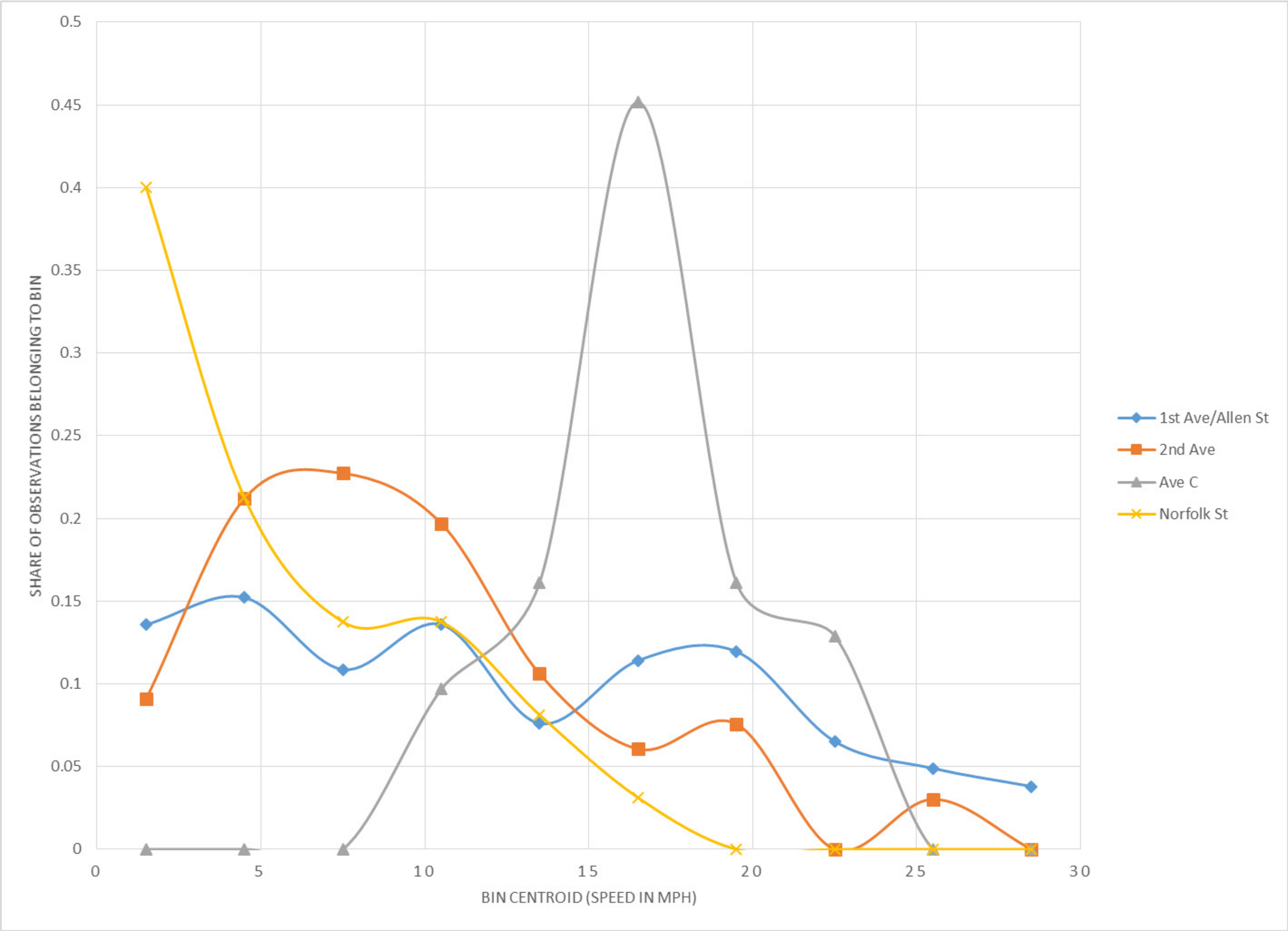


Figure B10. City Harvest, Midtown "Avenue" Corridor Speed Distributions - Trucks

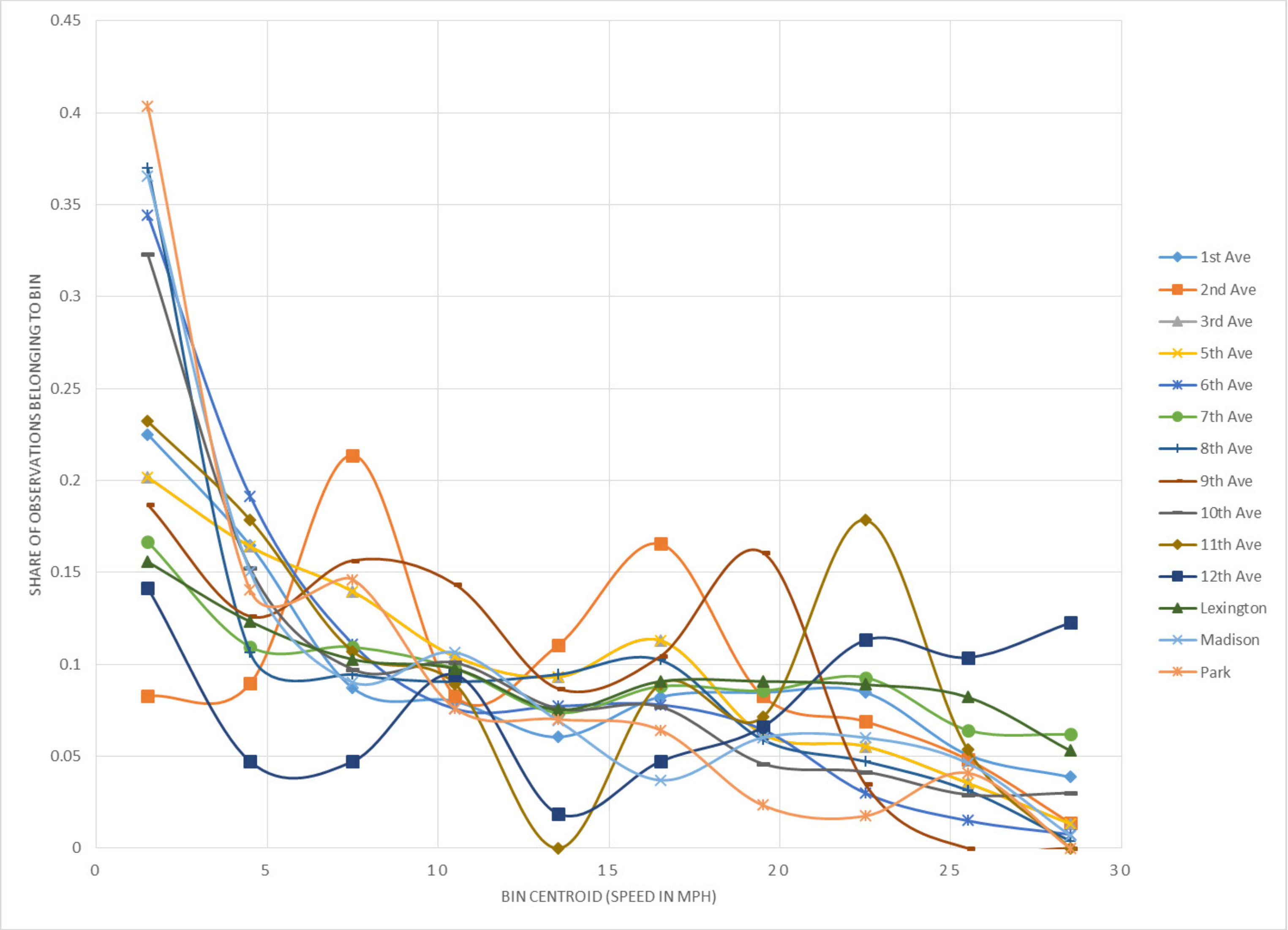


Figure B11. City Harvest, Uptown "Avenue" Corridor Speed Distributions - Trucks

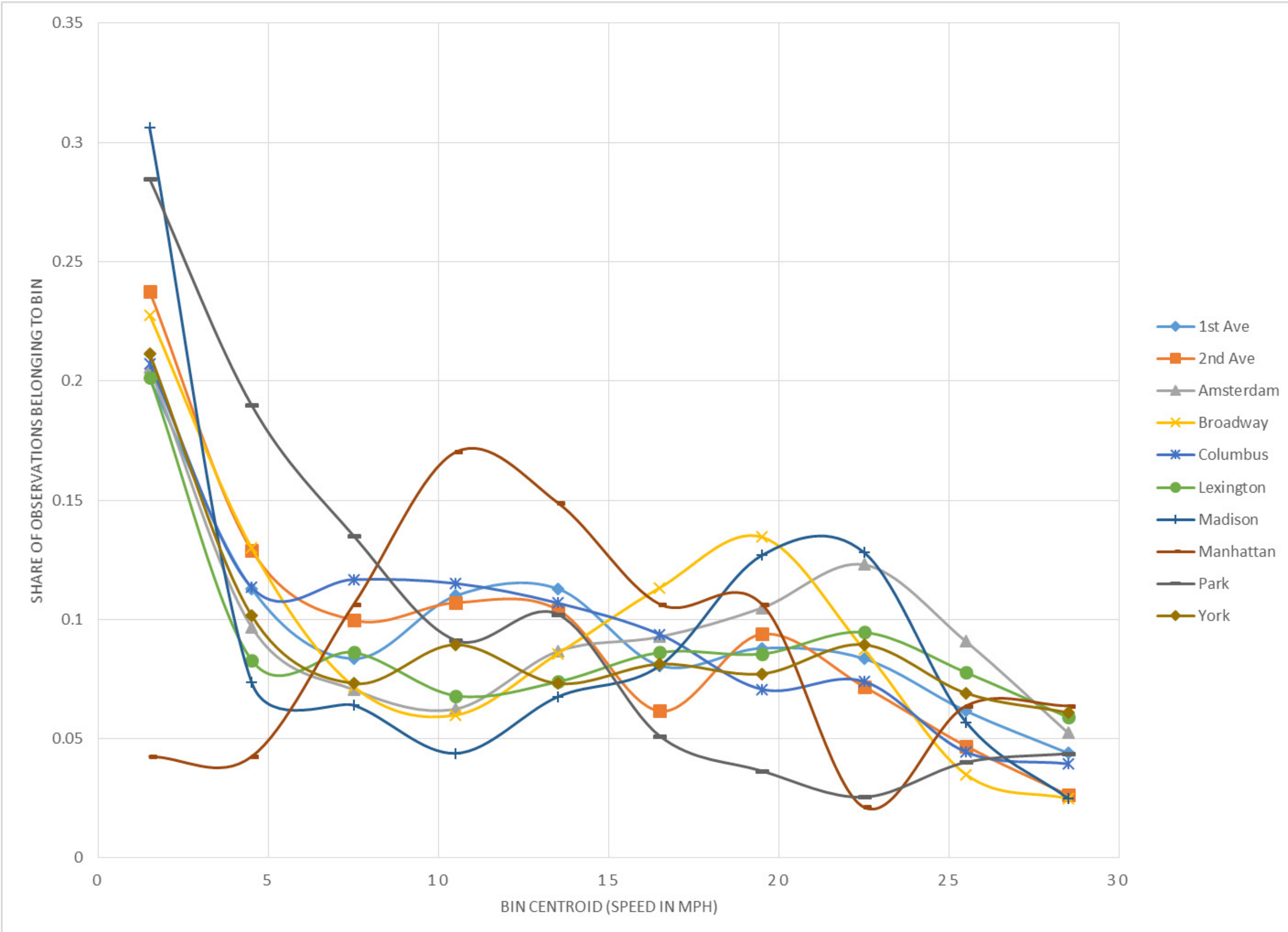


Figure B12. City Harvest, Downtown and Midtown "Street" Corridor Speed Distributions - Trucks

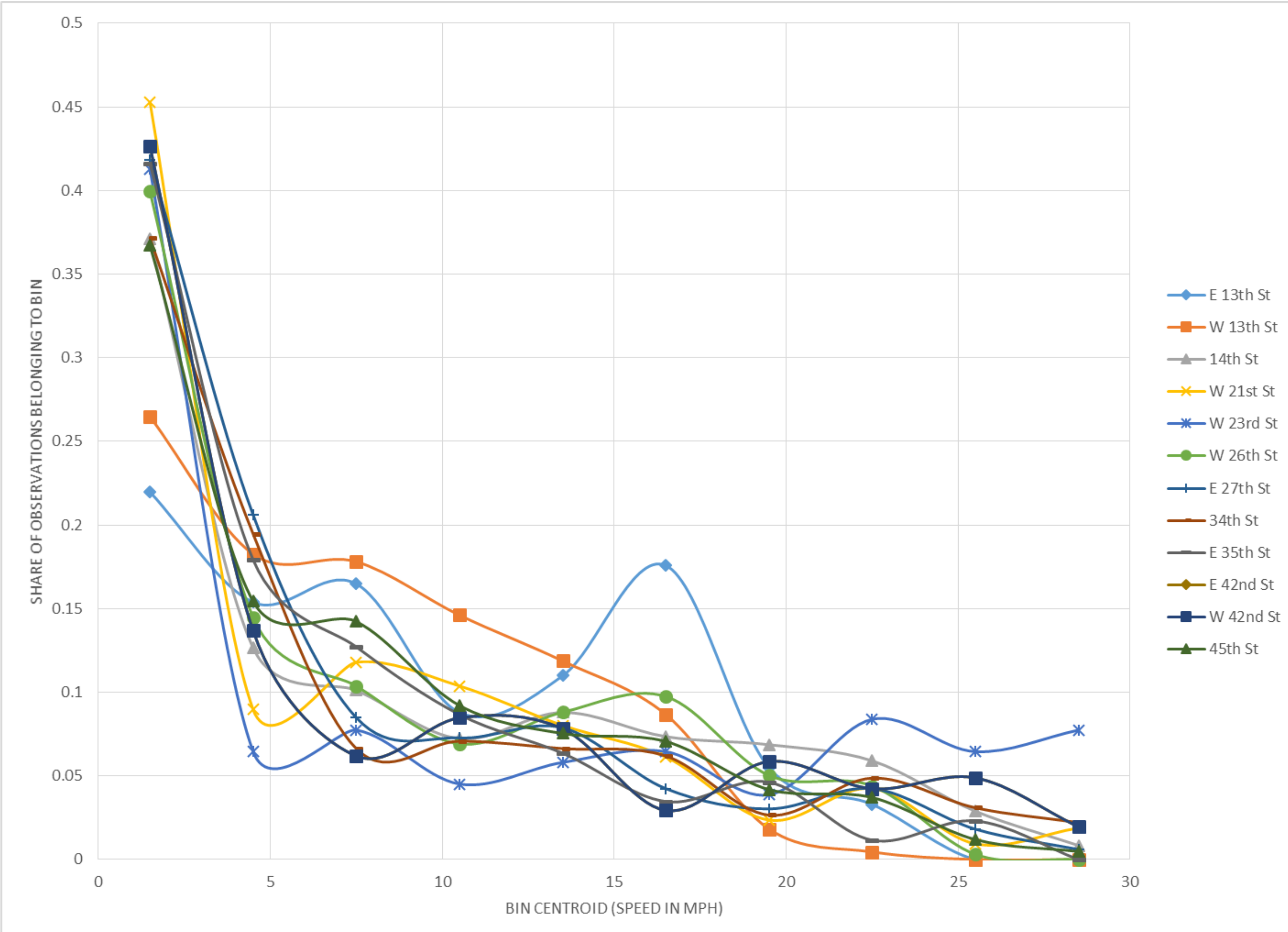
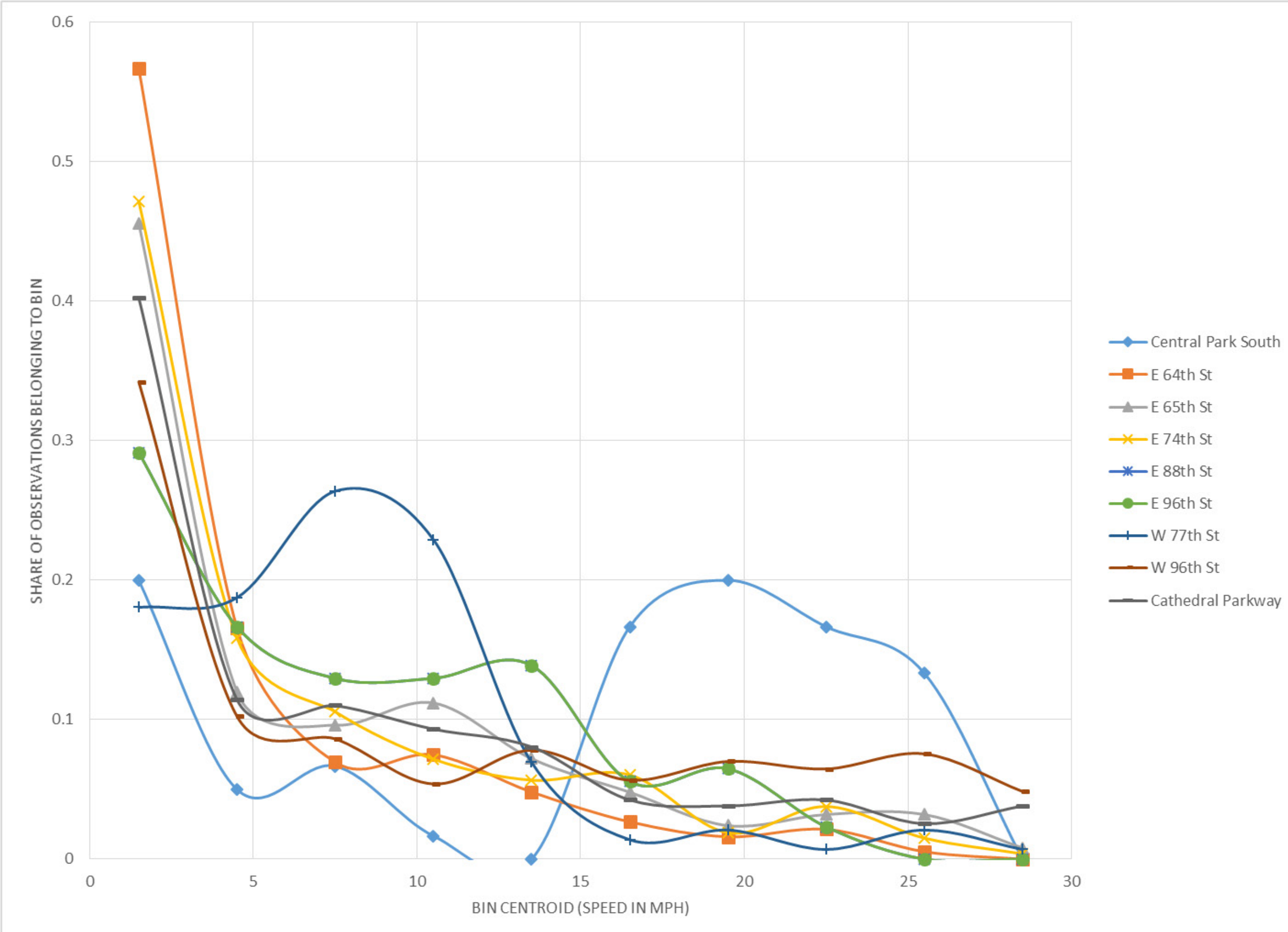


Figure B13. City Harvest, Uptown "Street" Corridor Speed Distributions - Trucks



Appendix C: Case Study Service Areas

Figure C1. City Bakery Service Area

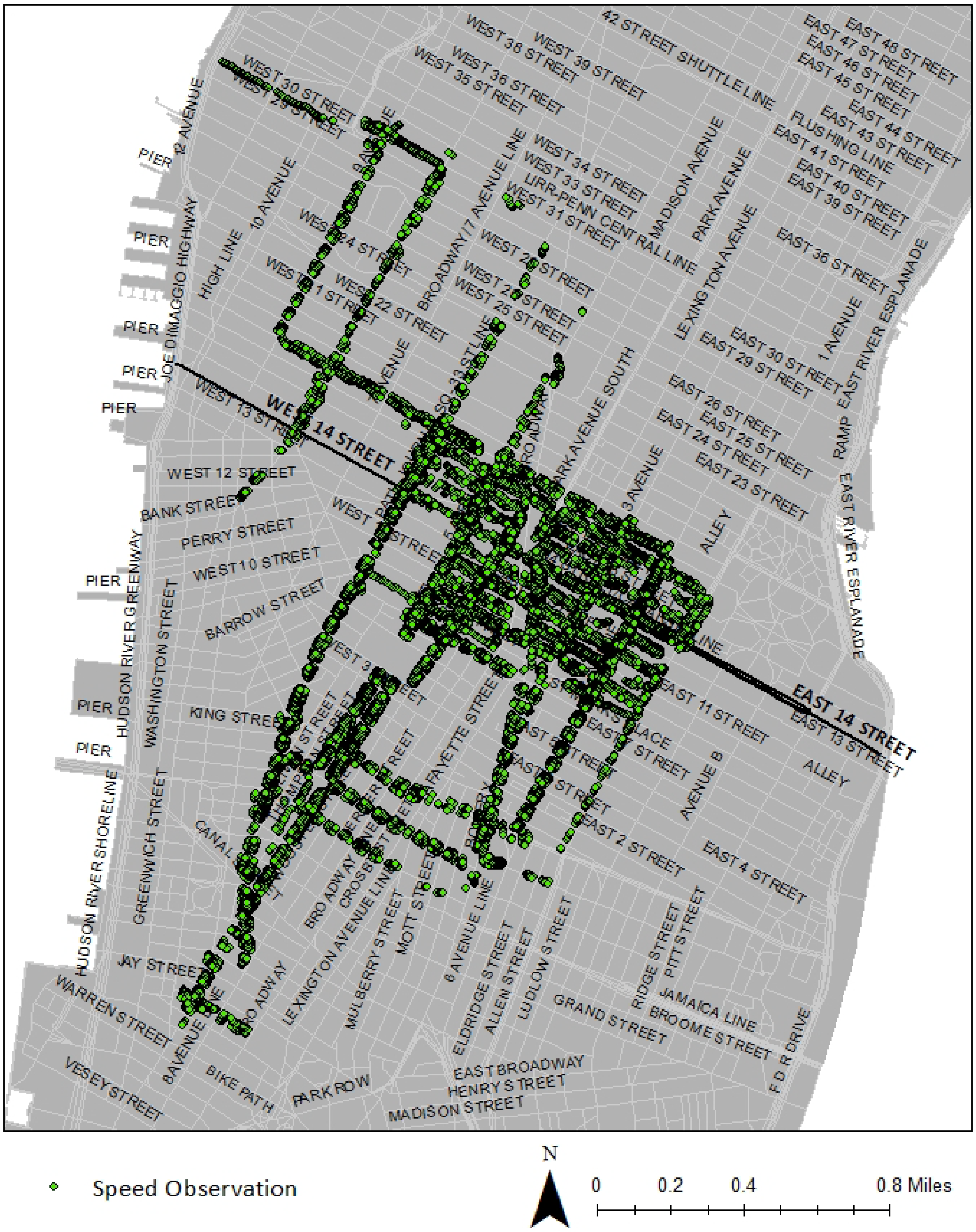


Figure C2. City Harvest Tricycle Service Area

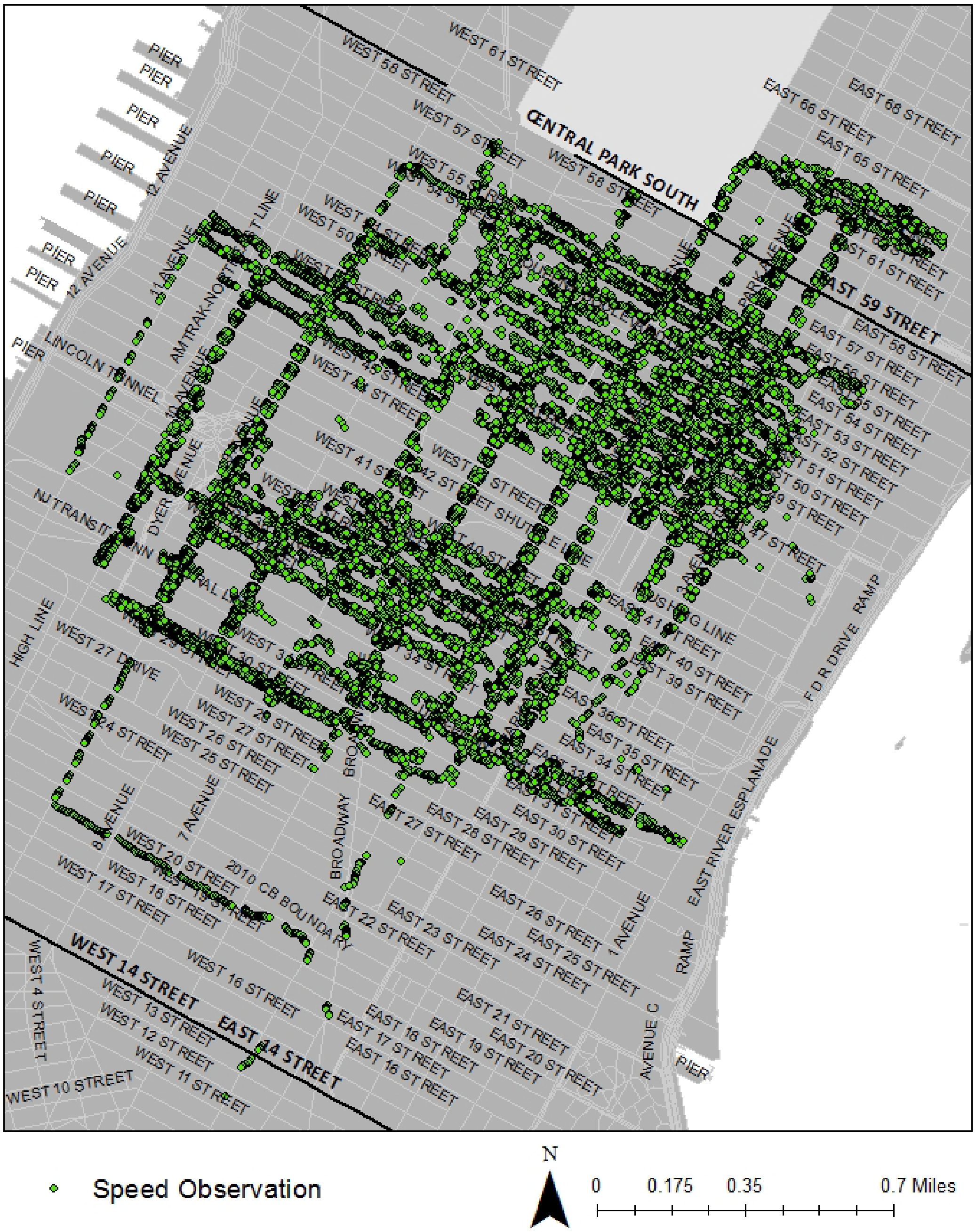
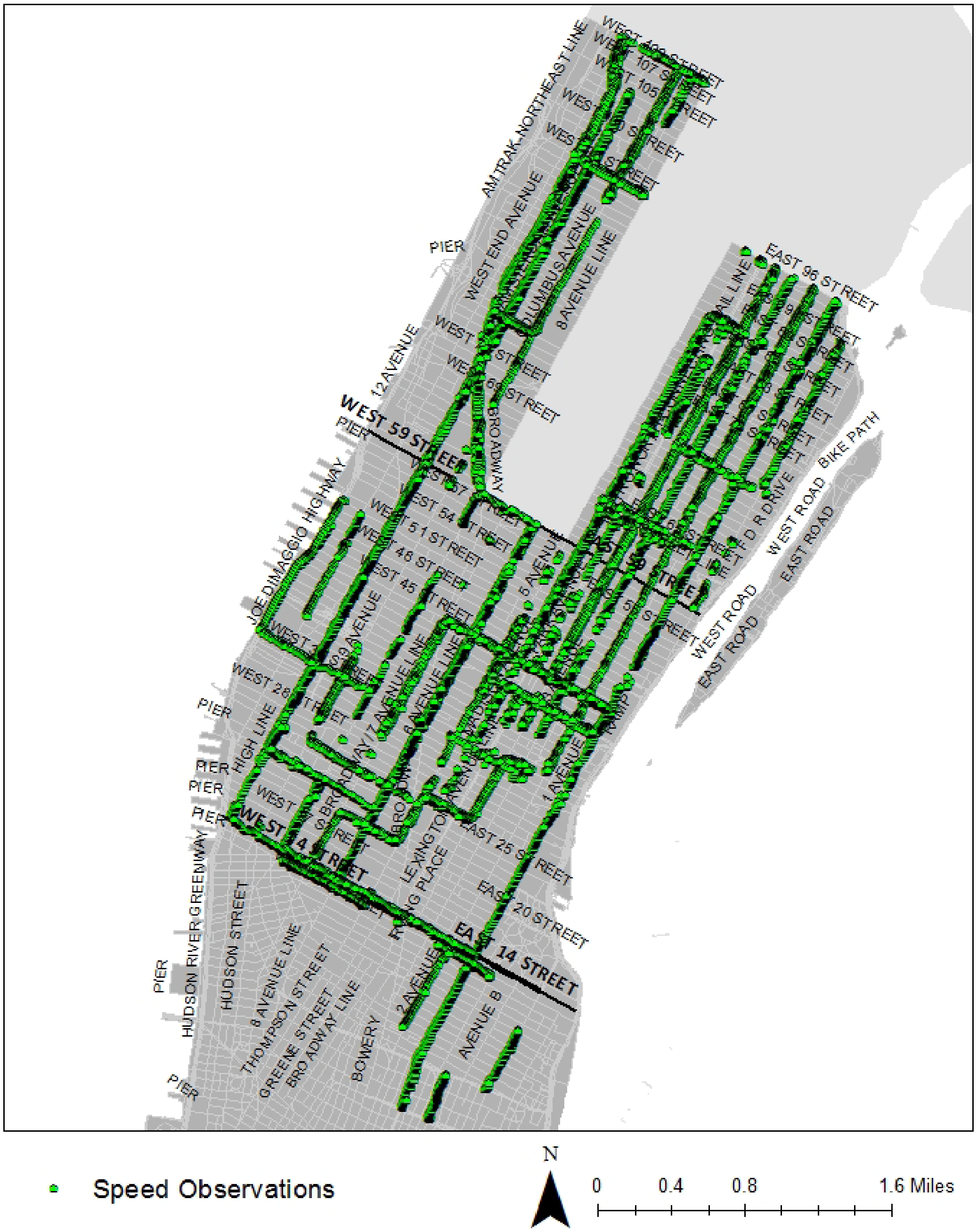


Figure C3. City Harvest Truck Service Area



Appendix D: MOVES Model Emissions Rate Estimates

Table D1. Passenger Car CO_2 Emissions Rates (g/mi)

Age	Speed	Temperature	Humidity	Fuel Type	Vehicle Type	Rate Per Mile
1	3	29	62	Gasoline	Passenger Car	1513.9
1	5	29	62	Gasoline	Passenger Car	996.902
1	10	29	62	Gasoline	Passenger Car	621.974
1	15	29	62	Gasoline	Passenger Car	488.986
5	3	29	62	Gasoline	Passenger Car	1616.03
5	5	29	62	Gasoline	Passenger Car	1064.16
5	10	29	62	Gasoline	Passenger Car	650.254
5	15	29	62	Gasoline	Passenger Car	512.285
10	3	29	62	Gasoline	Passenger Car	1647.33
10	5	29	62	Gasoline	Passenger Car	1084.77
10	10	29	62	Gasoline	Passenger Car	662.848
10	15	29	62	Gasoline	Passenger Car	522.206
1	3	70	65	Gasoline	Passenger Car	1552.89
1	5	70	65	Gasoline	Passenger Car	1020.93
1	10	70	65	Gasoline	Passenger Car	621.974
1	15	70	65	Gasoline	Passenger Car	488.986
5	3	70	65	Gasoline	Passenger Car	1657.24
5	5	70	65	Gasoline	Passenger Car	1089.56
5	10	70	65	Gasoline	Passenger Car	663.798
5	15	70	65	Gasoline	Passenger Car	521.878
10	3	70	65	Gasoline	Passenger Car	1688.91
10	5	70	65	Gasoline	Passenger Car	1110.4
10	10	70	65	Gasoline	Passenger Car	676.515
10	15	70	65	Gasoline	Passenger Car	531.887

Table D2. Cargo Van CO_2 Emissions Rates (g/mi)

Age	Speed	Temperature	Humidity	Fuel Type	Vehicle Type	Rate Per Mile
1	3	29	62	Diesel	Passenger Truck	2612.61
1	5	29	62	Diesel	Passenger Truck	1770.38
1	10	29	62	Diesel	Passenger Truck	1138.71
1	15	29	62	Diesel	Passenger Truck	928.152
5	3	29	62	Diesel	Passenger Truck	2759.07
5	5	29	62	Diesel	Passenger Truck	1869.59
5	10	29	62	Diesel	Passenger Truck	1202.49
5	15	29	62	Diesel	Passenger Truck	980.121
10	3	29	62	Diesel	Passenger Truck	2987.72
10	5	29	62	Diesel	Passenger Truck	2015.58
10	10	29	62	Diesel	Passenger Truck	1286.49
10	15	29	62	Diesel	Passenger Truck	1043.46
1	3	70	65	Diesel	Passenger Truck	2678.37
1	5	70	65	Diesel	Passenger Truck	1811.54
1	10	70	65	Diesel	Passenger Truck	1161.42
1	15	70	65	Diesel	Passenger Truck	944.719
5	3	70	65	Diesel	Passenger Truck	2827.82
5	5	70	65	Diesel	Passenger Truck	1912.63
5	10	70	65	Diesel	Passenger Truck	1226.24
5	15	70	65	Diesel	Passenger Truck	997.44
10	3	70	65	Diesel	Passenger Truck	3061.45
10	5	70	65	Diesel	Passenger Truck	2061.63
10	10	70	65	Diesel	Passenger Truck	1311.77
10	15	70	65	Diesel	Passenger Truck	1061.81

Table D3. Step Van CO_2 Emissions Rates (g/mi)

Age	Speed	Temperature	Humidity	Fuel Type	Vehicle Type	Rate Per Mile
1	3	29	62	Diesel	LCT	2637.46
1	5	29	62	Diesel	LCT	1782.28
1	10	29	62	Diesel	LCT	1140.91
1	15	29	62	Diesel	LCT	927.126
5	3	29	62	Diesel	LCT	2773.28
5	5	29	62	Diesel	LCT	1874.16
5	10	29	62	Diesel	LCT	1199.84
5	15	29	62	Diesel	LCT	975.057
10	3	29	62	Diesel	LCT	2985.6
10	5	29	62	Diesel	LCT	2009.97
10	10	29	62	Diesel	LCT	1278.26
10	15	29	62	Diesel	LCT	1034.35
1	3	70	65	Diesel	LCT	2703.87
1	5	70	65	Diesel	LCT	1823.8
1	10	70	65	Diesel	LCT	1163.77
1	15	70	65	Diesel	LCT	943.752
5	3	70	65	Diesel	LCT	2842.41
5	5	70	65	Diesel	LCT	1917.39
5	10	70	65	Diesel	LCT	1223.62
5	15	70	65	Diesel	LCT	992.366
10	3	70	65	Diesel	LCT	3059.31
10	5	70	65	Diesel	LCT	2055.95
10	10	70	65	Diesel	LCT	1303.45
10	15	70	65	Diesel	LCT	1052.62

Table D4. Box Truck CO_2 Emissions Rates (g/mi)

Age	Speed	Temperature	Humidity	Fuel Type	Vehicle Type	Rate Per Mile
1	3	29	62	Diesel	SU Short Haul Truck	6049.5
1	5	29	62	Diesel	SU Short Haul Truck	3676.84
1	10	29	62	Diesel	SU Short Haul Truck	2133.17
1	15	29	62	Diesel	SU Short Haul Truck	1680.77
5	3	29	62	Diesel	SU Short Haul Truck	6049.5
5	5	29	62	Diesel	SU Short Haul Truck	3676.84
5	10	29	62	Diesel	SU Short Haul Truck	2133.17
5	15	29	62	Diesel	SU Short Haul Truck	1680.77
10	3	29	62	Diesel	SU Short Haul Truck	6049.5
10	5	29	62	Diesel	SU Short Haul Truck	3676.84
10	10	29	62	Diesel	SU Short Haul Truck	2133.17
10	15	29	62	Diesel	SU Short Haul Truck	1680.77
1	3	70	65	Diesel	SU Short Haul Truck	6190.31
1	5	70	65	Diesel	SU Short Haul Truck	3762.06
1	10	70	65	Diesel	SU Short Haul Truck	2180.23
1	15	70	65	Diesel	SU Short Haul Truck	1715.81
5	3	70	65	Diesel	SU Short Haul Truck	6188.9
5	5	70	65	Diesel	SU Short Haul Truck	3761.2
5	10	70	65	Diesel	SU Short Haul Truck	2179.76
5	15	70	65	Diesel	SU Short Haul Truck	1715.47
10	3	70	65	Diesel	SU Short Haul Truck	6187.5
10	5	70	65	Diesel	SU Short Haul Truck	3760.34
10	10	70	65	Diesel	SU Short Haul Truck	2179.29
10	15	70	65	Diesel	SU Short Haul Truck	1715.11

Table D5. Passenger Car PM 2.5 Emissions Rates (g/mi)

Age	Speed	Temperature	Humidity	Fuel Type	Vehicle Type	Rate Per Mile
1	3	29	62	Gasoline	Passenger Car	0.070501597
1	5	29	62	Gasoline	Passenger Car	0.04628921
1	10	29	62	Gasoline	Passenger Car	0.018110365
1	15	29	62	Gasoline	Passenger Car	0.014352674
5	3	29	62	Gasoline	Passenger Car	0.07986749
5	5	29	62	Gasoline	Passenger Car	0.052628047
5	10	29	62	Gasoline	Passenger Car	0.033227492
5	15	29	62	Gasoline	Passenger Car	0.026658411
10	3	29	62	Gasoline	Passenger Car	0.164576496
10	5	29	62	Gasoline	Passenger Car	0.103733506
10	10	29	62	Gasoline	Passenger Car	0.059130627
10	15	29	62	Gasoline	Passenger Car	0.044160614
1	3	70	65	Gasoline	Passenger Car	0.045069943
1	5	70	65	Gasoline	Passenger Car	0.029076447
1	10	70	65	Gasoline	Passenger Car	0.018110365
1	15	70	65	Gasoline	Passenger Car	0.014352674
5	3	70	65	Gasoline	Passenger Car	0.047619399
5	5	70	65	Gasoline	Passenger Car	0.030801792
5	10	70	65	Gasoline	Passenger Car	0.019217624
5	15	70	65	Gasoline	Passenger Car	0.015253908
10	3	70	65	Gasoline	Passenger Car	0.070619762
10	5	70	65	Gasoline	Passenger Car	0.044678193
10	10	70	65	Gasoline	Passenger Car	0.026251065
10	15	70	65	Gasoline	Passenger Car	0.020006366

Table D6. Cargo Van PM 2.5 Emissions Rates (g/mi)

Age	Speed	Temperature	Humidity	Fuel Type	Vehicle Type	Rate Per Mile
1	3	29	62	Diesel	Passenger Truck	0.098822783
1	5	29	62	Diesel	Passenger Truck	0.06241387
1	10	29	62	Diesel	Passenger Truck	0.036417435
1	15	29	62	Diesel	Passenger Truck	0.027621565
5	3	29	62	Diesel	Passenger Truck	0.141528886
5	5	29	62	Diesel	Passenger Truck	0.088711716
5	10	29	62	Diesel	Passenger Truck	0.050417685
5	15	29	62	Diesel	Passenger Truck	0.037511859
10	3	29	62	Diesel	Passenger Truck	1.7671572
10	5	29	62	Diesel	Passenger Truck	1.101016193
10	10	29	62	Diesel	Passenger Truck	0.602724301
10	15	29	62	Diesel	Passenger Truck	0.436496226
1	3	70	65	Diesel	Passenger Truck	0.098884465
1	5	70	65	Diesel	Passenger Truck	0.062452485
1	10	70	65	Diesel	Passenger Truck	0.036438731
1	15	70	65	Diesel	Passenger Truck	0.027637113
5	3	70	65	Diesel	Passenger Truck	0.141593376
5	5	70	65	Diesel	Passenger Truck	0.08875208
5	10	70	65	Diesel	Passenger Truck	0.050431904
5	15	70	65	Diesel	Passenger Truck	0.037528101
10	3	70	65	Diesel	Passenger Truck	1.767239603
10	5	70	65	Diesel	Passenger Truck	1.101067632
10	10	70	65	Diesel	Passenger Truck	0.602752523
10	15	70	65	Diesel	Passenger Truck	0.436516745

Table D7. Step Van PM 2.5 Emissions Rates (g/mi)

Age	Speed	Temperature	Humidity	Fuel Type	Vehicle Type	Rate Per Mile
1	3	29	62	Diesel	LCT	0.103304592
1	5	29	62	Diesel	LCT	0.065229739
1	10	29	62	Diesel	LCT	0.038005535
1	15	29	62	Diesel	LCT	0.028798247
5	3	29	62	Diesel	LCT	0.147090689
5	5	29	62	Diesel	LCT	0.0921533
5	10	29	62	Diesel	LCT	0.052282203
5	15	29	62	Diesel	LCT	0.038859373
10	3	29	62	Diesel	LCT	1.804481354
10	5	29	62	Diesel	LCT	1.123218712
10	10	29	62	Diesel	LCT	0.613614387
10	15	29	62	Diesel	LCT	0.443611505
1	3	70	65	Diesel	LCT	0.10336689
1	5	70	65	Diesel	LCT	0.065268691
1	10	70	65	Diesel	LCT	0.038026975
1	15	70	65	Diesel	LCT	0.028813842
5	3	70	65	Diesel	LCT	0.147155547
5	5	70	65	Diesel	LCT	0.092193844
5	10	70	65	Diesel	LCT	0.052304514
5	15	70	65	Diesel	LCT	0.03887561
10	3	70	65	Diesel	LCT	1.804563638
10	5	70	65	Diesel	LCT	1.123270076
10	10	70	65	Diesel	LCT	0.613642476
10	15	70	65	Diesel	LCT	0.443631898

Table D8. Box Truck PM 2.5 Emissions Rates (g/mi)

Age	Speed	Temperature	Humidity	Fuel Type	Vehicle Type	Rate Per Mile
1	3	29	62	Diesel	SU Short Haul Truck	0.340788025
1	5	29	62	Diesel	SU Short Haul Truck	0.206210518
1	10	29	62	Diesel	SU Short Haul Truck	0.116307701
1	15	29	62	Diesel	SU Short Haul Truck	0.079845821
5	3	29	62	Diesel	SU Short Haul Truck	0.38780315
5	5	29	62	Diesel	SU Short Haul Truck	0.234670097
5	10	29	62	Diesel	SU Short Haul Truck	0.132103635
5	15	29	62	Diesel	SU Short Haul Truck	0.091647195
10	3	29	62	Diesel	SU Short Haul Truck	3.147182336
10	5	29	62	Diesel	SU Short Haul Truck	1.904801438
10	10	29	62	Diesel	SU Short Haul Truck	1.057892794
10	15	29	62	Diesel	SU Short Haul Truck	0.781293787
1	3	70	65	Diesel	SU Short Haul Truck	0.340920099
1	5	70	65	Diesel	SU Short Haul Truck	0.206290438
1	10	70	65	Diesel	SU Short Haul Truck	0.116351836
1	15	70	65	Diesel	SU Short Haul Truck	0.079878697
5	3	70	65	Diesel	SU Short Haul Truck	0.387933925
5	5	70	65	Diesel	SU Short Haul Truck	0.234749225
5	10	70	65	Diesel	SU Short Haul Truck	0.13214734
5	15	70	65	Diesel	SU Short Haul Truck	0.091679738
10	3	70	65	Diesel	SU Short Haul Truck	3.147336265
10	5	70	65	Diesel	SU Short Haul Truck	1.904894808
10	10	70	65	Diesel	SU Short Haul Truck	1.057944293
10	15	70	65	Diesel	SU Short Haul Truck	0.78133212

Table D9. Passenger Car PM 10 Emissions Rates (g/mi)

Age	Speed	Temperature	Humidity	Fuel Type	Vehicle Type	Rate Per Mile
1	3	29	62	Gasoline	Passenger Car	0.174904636
1	5	29	62	Gasoline	Passenger Car	0.112824575
1	10	29	62	Gasoline	Passenger Car	0.058556596
1	15	29	62	Gasoline	Passenger Car	0.046271536
5	3	29	62	Gasoline	Passenger Car	0.185076038
5	5	29	62	Gasoline	Passenger Car	0.119708604
5	10	29	62	Gasoline	Passenger Car	0.074973816
5	15	29	62	Gasoline	Passenger Car	0.059635477
10	3	29	62	Gasoline	Passenger Car	0.277070264
10	5	29	62	Gasoline	Passenger Car	0.175209153
10	10	29	62	Gasoline	Passenger Car	0.103104623
10	15	29	62	Gasoline	Passenger Car	0.078642937
1	3	70	65	Gasoline	Passenger Car	0.147285936
1	5	70	65	Gasoline	Passenger Car	0.094131552
1	10	70	65	Gasoline	Passenger Car	0.058556596
1	15	70	65	Gasoline	Passenger Car	0.046271536
5	3	70	65	Gasoline	Passenger Car	0.15005456
5	5	70	65	Gasoline	Passenger Car	0.096005282
5	10	70	65	Gasoline	Passenger Car	0.059759081
5	15	70	65	Gasoline	Passenger Car	0.047250271
10	3	70	65	Gasoline	Passenger Car	0.1750329
10	5	70	65	Gasoline	Passenger Car	0.111074958
10	10	70	65	Gasoline	Passenger Car	0.067397432
10	15	70	65	Gasoline	Passenger Car	0.052411444

Table D10. Cargo Van PM 10 Emissions Rates (g/mi)

Age	Speed	Temperature	Humidity	Fuel Type	Vehicle Type	Rate Per Mile
1	3	29	62	Diesel	Passenger Truck	0.251299852
1	5	29	62	Diesel	Passenger Truck	0.159845894
1	10	29	62	Diesel	Passenger Truck	0.096719418
1	15	29	62	Diesel	Passenger Truck	0.075134014
5	3	29	62	Diesel	Passenger Truck	0.295325573
5	5	29	62	Diesel	Passenger Truck	0.186956387
5	10	29	62	Diesel	Passenger Truck	0.111144025
5	15	29	62	Diesel	Passenger Truck	0.085329622
10	3	29	62	Diesel	Passenger Truck	1.971167482
10	5	29	62	Diesel	Passenger Truck	1.230532258
10	10	29	62	Diesel	Passenger Truck	0.680518162
10	15	29	62	Diesel	Passenger Truck	0.496636985
1	3	70	65	Diesel	Passenger Truck	0.251363422
1	5	70	65	Diesel	Passenger Truck	0.159885691
1	10	70	65	Diesel	Passenger Truck	0.096741416
1	15	70	65	Diesel	Passenger Truck	0.075149712
5	3	70	65	Diesel	Passenger Truck	0.295392037
5	5	70	65	Diesel	Passenger Truck	0.186997991
5	10	70	65	Diesel	Passenger Truck	0.111166982
5	15	70	65	Diesel	Passenger Truck	0.085346312
10	3	70	65	Diesel	Passenger Truck	1.971252002
10	5	70	65	Diesel	Passenger Truck	1.230585008
10	10	70	65	Diesel	Passenger Truck	0.680547129
10	15	70	65	Diesel	Passenger Truck	0.496658011

Table D11. Step Van PM 10 Emissions Rates (g/mi)

Age	Speed	Temperature	Humidity	Fuel Type	Vehicle Type	Rate Per Mile
1	3	29	62	Diesel	LCT	0.265521745
1	5	29	62	Diesel	LCT	0.168973779
1	10	29	62	Diesel	LCT	0.102115679
1	15	29	62	Diesel	LCT	0.079277389
5	3	29	62	Diesel	LCT	0.310660837
5	5	29	62	Diesel	LCT	0.196729295
5	10	29	62	Diesel	LCT	0.116833525
5	15	29	62	Diesel	LCT	0.089649415
10	3	29	62	Diesel	LCT	2.019245023
10	5	29	62	Diesel	LCT	1.259647073
10	10	29	62	Diesel	LCT	0.695503401
10	15	29	62	Diesel	LCT	0.506902898
1	3	70	65	Diesel	LCT	0.265585949
1	5	70	65	Diesel	LCT	0.16901392
1	10	70	65	Diesel	LCT	0.102137763
1	15	70	65	Diesel	LCT	0.079293463
5	3	70	65	Diesel	LCT	0.310727692
5	5	70	65	Diesel	LCT	0.196771079
5	10	70	65	Diesel	LCT	0.116856519
5	15	70	65	Diesel	LCT	0.08966615
10	3	70	65	Diesel	LCT	2.019329423
10	5	70	65	Diesel	LCT	1.259699808
10	10	70	65	Diesel	LCT	0.695532227
10	15	70	65	Diesel	LCT	0.506923826

Table D12. Box Truck PM 10 Emissions Rates (g/mi)

Age	Speed	Temperature	Humidity	Fuel Type	Vehicle Type	Rate Per Mile
1	3	29	62	Diesel	SU Short Haul Truck	1.097033525
1	5	29	62	Diesel	SU Short Haul Truck	0.663692039
1	10	29	62	Diesel	SU Short Haul Truck	0.375828271
1	15	29	62	Diesel	SU Short Haul Truck	0.253784849
5	3	29	62	Diesel	SU Short Haul Truck	1.14550133
5	5	29	62	Diesel	SU Short Haul Truck	0.69303089
5	10	29	62	Diesel	SU Short Haul Truck	0.392112367
5	15	29	62	Diesel	SU Short Haul Truck	0.265950836
10	3	29	62	Diesel	SU Short Haul Truck	3.990101911
10	5	29	62	Diesel	SU Short Haul Truck	2.414752675
10	10	29	62	Diesel	SU Short Haul Truck	1.34649688
10	15	29	62	Diesel	SU Short Haul Truck	0.976897491
1	3	70	65	Diesel	SU Short Haul Truck	1.097169659
1	5	70	65	Diesel	SU Short Haul Truck	0.663774402
1	10	70	65	Diesel	SU Short Haul Truck	0.375873764
1	15	70	65	Diesel	SU Short Haul Truck	0.253818739
5	3	70	65	Diesel	SU Short Haul Truck	1.145636106
5	5	70	65	Diesel	SU Short Haul Truck	0.693112431
5	10	70	65	Diesel	SU Short Haul Truck	0.392157399
5	15	70	65	Diesel	SU Short Haul Truck	0.26598438
10	3	70	65	Diesel	SU Short Haul Truck	3.990259893
10	5	70	65	Diesel	SU Short Haul Truck	2.41484843
10	10	70	65	Diesel	SU Short Haul Truck	1.346549749
10	15	70	65	Diesel	SU Short Haul Truck	0.976936838

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Freight Tricycle Operations in New York City

Final Report
October 2014

Report Number 14-33

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