Micro-consolidation practices in urban delivery systems: Comparative evaluation of last mile deliveries using e-cargo bikes and microhubs

Seyma Gunes

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Anne Goodchild, Chair

Xuegang Ban

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Abstract

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Seyma Gunes

Chair of the Supervisory Committee:
Anne Goodchild, PhD
Department of Civil and Environmental Engineering

The demand for home deliveries has seen a drastic increase, especially in cities, putting urban freight systems under pressure. As more people move to urban areas and change consumer behaviors to shop online, busy delivery operations cause externalities such as congestion and air pollution. Micro-consolidation implementations and its possible pairing with soft transportation modes offer practical, economic, environmental, and cultural benefits. Early implementations of micro consolidation practices were tested but cities need to understand their implications in terms of efficiency and sustainability. This study includes a research scan and proposes a typology of micro-consolidation practices. It focuses on assessing the performance of microhubs that act as additional transshipment points where the packages are transported by trucks and transferred onto e-bikes to complete the last mile. The purpose of the study is to assess the performance of delivery operations using a network of microhubs with cargo logistics and identify the conditions under which these solutions can be successfully implemented to improve urban freight efficiencies and reduce emissions. The performance is evaluated in terms of vehicle miles traveled, tailpipe CO_2 emissions, and average operating cost per package using simulation tools. Three different delivery scenarios were tested that represents 1) the baseline scenario, where only vans and cars make deliveries; 2) the mixed scenario, where in addition to vans and cars, a portion of packages are delivered by e-bikes; and 3) the e-bike only scenario, where all package demand is satisfied using microhubs and e-bikes. The results showed that e-bike delivery operations perform the best in service areas with high customer density. At the highest customer demand level, e-bikes traveled 7.7% less to deliver a package and emitted 91% less tailpipe CO_2 with no significant cost benefits or losses when compared with the baseline scenario where only traditional delivery vehicles were used. Cargo logistics, when implemented in areas where the demand is densified, can reduce emissions and congestion without significant cost implications.

Table of Contents

List of Figures

List of Tables

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Chapter 1. Introduction

Freight delivery systems in urban areas are under tremendous pressure as the result of new trends in technology and consumer behavior, shifts in the population, and increased environmental focus. The global population is becoming increasingly urban; specifically, 68% of the world population is projected to live in urban areas by 2050, according to the United Nations [1]. North America is already the most urbanized region in the world with 82% of its population living in urban areas in 2018. Following the development and diffusion of new technologies, e-commerce sales are growing and constitute higher portions of GDP year-on-year. UNCTAD estimates that the global value of e-commerce sales hit $25.6 trillion in 2018, an increase of 8% from 2017. The United States is by far the largest e-commerce market, where 42% of GDP comes from e-commerce sales in 2018 and 80% of internet users are online shoppers [2]. This growth in online shopping and the associated last-mile movement of these purchases lead to increase in delivery activity in urban city cores. With every passing day, more delivery vehicles are entering city centers to deliver more packages. Amazon (3.5 B) and UPS (5.5 B) cumulatively delivered 9 billion packages and documents globally in 2019 [3]. In Great Britain, light commercial vehicle (van) traffic has seen the fastest growth (97.3%) of any motor vehicle, in the 25 years between 1993 and 2018 [4]. Urban freight systems are struggling to satisfy growing demand induced by both urban population growth and booming e-commerce sales.

Moreover, e-commerce sales customers are demanding ever faster, more reliable, and convenient delivery services which have led carriers to seek better solutions to satisfy customers such as timed delivery windows, parcel traceability, and alternative delivery locations including collection points and locker banks [5]. Rising expectations of service quality, such as same-day delivery or short delivery time windows, have led to increasingly inefficient delivery systems due to lack of shipment consolidation [6]. Between 2013 and 2015 the proportion of next day delivery for non-food online shopping increased by 50% in the UK [7]. The parcel delivery sector is very competitive with many independent players operating with poor vehicle utilization for low profit margins following a “customer-focused” business culture. Harder to satisfy customer expectations and the nature of the parcel delivery industry results in the duplication of delivery operations in urban centers [5].

Despite the substantial growth in total parcel volumes, online retailers and carrier companies are struggling to achieve profitability due to the mismatch between what consumers are willing to pay for delivery and the cost of providing the delivery service [5], and the severe competition in the market [8]. It is especially harder to maintain cost-efficiency and sustainability for attended home deliveries since it requires negotiation of delivery time with the receiver/customer and is associated with a high rate of first time delivery failures [8]. A failed delivery incurs extra costs for both carrier company, the city and ultimately the society; additional vehicle miles traveled increase operational costs for the carrier and externalities such as emissions, noise pollution, reduced road safety. Furthermore, carrier companies operating in city cores compete for limited parking spaces in city centers to load/unload close to destination and reduce turnover time. These parking spaces are also shared with service vehicles that have minimal cargo or equipment to be carried, and therefore doesn’t need to be parked close to the destination [9]. Consequently, freight companies pay high amounts of park-fines. According to the New York City Department of Finance, in 2019 FedEx and UPS collectively incurred $32.8 million for 494,909 violations [10].

Busy delivery services, also coupled with the lack of shipment consolidation, especially in densely populated inner-city areas, account for increased traffic congestion, air pollution, noise, and reduction in road safety [11]. Moreover, the rising awareness towards sustainability and air pollution, especially in cities, coincides with the increasing delivery activity. Since 2008, the Clean Air for Europe Act prescribes limits on the concentration of air pollutants, and fines European cities which violate the air quality standards. The public authorities in London implemented policies such as the Ultra Low Emission Zone (ULEZ) and improved electric vehicle infrastructure in 2019 [12]. Similarly in the US, under the Clean Air Act, the Environmental Protection Agency (EPA) is required to regulate emission of pollutants that "endanger public health and welfare." State and local governments also monitor and enforce Clean Air Act regulations, with oversight by the EPA [13]. The transportation sector is the largest contributor to greenhouse gas emissions in the United States and has seen the largest increase in absolute terms than any other sector (i.e. electricity generation, industry, agriculture, residential, commercial) [14]. In efforts to minimize emissions and therefore meet air quality restrictions, transportation planners, public agencies and private companies are leaning towards environmentally friendlier and more sustainable solutions in city freight systems.

To sum up, urban freight systems are working to meet increased package delivery demand in increasingly denser areas, in shorter amount of times, with sustainable solutions and increased efficiency to maintain profitability.

1.1. Motivation

In the last years, sustainability has become a common notion in many production and distribution fields including city logistics [15]. This environmentally-friendly trend is driven not only by pollution issues and air quality targets, but also the overall economic sustainability. According to Gonzalez-Feliu et al., a sustainable city logistics system can be conceived only if the economic issues have at least the same importance than the environmental once in the conception phase of the project [15]. At the same time, customers increasingly prefer environmentally friendlier options but are unaware of the cost implications of shifting to green choices [16]. Home delivery is very important for customers; more than 90% of the German customers stated in an online survey that home delivery is important or very important to them [17].

Parcel delivery is characterized by a very high number of destination addresses and low unit volume, compared to other transportation networks such as chain store logistics [6]. Business-to-consumer (B2C) online sales segment is growing; this segment is associated with higher number of individual addresses in contrast to business-to-business (B2B) online sales. In recent years, both smaller and higher-value products such as books, clothing and electronic equipment are being ordered in increasingly larger numbers [6]. The trends in consumer behavior require parcel carriers to provide frequent, just-in-time delivery to satisfy basic expectations in the sector. Under these circumstances and in search of environmentally and economically sustainable city logistics solutions, consolidation practices stand out to avoid freight vehicles traveling into urban centers with partial loads. The Organisation for Economic Cooperation and Development (OECD) study on urban distribution recommended that consolidation of goods delivery is a key to achieving sustainable urban goods transport [18]. Freight companies have been implementing new consolidation initiatives to not only better manage the environmental impact of their delivery operations but also increase their efficiency in terms of time, travel, and cost. Companies are shifting towards delivery services that do not involve delivering to residential addresses and finding parking space to increase drop density, while also decreasing unit cost and the risk of delivery failure [5]. Consolidation in the urban freight system can decrease the driving and walking time taken between delivery addresses as well as the time taken for finding parking spaces [5].

Chapter 2. Literature Review

2.1. Early consolidation initiatives and transition to micro-consolidation

Urban freight consolidation practices have been implemented starting in the 1970s with urban consolidation centers in several European cities and urban regions. Urban consolidation centers (UCC) allow for multiple companies to deliver goods destined for the nearby service area to the designated logistics base, from which consolidated deliveries as well as additional logistic and retail services are realized [19]. The motivation behind urban consolidation centers is to reduce the unit cost of parcel delivery by delivering larger volumes of parcels to a smaller number of locations (UCCs), without the risk of delivery failure. Goods are bundled close to the delivery point at these UCCs to avoid freight vehicles traveling into urban centers with partial loads [20]. Many of UCC implementations failed to operate in the long term due to low parcel delivery demand in the area, continued financial dependence on governmental support, and unsatisfactory service levels [21] [22]. These centers were initiated by private companies and were generally supported by temporary or even structural governmental support [23]. The cost of additional transshipment point was expected to be compensated by efficiency gains in the long run, but the governmental support was often crucial to achieve economic stability upon implementation. The experiences with publicly operated UCCs were mostly negative, especially from a commercial standpoint, but the idea of an additional transshipment point is still relevant and compelling [16] [19].

Micro-consolidation practices are often referred as the transition from the classic urban consolidation center concept [16] [24]. The last mile of parcel delivery is the most expensive and complex leg of the supply chain [25]. Prior UCC implementations have focused on micro-consolidation and did not pay much attention to the problems associated with the last mile. The distance between the logistic base and the delivery address is not walkable or bikeable in the case of UCCs. Micro-consolidation initiatives have closer proximity to the delivery point and serve a smaller service area. Scaling down the scope of consolidation practices and moving the facility into the city center allows for a mode shift to low-emission vehicles or soft transportation modes for last mile deliveries [26]. In this project, a delivery microhub (or simply a microhub) is defined as a logistics facility where goods are bundled inside the urban area boundaries, that serves a limited spatial range, and from which a mode shift to low-emission vehicles or soft transportation modes (e.g., walking or cargo-bikes) for last mile deliveries is possible [15] [27] [28].

2.2. Potential Benefits & Challenges

Micro-consolidation implementations and its possible pairing with soft transportation modes offer practical, economic, environmental, and cultural benefits. Microhubs, by having additional transshipment points near the service area allow for the consolidation of delivery addresses in the area at neighborhood scale. Delivery vehicles traveling from the suburban depot (or the previous leg of the supply chain) make fewer, shorter and consolidated trips to the city center. The reduction in the vehicle miles traveled results in less congestion and freight vehicle traffic in urban cores, which offer cultural value and touristic attractions in the forms of historical sites, buildings, and infrastructure. The resident life, traffic safety, shopping environment and cultural site preservation is improved with fewer large freight vehicles in the city, as the result of consolidation [27] [9] [29]. Having the additional transshipment point in the vicinity of the city center offers the guarantee of an available and secure unloading area close to the service area. Micro-consolidation practices typically take place in city centers, where the competition for limited curbside space is heightened [21]. Reduced parking needs eventually lead to lower unauthorized parking and therefore, lower parking tickets/fees paid for by freight companies. In 2019, the amount of fines paid by UPS decreased from 2018; the company spokesperson explained the reason behind this achievement as the company's "innovative uses of pedal-assist bikes, including in New York City, and working together with micro-depot solutions in crowded inner-cities." [10].

Also, as the global awareness towards the environment and sustainability is on the rise, shifting to softer modes of transportation for the last leg of delivery can mitigate the adverse environmental impacts in the city by lowering the pollutant emissions. As mentioned before, cities are moving towards restrictive environmental policies (e.g. low emission zones in city centers) that force carrier companies to shift to greener operations; these urban freight facilities allow carrier companies to adapt to these policies better.

As with any implementation or a pilot test putting micro-consolidation practices in place within the existing urban freight system has its challenges. Maintaining high level of cooperation between the stakeholders through different stages of the implementation is very crucial. Urban freight systems, by nature, involve various private and public players and require inter-disciplinary planning. In case of micro-consolidation initiatives, operating a logistics hub inside the city core requires the agreement and collaboration of multiple stakeholders. While diversifying the activities overseen at the microhub increases flexibility and profitability, this necessitates as many stakeholders to cooperate. Another challenge is finding available logistic infrastructure to locate microhubs, especially in dense and urban areas where they are needed the most. Due to rising land values in cities, it is becoming more difficult to find affordable local depots from which last mile deliveries can be completed [5]. Additional transshipment points, microhubs, can add costs associated with loading/unloading and intermediate storage for operating freight companies.

Therefore, micro-consolidation initiatives often depend on governmental support and/or subsidies from various actors.

2.3. Micro-consolidation initiatives typology

The scope of this study covers consolidation practices at micro scale that necessitates a logistic hub, namely a microhub, with high proximity to urban centers from where goods destined to the surrounding service area are delivered and last mile services are realized possibly using soft transportation modes. The review covers the spectrum of micro-consolidation practices that can be applied by freight companies with a focus on last mile delivery operations near the final destination. Thus, urban consolidation centers (UCC), detailed in the previous section, fall out of the scope of this study. Micro-consolidation centers, microhubs, essentially adapt two distinct roles when handling the last leg of delivery: 1) collection and delivery point, where customers travel to the microhub to collect their purchased goods, or 2) transshipment point, where the operator freight company completes home deliveries.

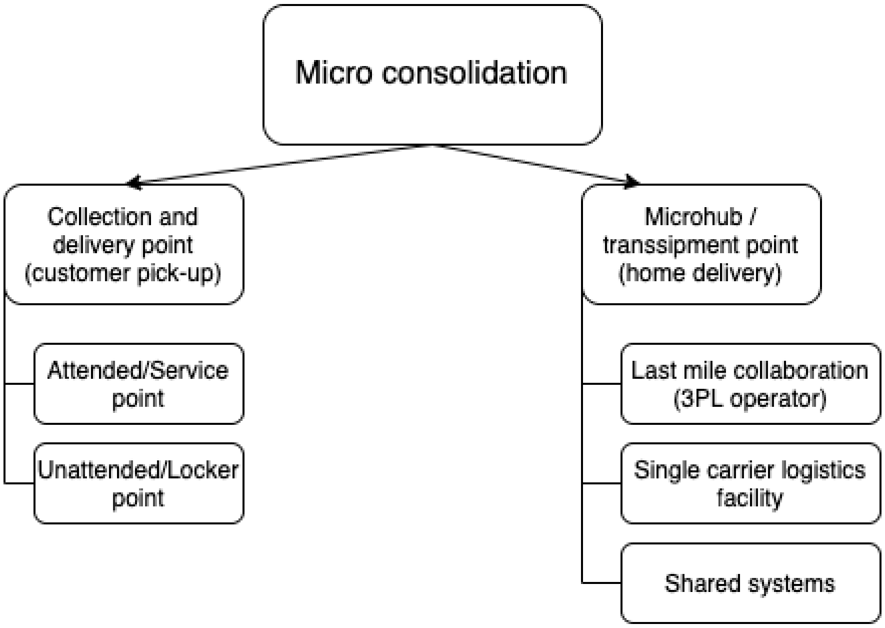


Figure 1: Typology of micro-consolidation practices

2.3.1. Collection and Delivery Points (CDP)

Microhubs that allow for customer pick-up and drop-offs are referred as collection and delivery points (CDP), and they have a great potential to eliminate the risk of failed deliveries. When customers demand their packages to be delivered to a CDP instead of their home addresses, the freight operations end once the carrier company deliver to the CDP. The customer completes the last mile of the supply chain by their choice of transportation mode. Customers can also drop-off packages to a CDP to return their purchased goods. A collection and delivery point (CDP) can either be attended/service point or unattended/locker point.

Attended CDPs are typically located at customer-facing facilities that have staff overseeing and assisting with customer pick-up operations on site. Store-based online retailers often locate attended CDPs at their physical stores and offer click and collect services (10); customers collect inventory at the store, and often make additional purchases. A study in the UK revealed that click and collect services are favorable for retailers, since 39% of the customers made an additional purchase when collecting their delivery in 2015 [30]. The same study states that a growing number of customers are choosing click and collect services to avoid delivery fees. Alternatively, unattended CDPs are locker banks that do not require available staff and can be situated in public areas, transit stations, gas stations, shopping malls, business offices and residential buildings [19]. Customers are expected to collect their parcels using a digitally and physically secured locker system that does allow for self-service and protection against theft. Digital traceability of the package is crucially important for both operators and customers in CDP practices.

Collection and delivery points, attended or unattended, can also be located in already existing businesses such as shops, grocery stores, convenience stores, petrol stations and post offices. The customers are offered a list of alternative delivery addresses from which they can choose to collect their packages. These CDPs are open during the existing business' operation hours, while they use valuable retail space, and possibly staff hours to manage CDP operations [19]. In return, existing store owners expect to benefit from increased customer foot traffic and time spent at their store. These CDP partnerships are typically exclusive and operated by only one carrier. These single-carrier CDPs, can also be interpreted as strategic partnerships between indirect competitors (freight companies and retailers, convenience stores etc.) against their other rivals in their industry [31]. The motivation for the existing store owners is to follow their competitors and ramp up their ecommerce business. Companies that have been traditionally operating with the focus on offline channels are working to increase their sales volumes online, but still want it to grow together with their offline sales. Partnerships with carrier companies such as Amazon, UPS etc. bring online shoppers to the store, where they can potentially be drawn into the hosting business' omnichannel sales strategy. UPS and FedEx partnered with drugstores like Walgreens and CVS, other companies like Walmart, Office Depot, Staples Dollar General, and select grocery stores like Albertsons, Kroger, Fred Meyer, Jewel-Osco, Randalls, Safeway, Shaws, StarMarket, and Vons [32]. For store owners, joining a carrier company's CDP network may not only help drive traffic to the store but also provide customers with the option to consolidate their trips with shopping at the store for their needs instead of the competitor, and also seaming the online and offline shopping experience. Of customers who use services that have a 'buy online pick up in store' component, 30-40% are likely to make additional purchases at the store [33]. Amazon operates a network of its Amazon Lockers/Hubs in 900 U.S. cities, located in grocery stores, banks, convenience stores, dedicated Amazon pick-up stores (Amazon Go, Amazon Hub+), or in apartment buildings by the residents' request. Apartment lockers are only available to its residents free of charge, not open to the public, but accepts both Amazon and non-Amazon packages [34]. These solutions help Amazon maintain its reliable and competitively fast delivery services.

2.3.2. Transshipment Points

Delivery options, especially home delivery, are very important to online shoppers and their decision-making mechanisms. A survey study found that 50% of online shoppers stated that they decided not to purchase a product due to unsatisfactory delivery services offered [35]. CDP strategy could be promising, but its application depends on customers' willingness to complete the last mile. Additionally, even though carrier companies can reduce vehicle miles traveled and emissions by using CDPs; some of these savings are actually eliminated by additional customer trips to collect packages depending on the choice of transportation mode. Microhubs that can be facilitated as transshipment points where delivered packages are deconsolidated, sorted, consolidated and distributed. The microhubs that allow for home deliveries can be divided in three groups; shared systems, last-mile collaboration, and private systems.

2.3.2.1. Shared systems

Carrier companies experience heightened competition in their industry, but they may have a mutual interest in opportunities in consolidating shipments through shared resources. The sharing of resources naturally results in increased efficiencies; package consolidation occurs within and between each carrier company's shipments. Thompson et al. used a hypothetical urban distribution system to estimate the performance of collaboration and found that savings of approximately 70% in travel distance and 25 to 50% in the number of vehicles required can be achieved by using a collaborative distribution network [36].

Logistic Hotels

To operate last mile deliveries using e-bikes, a physical infrastructure/platform that allows for the mode shift from heavy freight vehicles to nimbler and smaller e-bikes is needed. Logistics depots in central urban areas are scarce and increasingly high in demand. Municipalities work with industrial partners to create multi-use shared facilities that are called logistic hotels. Paris municipality introduced logistic hotels to reduce freight vehicle miles traveled in the city center, especially for the last mile, and also reduce emissions by encouraging the use of soft transportation modes such as biking [5] [37]. Logistic hotels are multi-story urban facilities that vertically mix different uses, such as office space, retail shops, and small businesses [38]. These projects are government supported, and they receive better public feedbacks when multiple transportation modes are available at the site, such as areas served by railways and/or waterways. The delivery operations can be managed by a single carrier or multiple carriers. Logistic hotels allow for upstream consolidation, building sharing and downstream consolidation for the last mile delivery [38]. Beaugrenelle logistic hotel, which was repurposed from a parking lot, is a multi-use, multi-story urban warehouse located in a very dense and commercial urban area to limit logistics sprawl in Paris [37]. The facility, rented by a local carrier company Chronopost, is reported to contribute emission savings of 50.4% CO_2; 52.4% PM; 47.8% SO2; 34.3% CO and 34.7% HO; as well as a 52% reduction in VMT [37].

Improved staging areas

Consolidation process necessitate a designated area for carrier companies to sort and deconsolidate their shipments to smaller delivery vehicles. Improved staging areas are on-site and off-street loading/unloading areas implemented at/near buildings that regularly receive freight. In urban areas where the competition for limited curb space is heightened, the lack of parking space and/or loading facilities may require the use of common staging areas. The common spaces for loading/unloading activities and transshipments, informal microhubs, can be facilitated at on street areas such as designated curb spaces, public or private parking lots or empty lots. When improved staging areas are formally designated, they are referred as ‘shared drop zones’ [5], ‘proximity logistics spaces’ [39] or ‘nearby delivery areas’ [40] [21] [23] (espace de livraison de proximité (ELP) in French) in the reviewed literature. Nearby delivery areas are reserved for freight carrier company vehicles and act as urban transshipment platforms, possibly with dedicated staff to assist in the dispatching of shipments and completing the last mile. Delivery vehicles carrying goods destined for the nearby residents and shops can use the shared drop zone to load/unload, organize packages and potentially shift to soft transportation modes for the last mile. Securing the necessary space and avoiding possible conflicts with nearby residents are the common challenges to implement these facilities [9].

In France, urban consolidation practices were adopted earlier than other European countries, starting in 1960s. These facilities, many of which are still operational to date, are nearby delivery areas located in many French cities such as Paris, Bordeaux and Rouen. According to Verlinde et al., offering dedicated loading/unloading spaces available for carrier companies, without the need of rerouting, decreased the freight vehicle road occupancy drastically [23]. In 2006, 700.000 deliveries were carried out this way resulting in a total reduction of 660.000 km of diesel vehicle mileage [23]. Proximity logistics space in Bordeaux is a collaboration between freight companies, the Chamber of Commerce of Bordeaux and the Bordeaux metropolitan authority [27]. The microhub operations started in June 2003 as a public initiative and remained as such until in 2005, when a French green last mile transportation carrier company, La Petite Reine, became the private operator [40].

Microhub operations that use shared systems rely heavily on mutual trust and collaboration between stakeholders. Governmental support is often present and needed (also as a mediator) in projects where logistic companies share space with other users and/or competitors. According to Diziain et al., private companies in France are not willing to invest in microhub projects presented above without the support of public authorities. Generally, governmental support is highly favored and common in micro-consolidation projects in Europe, both in forms of funding and planning. As online shopping becomes the new norm and the demand for home delivery increase, public authorities in Europe are working to prevent repetitive and redundant logistic facilities and operations to limit the logistics sprawl [38].

2.3.2.2. Last Mile Collaboration

The primary objective to all micro-consolidation practices is to better manage last mile operations. Large-scale freight companies, online retailers that offer home deliveries, or a group of customers (i.e. receivers, mostly shop owners) can contract 3rd party logistics (3PL) companies and delegate them to complete home deliveries. The 3PL companies act as ‘carrier’s carrier’ and are usually regional last mile delivery companies focusing on green transportation modes, possibly with electrified fleets.

Binnenstadservice (BSS), a regional carrier company, started business and received governmental subsidsidies in the establishment phase in April 2008 in the Dutch city of Nijmegen. [29]. The microhub is located within 1.5 km from the city center and adopts a receiver-led consolidation approach. Shop owners who receive shipments regularly, ask Binnenstadservice to receive, store and deliver them at a given time they decide. Van Rooijen et al. examined the local impacts of BSS and reported that it decreased the number of trucks and truck miles traveled in the city center. They also reported that the number of BSS stores and clients increased, the truck miles traveled continued to decrease. In addition, residents faced less inconvenience caused by freight transport operating in urban centers. The inconvenience for residents was measured as the number of loading/unloading activities that each resident experienced within 100 meters of their home [29]. Similarly, an association of retail shop owners implemented a receiver-led consolidation center in Yokohama, Japan, following a pilot project with financial support by the municipality [41]. The Motomachi Shopping Street Association manages and financially supports the microhub and asks carriers to deliver packages destined to Motomachi Street to the microhub and to pay the neutral 3PL carrier to complete the delivery using low emission (compressed natural gas) vehicles. Taniguchi et. al. reported that the number of trucks decreased from 100 vehicles operated by 11 companies to 29 vehicles operated by 1 company in 10 days [41] [42].

As mentioned before, cities in Europe and all over the world are implementing air pollution restrictions, and more businesses are encouraged to use green urban freight delivery systems, which are typically offered by 3PL companies. Gnewt Cargo in London uses a network of microhubs to complete deliveries to its clients such as Hermes, TNT, and other retailers nearby. During off-hours, client company’s trucks transfer packages destined to their customers in the city to their depot (if central enough) or Gnewt Cargo’s microhubs, some of which are shared by multiple clients [43]. The report prepared for the Greater London Authority stated that as a result of this practice, CO_2 emissions decreased by 88 percent per parcel, and the total distance traveled for all vehicles in London decreased by 52 percent per parcel [44].

2.3.2.3. Private systems

Businesses may choose to implement a completely private operational model to integrate microhubs into their logistics operations [26]. Single carrier microhubs are typically private company initiatives that do not require collaboration but also do not allow for multi-carrier consolidation. These microhubs act as additional transshipment platforms in freight company's existing and exclusive delivery network and can be structured as stable or mobile.

A mobile microhub can be a bus, truck (trailer), barge or a tram that circles or is stationed during the day in the city and connects to low emission last mile delivery options. TNT Express pilot tested its innovative mobile depot concept in Brussels, an area with a high density of small shipment deliveries, for three months in 2013 [26] [45]. The mobile depot was a trailer outfitted with a loading dock, a small warehousing facility, and an office. TNT Mobile depot transported consolidated inner-city deliveries during off-hours and was towed to a central location on the city, from where packages were distributed using electrically assisted or human-powered vehicles in a cyclic fashion. Verlinde et. al. studied this pilot test and found a significant drop in emissions of pollutants and the number of diesel kilometers [46]. Similar examples of mobile city hubs include a private green delivery service provider in Paris, Vert Chez Vous, that used a barge on the River Seine as a mobile city depot [27] [47]. Mercedes-Benz created a prototype van named 'Robovan' that can host eight small delivery robot vehicles. The van is loaded with delivery robots carrying packages destined to the service area and is parked to a central location. The manufacturers claim that the delivery robots will complete 400 packages in one workday [48].

Examples of single carrier microhubs are typically e-bike pilot tests conducted by large freight companies such as Amazon, UPS and DHL. These projects are not supported by public agencies but approved and encouraged. For example, New York City Department of Transportation (NYCDOT) announced that Amazon, UPS and DHL will be allowed to park e-bikes in commercial vehicle loading zones, and are the first participants in a pilot program focused on reducing congestion south of Manhattan's 60th Street [49] [50]. E-bikes or cargo bikes are piloted in other cities such as Seattle and Miami. The City of Miami has partnered with shipping company DHL

Express and mobility logistics hub Reef Technology to pilot four low-powered electric-assist e-cargo bikes that will be used for deliveries across the city [51]. Cargo containers/trailers for e-bikes will be carried by DHL trucks to the microhub, from where the same containers are loaded on the e-bikes and complete last-mile deliveries during the day. In Miami, the microhub operations coupled with the use of e-bikes are expected to reduce CO_2 emissions by 101,000 kg every year, which is also aligns which DHL's sustainability goals [51].

Private systems do not directly require government cooperation, but they need public support to approve their initiatives. Delivery operations take place in public areas and are in frequent interaction with the society. Therefore, cooperation between private companies and public agencies is key ensure delivery activities are beneficial for both private companies and the society as a whole.

Chapter 3. Methodology

3.1. Objectives

To provide sustainable city logistics solutions and reduce air pollution, early implementations of micro-consolidation practices are being tested and cities need to understand what the implications are. The goal of this study is to identify potential benefits and costs of micro-consolidation practices in business-to-consumer (B2C) urban delivery systems and the necessary conditions under which these can be successfully implemented to improve urban freight efficiencies and reduce emissions. The scope of this study covers only residential home package deliveries and the use of microhubs as transshipment points.

3.2. Methods

To effectively assess and compare different city logistics solutions to implement, this study made use of simulation tools to demonstrate 'what-if' scenarios. The approach covered a realistic assessment of the current situation and proposed scenarios using different mixes of vehicle types for urban freight deliveries. Real life implementations of these solutions can be intractable since they require high costs and coordination. Conversely, simulation modeling is a feasible, flexible and scalable approach which is used to generate a multitude of virtual cases and collect sufficient data for comparative analysis [52].

The modeling consisted of simulation of urban freight deliveries using vans, cars, or electrically assisted cargo-bikes with a network of microhubs. Simulation is an abstraction of reality through assumptions made in the modeling process and produce results that have meaningful practical implications. To explore the effect of customer density and the delivery vehicle type, a 3x3 factorial simulation experiment was designed.

Three scenarios were modeled to represent different delivery systems using different vehicle types at different capacities. The customer demand was defined as the number of customers that demand a package delivery on a given day. Multiple packages can be delivered to a customer address.

In the baseline scenario, the customer demand was shared between only internal combustion engine vehicles vans and cars, depicting the traditional delivery systems that are currently in place. It was assumed that vans delivered to 70 % of customers, while the remaining 30% was delivered by cars. In the only e-bike scenario, all customer delivery demand is met using a network of microhubs, and e-bikes located at each microhub. The mixed scenario showed the transition state between the baseline and only e-bike scenario, shifting from traditional delivery vehicles to a fully electric e-bike fleet. In the mixed scenario the customer delivery demand is shared between vans, cars, and e-bikes, delivering to 50 %, 20 %, and 30 % of customers respectively. To observe the effect of customer density, three different levels of customer demand were tested: 200, 500, and 100. Since the study area was not changed throughout the scenarios, the number of customer addresses can also be interpreted as the customer density. The size of the microhub network is set to be 0, 2, and 4 microhubs for the baseline, mixed, and only e-bike scenarios, due to the different levels of customer demand to be satisfied by the microhub network. Table 1 shows the simulation scenarios with delivery vehicles distributions and microhub network sizes.

Table 1: Simulated scenarios

Scenario	**Delivery vehicle distribution**	**Number of microhubs in the network**
Baseline	70 % vans, 30 % cars	0
Mixed	50 % vans, 20 % cars, 30 % e-bikes	2
E-bike	100 % e-bikes	4

Urban freight deliveries were simulated by creating routes for delivery agents to satisfy the customer delivery demand. This is done in five steps: generation of customer demand, selecting candidate microhub locations, facility selection and customer allocation for microhub routes, computation of vehicle routes, and discrete event simulation of deliveries. In the final section of this chapter, the performance metrics used to assess the compare the scenarios are explained.

3.2.1. Study Area and Generation of Customer Demand

The study area for this study covers two residential neighborhoods in Seattle, WA, as seen in figure 2 below. The two zip codes from where the customer demand was sampled from were 98109 and 98119 covering Westlake and Queen Anne neighborhoods. These neighborhoods were selected since they had high residential densities.

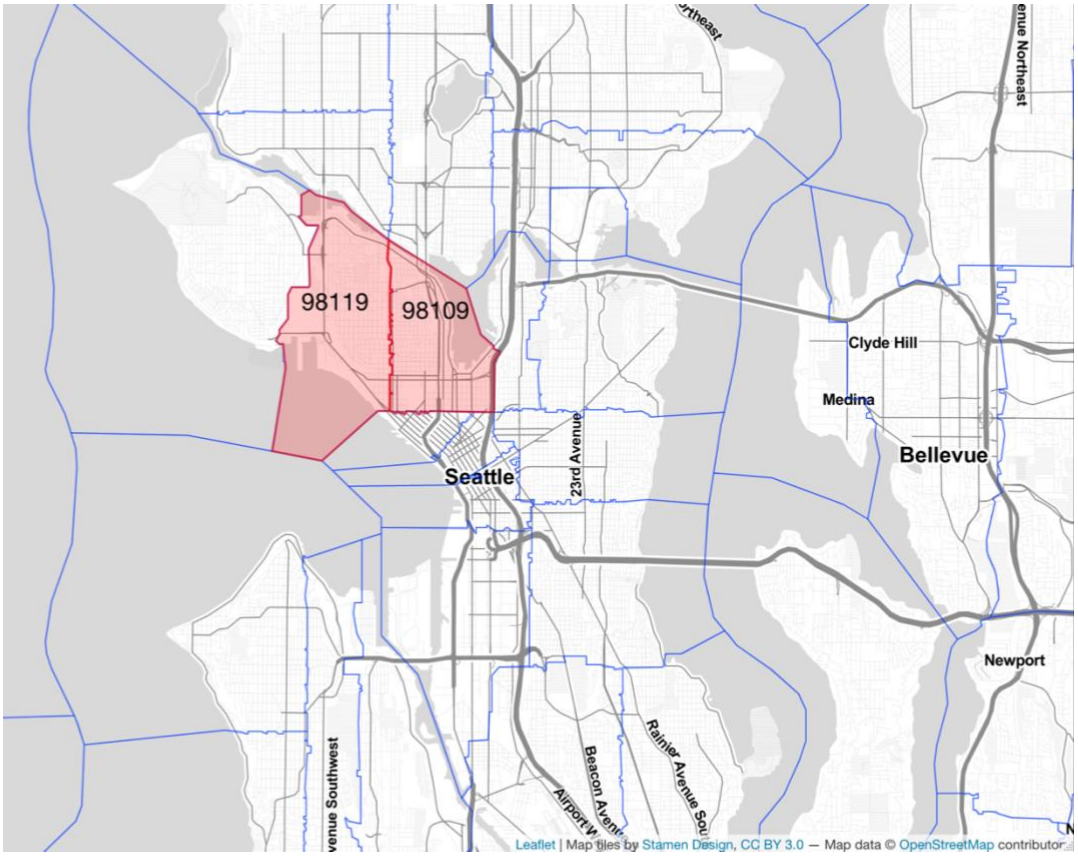


Figure 2: The study area and zip-codes

To create a delivery simulation model, first a pool of customers who are demanding package deliveries was created within the study area. Publicly available 'Address points in King County' geospatial dataset was used to obtain the customer locations in terms of geolocated points. The data set was filtered to include only 'Single Family', 'Multi Family', 'Gated w/ Building', 'Seasonal Home' site types defined by King County. All commercial site types were excluded. The simulation framework included three different levels of customer demand at 200, 500, and 1000 customer addresses. For each simulation scenario, and delivery vehicle type the customer addresses were randomly sampled from the address points dataset with respect to the customer demand and delivery vehicle distribution. As mentioned before, the customer demand was equal to the number of customer addresses that need home delivery on a given day, and multiple packages can be delivered to a customer. Thus, Poisson distribution with mean 1.5 packages was assumed to represent the distribution of number of packaged per customer. All packages were assumed to have a standard weight and size to reduce the complexity of the methodology.

The publicly available ‘Block Faces in Seattle’ dataset from Seattle GeoData was used to extract the count of spaces allocated for various loading activities including commercial vehicle loading zone (CVLZ), Load/Unload, and Truck Load. In this dataset, each row represented a block face and included block elements such as peak hour restrictions, parking categories, and restricted parking zones [53]. The number of loading zones within the vicinity of a customer address is calculated as the number of loading zones located on block faces within 100 m radius buffer zone from the customer address.

3.2.2. Candidate Microhub Locations

To find suitable candidate microhub locations in the study area, all customer addresses in the study area were partitioned using k-means clustering method. The optimal value of number of clusters, k, is found using the elbow method.

The clustering model was built iterating values of k from 1 to 10, considering the calculated values of: distortion and inertia. Distortion, also known as within cluster sum of square errors, is the average of the Euclidean squared distance between the centroid and a data point. Inertia, a method to measure the cluster quality, indicates how spread out the points within a cluster are. Inertia is calculated as the sum of squared distances of points to their closest cluster center [54]. The optimal number of clusters, k, is found to be 7 where the change in distortion or inertia was minimized, and the derivative was the lowest. Figures 3 and 4 shows distortion and inertia plots with varying numbers of clusters.

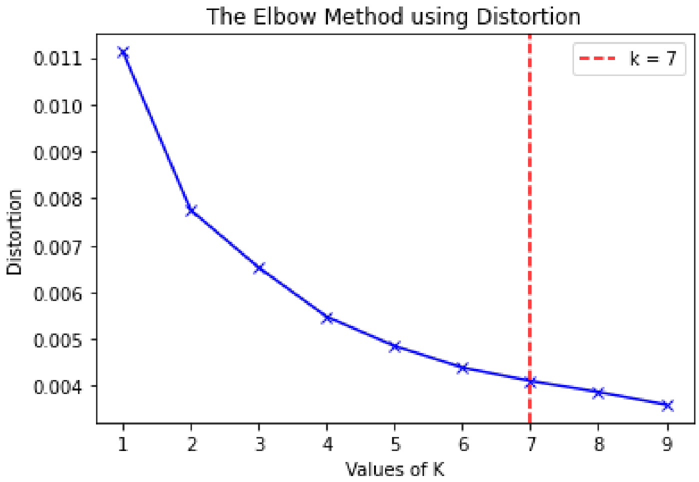


Figure 3: Elbow method for clustering using distortion

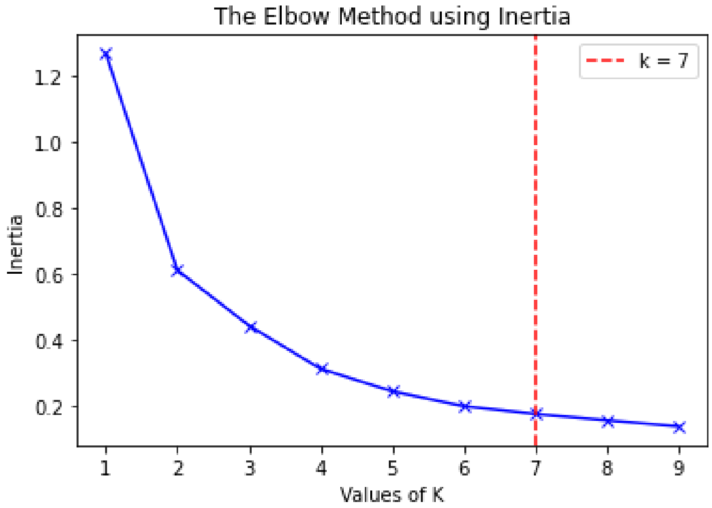


Figure 4: Elbow method for clustering using inertia

After the customer addresses were grouped in 7 clusters, the candidate microhub locations were set as the centroid of each cluster. Figure 5 shows the location of customer addresses and the candidate microhub locations at the cluster centroids.

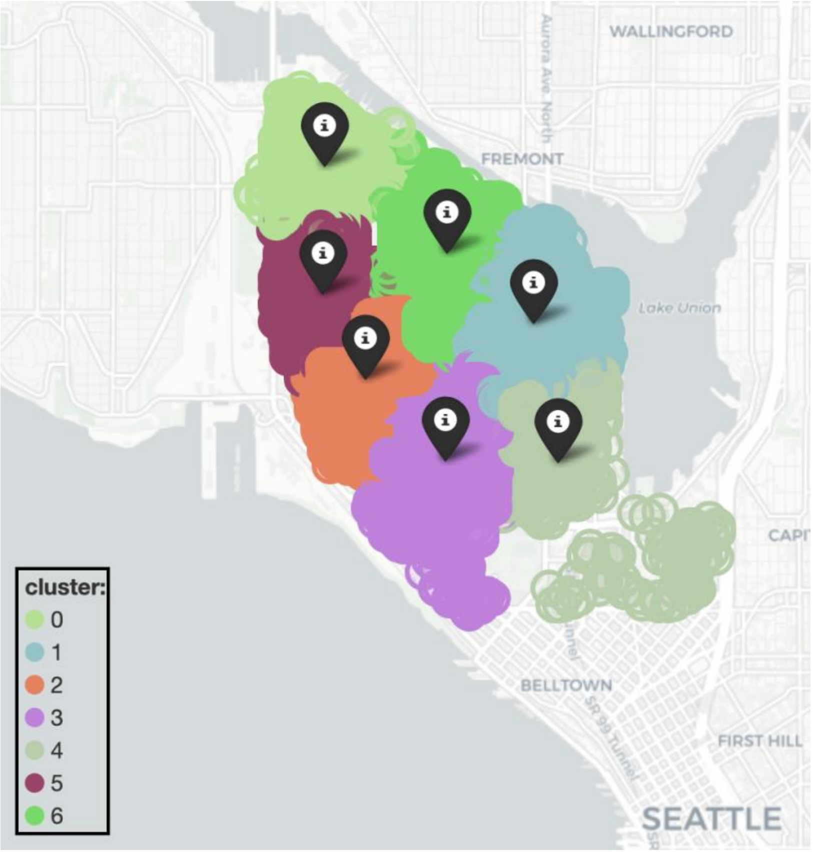


Figure 5: Clustered customer addresses and candidate microhub locations

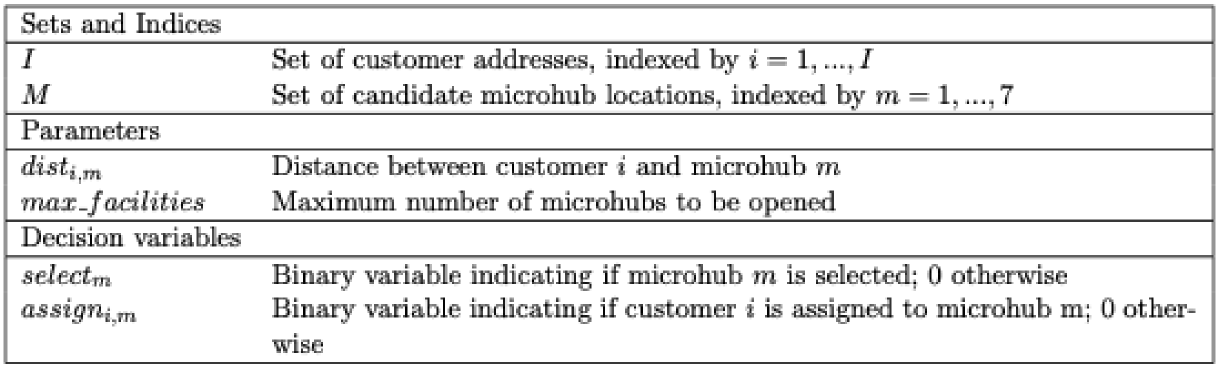
3.2.3. Facility selection and customer allocation problem

In simulation scenarios where deliveries were completed by e-bikes, in mixed and only e-bike scenarios, a network of microhubs was created. As mentioned before, there were 2 and 4 microhubs in the network in mixed and only e-bike scenario, respectively. Thus, this step is skipped for the baseline scenario simulation runs.

A mixed-integer optimization model was formulated to minimize the total distance between the customers and their assigned facility. The optimization model was used to select the microhub locations from the pool of candidate locations, and to assign each customer to the closest microhub facility. There were seven candidate microhub locations considered, where each was indexed by

m. Customer addresses that were randomly sampled from the address points dataset, were indexed by i. The decision variable $assign_{i,m}$ was a binary variable, which was equal to 1 if assignment of microhub m to customer i; 0 otherwise. Another binary decision variable $select_m$ was used to indicate if microhub m was selected to open, which was equal to 1 was selected; 0 otherwise. The distances between each microhub m, and customer was calculated using Manhattan distances, which is generally assumed for distances in urban grid networks. The maximum number of microhubs to be selected depends on the simulation scenario, equal to 2 and 4 in mixed and only e-bike scenario, respectively. The sets, decision variables, and parameters are summarized in table 2 below.

Table 2: Facility selection and customer assignment problem



Sets and Indices	
I	Set of customer addresses, indexed by $i = 1, ..., I$
M	Set of candidate microhub locations, indexed by $m = 1, ..., 7$
Parameters	
$dist_{i,m}$	Distance between customer i and microhub m
$max\_facilities$	Maximum number of microhubs to be opened
Decision variables	
$select_m$	Binary variable indicating if microhub m is selected; 0 otherwise
$assign_{i,m}$	Binary variable indicating if customer i is assigned to microhub m; 0 otherwise

The optimization problem in (1) – (6) was formulated as a mixed-integer programing model.

Minimize:

$$\sum_{i,m} dist_{i,m} * assign_{i,m} \tag{1}$$

Subject to:

$$\sum_{m=1}^{7} select_m \leq max\_facilities \tag{2}$$

$$assign_{i,m} \leq select_{i,m} \qquad \forall m \tag{3}$$

$$\sum_{i,m} assign_{i,m} = 1 \tag{4}$$

$$assign_{i,m} \in 0,1 \qquad \forall i,j \tag{5}$$

$$select_m \in 0,1 \qquad \forall m \tag{6}$$

The objective function (1) characterized the sum of all distances between customer addresses and their assigned microhub facility. Constraint (2) stated that the number of microhubs opened does not exceed the maximum limit. Constraint (3) ensured that each customer I can only be assigned to microhub m if it is selected. Constraint (4) required that every customer is assigned to exactly one microhub. Constraint (5) and (6) enforced binary values for customer assignment and microhub selection decision variables.

The model provided in (1) – (6) determined an optimal customer assignment and microhub facility selection that minimizes the total distance between each customer and their assigned facility. The optimization problem is solved using the commercial Gurobi solver [55].

3.2.4. Vehicle Routing Problem

The Capacitated Vehicle Routing Problem (CVRP) was applied to find optimal routes that minimized the total distance traveled for multiple vehicles with limited package carrying capacity visiting a set of customer addresses. The problem was solved separately for each delivery vehicle type, considering delivery vehicles’ different package carrying capacity, depot location, and number of packages to deliver. The customer demand was the number of addresses the vehicle must visit, and the number of packages to be delivered was sampled from a poison distribution at each customer address. Every customer could be visited exactly once, and the total number of packages to be delivered on a route could not exceed the capacity of the vehicle.

Every delivery route must start and finish their route at the depot location. For vans, the depot location was assumed to be a distribution center in South Seattle, currently operated by a private carrier company (UPS). (The address: 4455 7th Ave S, Seattle, WA 98108). Car deliveries were assumed to be completed by independent contractor drivers, and the depot location was assumed to be a distribution center that serves independent contractors in South Seattle (Amazon Flex/Prime Distribution Center). (The address: 6705 E Marginal Way S, Seattle, WA 98108). For e-bike routes, the CVRP was solved at each selected microhub location, serving the customers assigned by the optimization problem, explained in the previous section. The CVRP was solved for each microhub location, according to the number of customers assigned to that facility.

The CVRP was applied to minimize the total distance traveled where all customer demand is met. The set of delivery vehicles of the same type available at a depot location was indexed by k. The nodes to be visited in a route were indexed by i and j. The first and last node was always the depot location in a route. To calculate the optimal routes, the distance matrix was constructed calculating the Manhattan distance between each node. The parameter $d_{i,j}$ described the distance from node i to node j. The package demand at each node j was sampled from a poisson distribution with mean 1.5 at the demand generation step earlier. The package carrying capacity, Q, was assumed to be 120, 40, and 40 for vans, cars, and e-bikes respectively. The binary decision variable x_{ijk} was equal to 1 if the arc from node i to node j was in the optimal route, and was driven by vehicle k. The sets, decision variables, and parameters are summarized in table 3 below.

Table 3: Capacitated vehicle routing problem

Sets and Indices	
I	Set of nodes, indexed by $i = 1, \ldots, N$
J	Set of nodes, indexed by $j = 1, \ldots, N$
K	Set of delivery vehicles, indexed by $k = 1, \ldots, K$
Parameters	
$dist_{i,j}$	Distance between node i and node j
q_j	The package demand at node j
Q	Package carrying capacity of the delivery vehicle (same for all k)
Decision variable	
$x_{i,j,k}$	Binary variable indicating if the arc from node i to node j is in the optimal route and is driven by vehicle k; 0 otherwise

The CVRP in (7) – (12) was formulated as a linear integer programming model.

Minimize:

$$\sum_{k=1}^{K}\sum_{i=1}^{N}\sum_{j=1}^{N} dist_{i,j} * x_{i,j,k} \tag{7}$$

Subject to:

$$\sum_{i=1}^{N} x_{i,j,k} = \sum_{i=1}^{N} x_{j,i,k} \qquad \forall j \in 1, \ldots, N, k \in 1, \ldots, K \tag{8}$$

$$\sum_{k=1}^{K}\sum_{i=1}^{N} x_{i,j,k} = 1 \qquad \forall j \in 2, \ldots, N \tag{9}$$

$$\sum_{j=2} x_{1,j.k} = 1 \qquad \forall k \in 1, \ldots, K \tag{10}$$

$$\sum_{i=1}^{N}\sum_{j=2}^{N} q_j x_{i,j,k} \leq Q \qquad \forall k \in 1, \ldots, K \tag{11}$$

$$x_{i,j,k} \in 0, 1 \qquad \forall i, j, k \tag{12}$$

The objective function (7) represented the sum of vehicle distance traveled by all vehicles. A route was calculated for each vehicle. Constraint (8) required that the number of times a vehicle entered a node is equal to the number of times it leaves that node. Constraint (9), together with constraint (8) ensured that every node is entered once and is left by the same vehicle. Constraint (10) stated that every vehicle must leave the depot, and together with constraint (1) every vehicle was ensured to return to the depot. The capacity constraint (11) prevented the total package delivery demand assigned to a vehicle route to exceed the package carrying capacity of the vehicle. Constraint (12) enforced binary values for the decision variable.

The model provided in (7) – (12) was used to compute optimal routes for multiple vehicles, and was employed separately for different vehicle types, and respective depot locations. The optimization problem is solved using Google OR Tools Capacitated Vehicle Routing Problem module [56]. The VRP outputs the number of vehicles needed to complete the route, and the delivery schedule. The delivery schedules are created for individual routes and includes: 1) the nodes (customer addresses) in order, 2) the number of packages to deliver at the node, 3) the driving distance to the next node, and 4) the number of loading spaces available within 100 m radius. The number of packages to deliver at the node and the number of loading spaces within 100 m radius was determined for each customer address in the generation of demand step earlier. The figure 6 below summarizes all the steps completed to produce the delivery schedule for each route.

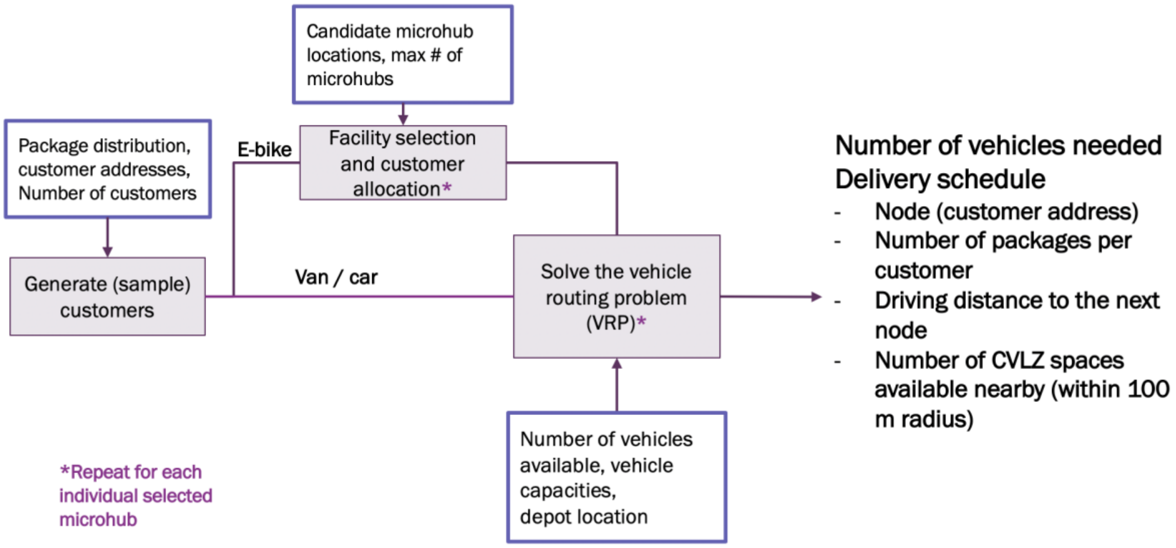


Figure 6: Flow diagram showing methods used to create delivery schedules

3.2.5. Simulation of Deliveries

To calculate the time spent driving, parking, and delivering; all delivery schedules were simulated using discrete event simulation coded using SimPy library in Python programming language. The delivery vehicles all followed the delivery process outlined in figure 7 below.

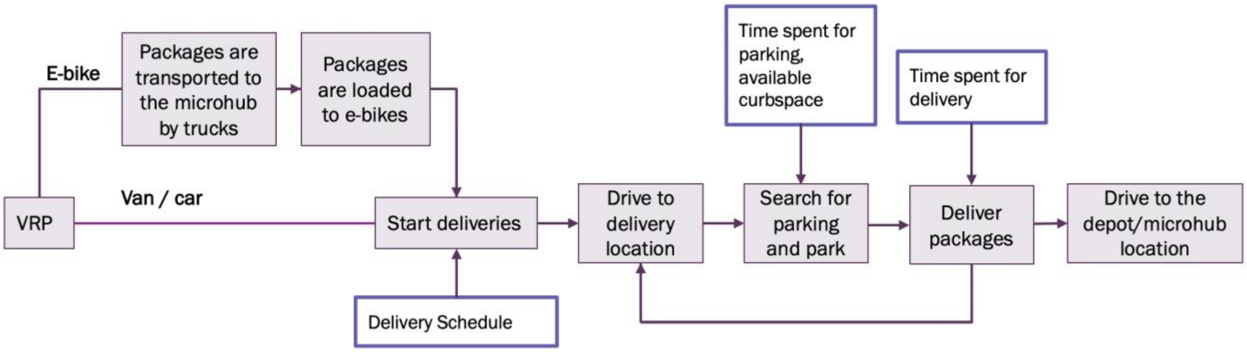


Figure 7: Flow diagram showing components of discrete event simulation

For e-bike routes, packages were first transported to the microhubs by trucks and loaded on to e-bikes to complete the last mile deliveries. It was assumed that the traveling distance between the depot and a microhub was 15 miles, and the trip took 30 minutes. E-bikes were stocked up on packages at microhubs before they start their deliveries. For each node in the delivery schedule, the vehicle first drove to the customer location, then searched for parking and parked, and delivered packages to the customer. The time spent for each activity were calculated stochastically, sampling from a probability distribution depending on the delivery vehicle type, as shown in table 4. This loop was repeated until all nodes (customer addresses) were visited. All delivery routes start and end at the same depot location. Microhubs were the depot locations for e-bike routes.

Dalla Chiara and Goodchild analyzed the cruising for parking times for urban commercial vehicles using empirical delivery route data (cite). They found that adding one commercial vehicle loading zone (CVLZ) reduced trip time by 1.3-6.5 %. In this study, it was assumed that each load space reduced the time spent for parking by 3.9 %.

The table 4 shows the model inputs for all delivery vehicles.

Table 4: Model inputs for van, car, and e-bike

Inputs	Van	Car	E-bike
Vehicle capacity (# of packages)	120	40	40
Average speed (mph)	10	15	7
Parking time	Normal distribution mean = 2.3 min	Normal distribution mean = 2 min	Normal distribution mean = 30 s
CVLZ impact on parking time	- 3.9%	- 3.9%	- 3.9%
Delivery time	Exponential dist. mean = 2 min	Exponential dist. mean = 2 min	Exponential dist. mean = 2 min
Package load distribution	N/A	N/A	Normal distribution mean = 30 s
Package distribution	Poisson dist. mean = 1.5	Poisson dist. mean = 1.5	Poisson dist. mean = 1.5

The assumptions made for the simulation model are summarized below:

1. Only residential deliveries were simulated.
2. Distance matrix was calculated assuming Manhattan distance.
3. Failed deliveries were not considered, i.e. the delivery agents did not visit customers that failed to receive the packages.
4. Bikeability, or hilliness in the neighborhood was not considered for e-bike routes.
5. Package weight and size was assumed to be standard.
6. Node consolidation: If the next node (customer address) was closer than 100 m, drive and park functions were skipped. Time spent for walking was assumed to be negligible.
7. The suburban depot from where the packages were transported to the microhubs is assumed to be 15 miles away for every microhub location. The trip was assumed to take 30 minutes.

3.3. Performance Metrics

Three performance metrics were used to evaluate different scenarios: vehicle miles traveled per package delivered, tailpipe CO_2 emissions per package delivered, and average daily operational cost. All metrics were calculated for each simulation run and then averaged over 30 trials.

The vehicle miles traveled per package delivered metric was measured as the total vehicle miles traveled divided by the number of packages delivered. Both were direct outputs from the simulation model.

The VMT per package metric was then used to calculate the tailpipe emissions for each vehicle type. According to the U.S. Environmental Protection Agency (EPA), 8.887 kg CO_2 is emitted per each US gallon of gasoline. Diesel fuel creates about 10.180 kg CO_2 per gallon, which is approximately 15 % more than gasoline [57]. Tailpipe CO_2 emissions for vans and cars were calculated assuming the fuel economy is 12.0 and 25 mpg for diesel vans and cars respectively [58] [57]. The tailpipe CO_2 emissions per mile metrics were calculated by dividing the amount of CO_2 emissions per gallon was divided by fuel economy, as seen in table 5 below. For e-bikes, the CO_2 emissions were calculated considering the electricity consumption to charge the e-bike. In 2019, 136.985 kg of CO_2 were emitted per MWh of electricity produced in Washington state [59]. An e-bike requires 0.05 kWh of electricity from the grid to travel each mile [60]. Combining these values, tailpipe CO_2emissions from riding an e-bike was calculated as 0.0068 CO_2 kg per mile. All calculated values for tailpipe CO_2 emissions were given in table 5.

Table 5: Tailpipe CO_2 emission calculations

Vehicle Type	Tailpipe emissions CO_2 per fuel	Fuel economy	Tailpipe emissions CO_2 per mile (kg/mi)
Car	8.887 kg/gallon (gas)	25.0 mpg	0.355
Van	10.180 kg/gallon (diesel)	12.0 mpg	0.960
E-bike	0.136 g/Wh	0.05 kWh/mi	0.0068

The average daily operational costs were calculated depending on the vehicle type, vehicle miles traveled, and time spent to complete the deliveries. Tables 6 and 7 below show the calculations and parameters used for average daily operational cost calculations.

Table 6: Average daily cost calculations

Cost Type	**Calculation**
Fuel cost ($)	(Cost of fuel / Fuel economy) x VMT
Maintenance cost ($)	Vans and cars: Maintenance cost per mile x VMT E-bikes: Daily maintenance cost x Number of vehicles
Vehicle cost ($)	(Purchasing cost per vehicle / Average lifetime) x Number of vehicles
Labor cost ($)	Hourly wage of vehicle operator x Total operational time

Table 7: Cost parameters

	VAN		**CAR**		**EBIKE**	
Cost Type	**Value**	**Source**	**Value**	**Source**	**Value**	**Source**
Fuel cost	$\frac{3.532\ \$/\mathrm{gal}}{12\ mpg} = 0.29\ \$/\mathrm{mi}$	[61], [58]	$\frac{3.635\ \$/\mathrm{gal}}{25\ mpg} = 0.15\ \$/\mathrm{mi}$	[61], [57]	$0.0976 \frac{\$}{\mathrm{kWh}} * 0.05 \frac{\mathrm{kWh}}{\mathrm{mi}} = 0.00488 \frac{\$}{\mathrm{mi}}$	[62], [60]
Maintenance cost	$0.130 /mile	[63]	$0.09 /mile	[64]	$3.33/day	[60]
Vehicle cost	$\frac{\$\ 70000}{3600\ days} = 19.44\ \$/\mathrm{day}$	[26], [65]	$\frac{\$\ 38960}{2880\ days} = 13.52\ \$/\mathrm{day}$	[66], [65]	$\frac{\$\ 9000}{1825\ days} = 4.93\ \$/\mathrm{day}$	[60]
Labor Cost	$23.83/hour	[67]	$20/hour	[68]	$24	[69]

Chapter 4. Results and Discussion

The following section describes the results obtained from the simulation model with varying vehicle type mix (traditional, mixed, ebike), and customer demand. Nine different scenario configurations were evaluated using the performance metrics: vehicle miles traveled per package delivered, tailpipe CO_2 emissions per package delivered, and average daily operational cost. Appendix A shows the boxplots for each performance metric to visualize the differences between measurements between each configuration. Appendix B includes the results of paired t-tests conducted to determine if the mean differences between pairs of measurements are statistically significant or not for each performance metric.

4.1. Vehicle Miles Traveled per Package Delivered

Figure 8 below shows the vehicle miles traveled per package delivered for the nine simulation configurations. The three facets in the figure depicts the different customer demand levels at 200, 500, and 1000. Since the study area remains the same through all simulation configurations, the customer demand levels also represent the customer density in the service area.

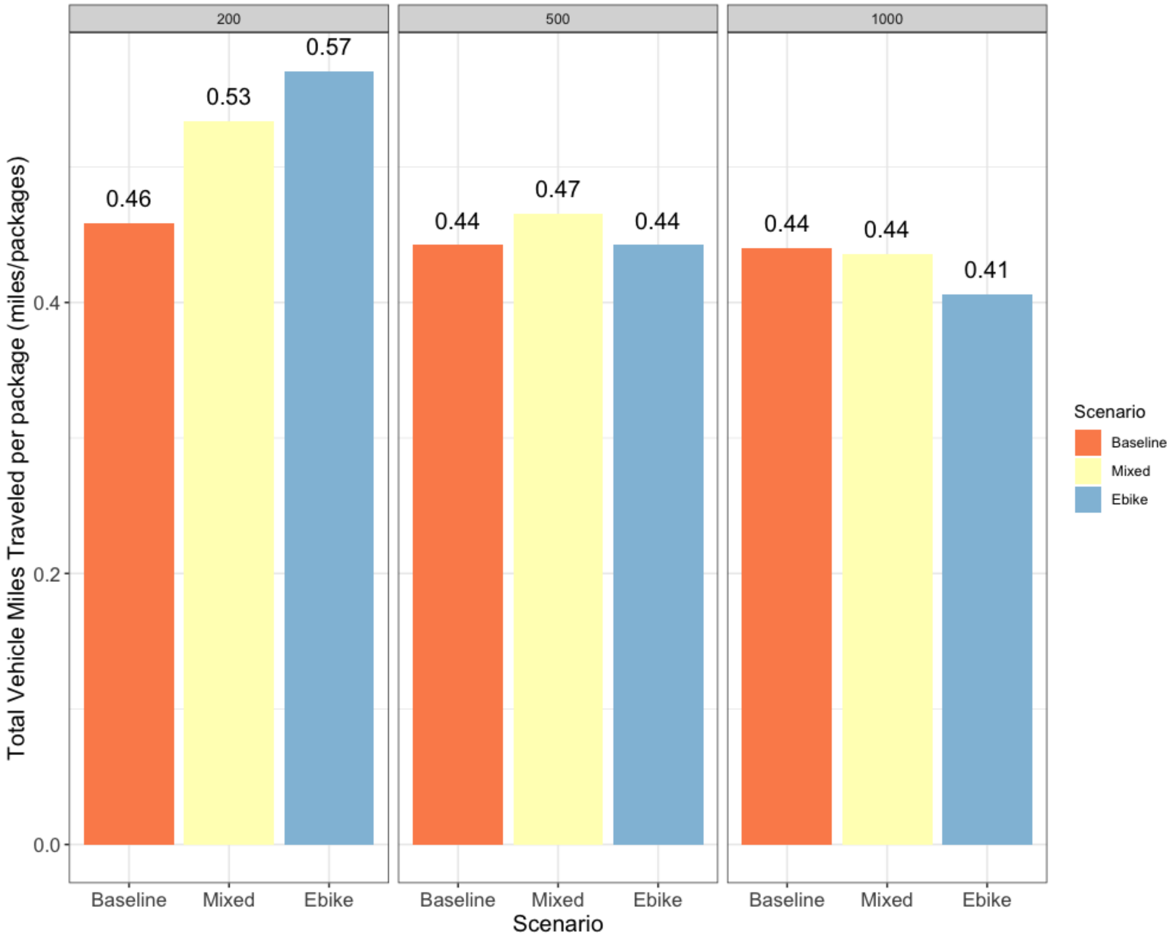


Figure 8: Vehicle miles traveled per package delivered at demand levels 200, 500, and 1000 under baseline, mixed, and e-bike only scenarios

For all scenarios, the vehicle miles traveled (VMT) per package decreases with increasing customer density, indicating that the vehicles had to travel less to deliver packages in denser service areas. In the e-bike only scenario, e-bikes traveled 0.57, 0.44, and 0.41 miles per package delivered under customer demand levels 200, 500, and 1000, respectively. The largest drop in VMT per package delivered with increasing customer density was observed in the only e-bike scenario; the VMT per package was 28 % less for customer demand level 1000, when compared to customer demand level 200.

In the mixed scenario, the delivery vehicles had to travel 0.53, 0.47, and 0.44 miles per package delivered under customer demand levels 200, 500, and 1000, respectively, showing a gradual decrease with increasing customer demand. In the baseline scenario, where the vehicle mix is comprised of vans and cars, the customer density did not have a significant impact on the VMT per package. Total VMT per package delivered was 0.46, 0.44, and 0.44 miles for customer demand levels 200, 500, and 1000, respectively, in the baseline scenario.

There are four microhubs operating in the e-bike only scenario, which means there are four trucks traveling to each of these microhubs carrying packages to be delivered by e-bike routes, even if they are partially loaded. When the number of packages to deliver is higher, the package carrying capacity of the trucks are utilized more efficiently that causes savings in VMT per package for the e-bike only scenario. Similarly, the VMT per package shows a decrease in the mixed scenario since truck trips traveling to the microhubs operate more efficiently at higher customer demand. This may be because the mixed scenario operates with two microhubs from which 20% of the package demand is delivered by e-bike routes and requires two truck trips to carry the packages to the microhubs. These results show that e-bike delivery operations perform better in high customer density service areas, where customers are located close to each other and the microhub. Thus, they should be implemented in urban areas where the population is densified and the demand for home deliveries is high. They are not a favorable solution to operate in low density rural areas since transshipping packages to the microhub as an additional stop does not provide any efficiencies in terms of VMT per package when the customer density is low.

The e-bike only scenario had the lowest VMT per package delivered at demand levels higher than 200, when compared with the other scenarios. At the highest customer demand level (1000), VMT per package delivered was 0.44, 0.44, and 0.41 for the baseline, mixed, and e-bike only scenarios, respectively. VMT per package delivered was 7.7% lower when only e-bikes were used, compared to the baseline scenario. On the contrary, VMT per package delivered was 23% higher at the lowest customer demand level (200) when only e-bikes were used, when compared to the baseline scenario. These results indicate that in dense urban areas, a network of microhubs and e-bike routes perform the best in terms of distance traveled, when compared with traditional delivery systems.

4.2. Tailpipe CO_2 emissions per Package Delivered

Figure 9 shows the tailpipe CO_2 emissions breakdown by vehicle type across different customer demand levels and scenarios. For each scenario, the tailpipe CO_2 emissions are calculated separately for different vehicle types to show the impact of vehicle type on carbon emissions. For example, in the baseline scenario under customer demand level 200, vans and cars emitted 0.28 kg and 0.06 kg tailpipe CO_2 per package to deliver 80 % and 20 % of the packages, respectively.

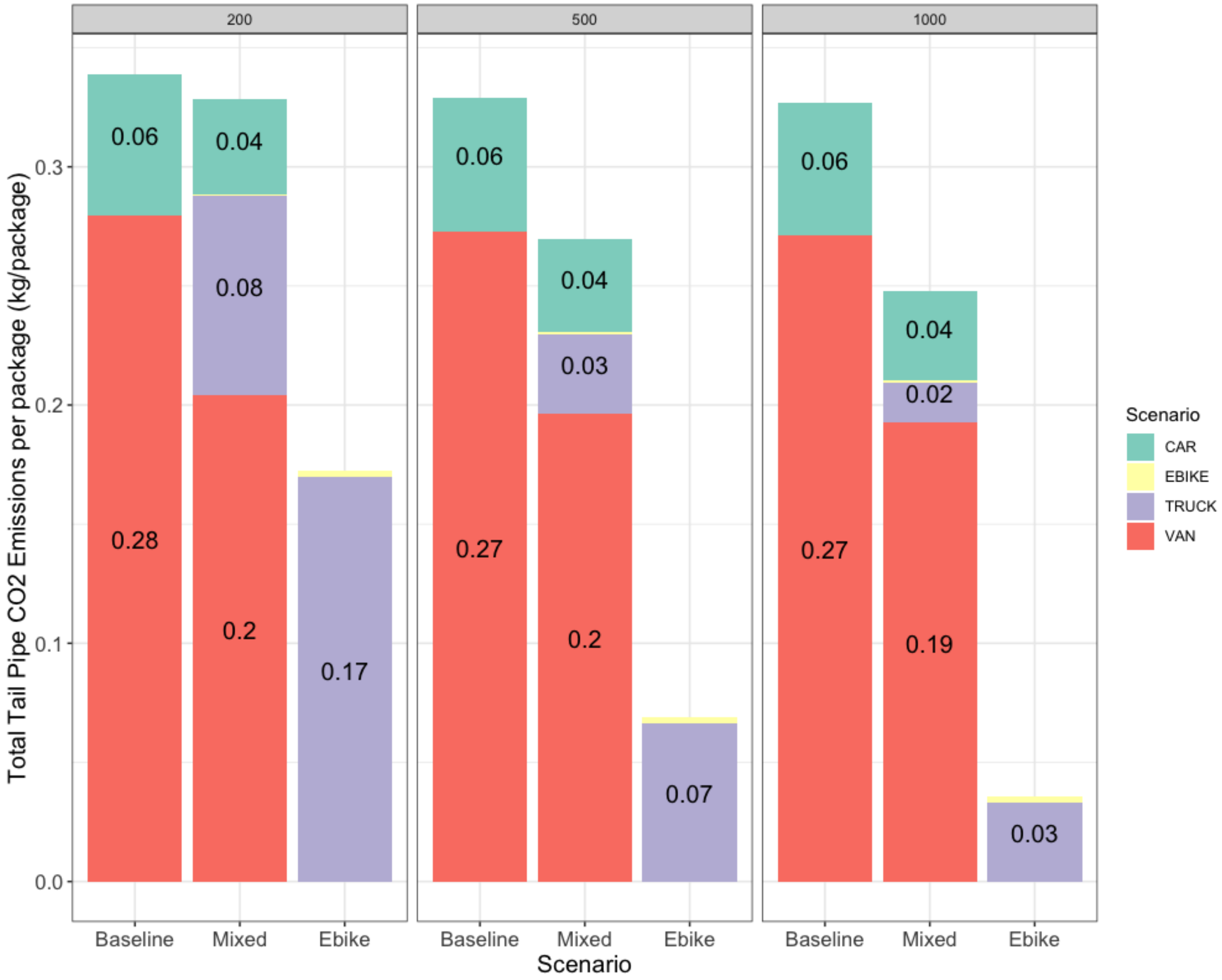


Figure 9: Tailpipe CO_2 emissions per package delivered at demand levels 200, 500, and 1000 under baseline, mixed, and e-bike only scenarios

The tailpipe CO_2 emissions per package delivered depended majorly on the scenario and the vehicle type mix. At all customer demand levels, the e-bike only scenario had the lowest tailpipe CO_2 emissions per package, when compared with the baseline and mixed scenarios. The truck trips carrying packages to the four microhubs to be delivered by e-bikes from the suburban depot constituted nearly all of tailpipe emissions in the e-bike only scenario. In the e-bike only scenario, the reduction in tailpipe CO_2 emissions increased with higher customer demand levels. The carbon savings in the e-bike only scenario when compared with the baseline scenario was 50 %, 78%, and

91% at customer demand levels 200, 500, and 1000, respectively. These results show that in high customer density areas, the e-bikes can drastically decrease carbon emissions when compared with traditional delivery systems.

Increasing the customer demand level did not create any carbon savings for vehicle types of van and car. In the baseline scenario, vans emitted 0.28, 0.27, and 0.27 kg tailpipe CO_2 emissions per package, whereas cars emitted 0.06, 0.06, and 0.06 kg tailpipe CO_2 emissions per package at demand levels 200, 500, and 1000. In the mixed scenario, vans emitted 0.20, 0.20, and 0.19 kg tailpipe CO_2 emissions per package, whereas cars emitted 0.04, 0.04, and 0.04 kg tailpipe CO_2 emissions per package at demand levels 200, 500, and 1000. Only the scenarios where e-bikes were used (mixed and e-bike only) demonstrated a reduction in carbon emissions with increasing customer demand. Tailpipe CO_2 emissions per package decrease as more e-bikes are assigned to deliveries and decrease even more with increased customer density. Internal combustion engine vehicles such as vans and cars emit drastically higher tailpipe CO_2 per package, when compared with e-bikes. These results show electrifying the delivery vehicle fleet can reduce carbon emissions drastically. For example, the trucks carrying packages were replaced by electric vans, the total tailpipe CO_2 emission per package could be nearly zero for the only e-bike scenario.

4.3. Average Daily Cost per Package

Table 8 shows the breakdown of average total daily cost per package delivered for different demand levels and scenarios. For every simulation configuration, the percent share of all cost types over the total cost is calculated.

Table 8: Average daily cost per package delivered at demand levels 200, 500, and 1000 under baseline, mixed, and e-bike only scenarios

		Total Customers					
		200		500		1000	
Scenario	Cost Type	Cost per package delivered ($/package)	Percent share of total cost	Cost per package delivered ($/package)	Percent share of total cost	Cost per package delivered ($/package)	Percent share of total cost
Baseline	Fuel	0.110	5%	0.106	5%	0.106	5%
Baseline	Labor	1.847	82%	1.804	82%	1.810	83%
Baseline	Maintenance	0.053	2%	0.051	2%	0.051	2%
Baseline	Vehicle	0.254	11%	0.235	11%	0.223	10%
Baseline	Total	2.263	100%	2.196	100%	2.190	100%
Mixed	Fuel	0.104	5%	0.086	4%	0.080	4%
Mixed	Labor	1.536	78%	1.864	84%	1.825	84%
Mixed	Maintenance	0.073	4%	0.067	3%	0.064	3%
Mixed	Vehicle	0.244	12%	0.213	10%	0.202	9%
Mixed	Total	1.958	100%	2.231	100%	2.170	100%
Ebike	Fuel	0.053	3%	0.022	1%	0.012	1%
Ebike	Labor	1.608	84%	1.881	88%	1.873	89%
Ebike	Maintenance	0.105	5%	0.095	4%	0.088	4%
Ebike	Vehicle	0.155	8%	0.140	7%	0.131	6%
Ebike	Total	1.921	100%	2.138	100%	2.104	100%

The labor cost had the highest share of the total cost, having at least 78% share in all scenarios and customer demand levels. At all demand levels, the e-bike only scenario had the highest labor cost when compared with the baseline and mixed scenarios, constituting 84%, 88%, and 89% of the total cost in that scenario. The labor cost per package in the e-bike only scenario was $1.608, $1.881, and $1.873 at demand levels 200, 500, and 1000. The labor cost is the most expensive cost type, and it is even more expensive for the e-bike routes. This can be explained by longer operational hours since e-bikes have lower package carrying capacities and they have to complete more routes to deliver the same number of packages when compared with traditional delivery vehicles. The time spent per package is longer with increasing number of delivery routes, which is the case for the e-bike routes with growing customer demand. Thus e-bikes have a higher labor cost under higher customer demand, since the labor cost is a function of the time spent per package delivered.

The fuel and maintenance costs were the lowest for all scenarios when compared with other cost types, constituting less than 10% of the total cost combined at all demand levels. The e-bike only scenario had the lowest fuel, maintenance and vehicle cost at all demand levels when compared with baseline and mixed scenarios. These results show that the cost competitiveness of the e-bike only scenario depend solely on the labor cost. Therefore, in areas where e-bike delivery driver workforce is established and the hourly wages are lower, e-bikes can even provide a cheaper solution when compared with traditional delivery vehicles.

The total daily cost per package was found to be $2.263, $1.958, and $1.921 under the baseline, mixed and e-bike only scenarios, respectively, at customer demand level 200. The total cost was 15 % lower in the e-bike only scenario when compared with the baseline at the lowest demand level. At customer demand levels 500 and 1000, the total daily cost per package for e-bikes was 2.6% and 3.9% higher than the baseline scenario. These results show that there are no significant cost benefits or losses of e-bike deliveries compared to the baseline at demand levels higher than 200.

Chapter 5. Conclusion

Micro consolidation practices in urban areas present an opportunity to find better ways to move our goods around in our densified cities with rapidly increasing demand for home deliveries. New trends in technology and consumer behavior are feeding the growth of an e-commerce industry that relies on home deliveries that replace customer trips to stores. The high competition in the package carrier industry and the increased environmental focus in the society puts urban delivery systems under pressure. Micro consolidation centers, when coupled with e-bikes, have the potential to increase delivery efficiency and reduce emissions, while also being cost competitive when compared with traditional delivery systems.

This research evaluated the performance of the micro consolidation practices and e-bikes and identified the conditions under which these solutions can be successfully implemented in terms of vehicle miles traveled, emissions and cost. Three scenarios with varying vehicle type mixes were created (baseline, mixed and e-bike only) and tested under three levels of customer demand (200, 500, 1000). For each of the nine scenario configurations, the vehicle routes are calculated and simulated to measure the distance and time spent. In scenarios where e-bikes were delivering, first the desired number of microhubs were selected from a pool of candidate microhub locations. Then, customers were assigned to the nearest microhub from which e-bikes start their deliveries. Performance metrics, VMT per package, tailpipe CO_2 emissions per package, and the average daily cost per package, were calculated using the simulation outputs.

The results of this study found that delivery systems using a network of microhubs and only e-bikes to complete the last mile to the customer perform the best under high customer density areas. At the highest customer demand level 1000, in the e-bike only scenario, e-bikes traveled 7.7% less to deliver a package and emitted 91% less tailpipe CO_2 with no significant cost benefits or losses when compared with the baseline scenario where only traditional delivery vehicles were used. These findings further support the idea that cargo logistics when implemented in areas where the demand is densified can reduce emissions and congestion without significant cost implications.

This study added to the evidence that delivery operations in dense urban areas can be replaced by a network of microhubs and e-bikes to complete the last mile. The literature review proposed an established definition and defined a typology for a variety of micro-consolidation practices. Pilot tests taking place in both North American and European cities can help carrier companies learn about micro consolidaiton practices. However, making a quantitative comparison between traditional delivery routes and e-bike routes to replace them remains a difficult practice in real life. This is because the customer demand and the service area to deliver change daily, which makes evaluating the impacts of replacing traditional vehicles with e-bike routes challenging. The simulation approach in this study helped quantify the efficiencies and carbon emissions savings. Also in this research, a mixed delivery vehicle scenario is tested where both e-bikes and traditonal delivery vehicles are operating, which represented the transition phase to microhub practices. Similarly, many cities introducing microhubs and e-bike routes still have vans and cars completing deliveries and thus have a mixed vehicle mix.

5.1. Recommendations for Future Research

This research provided useful insights into micro consolidation practices, more specifically the use of microhubs with e-bikes that complete the last mile to improve urban freight efficiencies and reduce emissions. The following section provides directions and recommendations for future work. To estimate the VMT per package, the distances can be calculated using the driving distance between each customer location instead of the Manhattan distance used in this study. In this study, the priority was to evaluate the VMT per package comparatively between different the scenario configuration. Depending on the objectives of the study, Google Maps API can be utilized to get driving distance estimates to calculate the VMT per package more realisticly.

Due to the nature of the proposed methodology, there were three different customer demand levels. The number of packages to be delivered to each customer was then calculated by sampling from a poisson distribution. Thus, the number of packages to be delivered was different in each simulation run. Since the package carrying capacity of each vehicle type was kept constant, in some simulation runs there may be delivery routes that were partially loaded. To overcome this future studies can build their methodology on the number of routes instead of number of customers to deliver to.

The labor cost calculations were done using hourly wages for three different delivery vehicle types which can be highly variable in the industry. These hourly wages depend on the company the driver works for and their experience. Plus, the hourly wages for delivery drivers in the gig economy show even higher irregularity that can't be reduced to a single metric. For future work, researchers can explore a range of hourly wages and present results accordingly. Another issue can be that there is no established workforce of e-bike delivery drivers, thus finding the right driver with delivery and biking experience can be difficult and costly. Bike messengers, pedicab drivers and commercial delivery vehicle drivers can be included in the pool of potential candidates for e-bike delivery driver positions. Drivers with delivery experience may require higher wages as an incentive to operate e-bikes instead of vans or cars.

Future research can look into the use of collection and delivery points (CDP) where the last mile of the package deliveries are completed by the customer. Microhubs can be utilized to work as both a transshipment point and a CDP, from which packages are delivered by e-bikes or collected by customers. Also, future work can consider the effect of failed delivery attempts where the customer is not available to pick up the package delivered by e-bikes. These packages can be delivered the next day and added to delivery routes or picked up by the customers from the CDP.

Chapter 6. Bibliography

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Appendix A: Boxplots for Performance Metrics

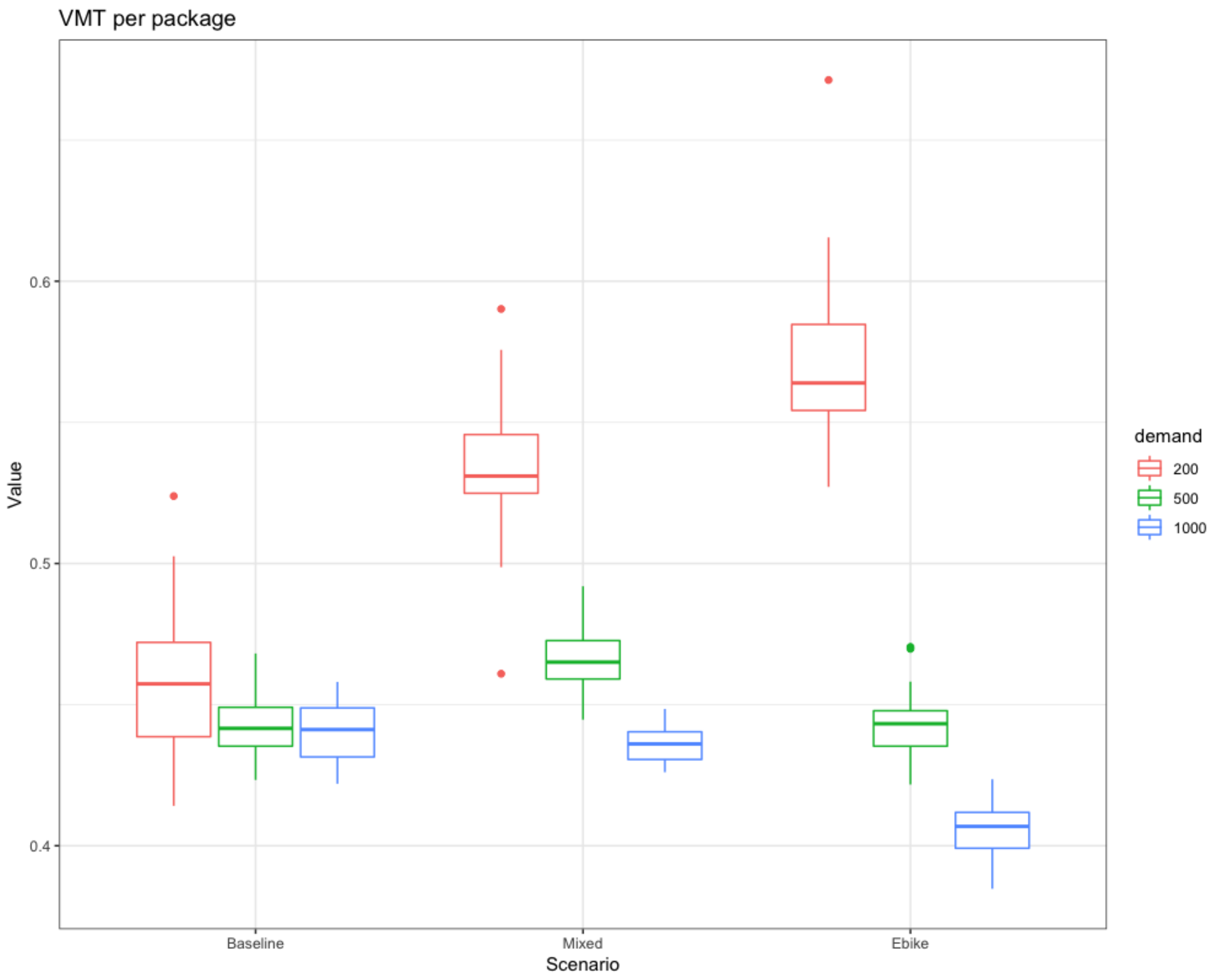

Figure A-1: Boxplot for the performance metric VMT per package

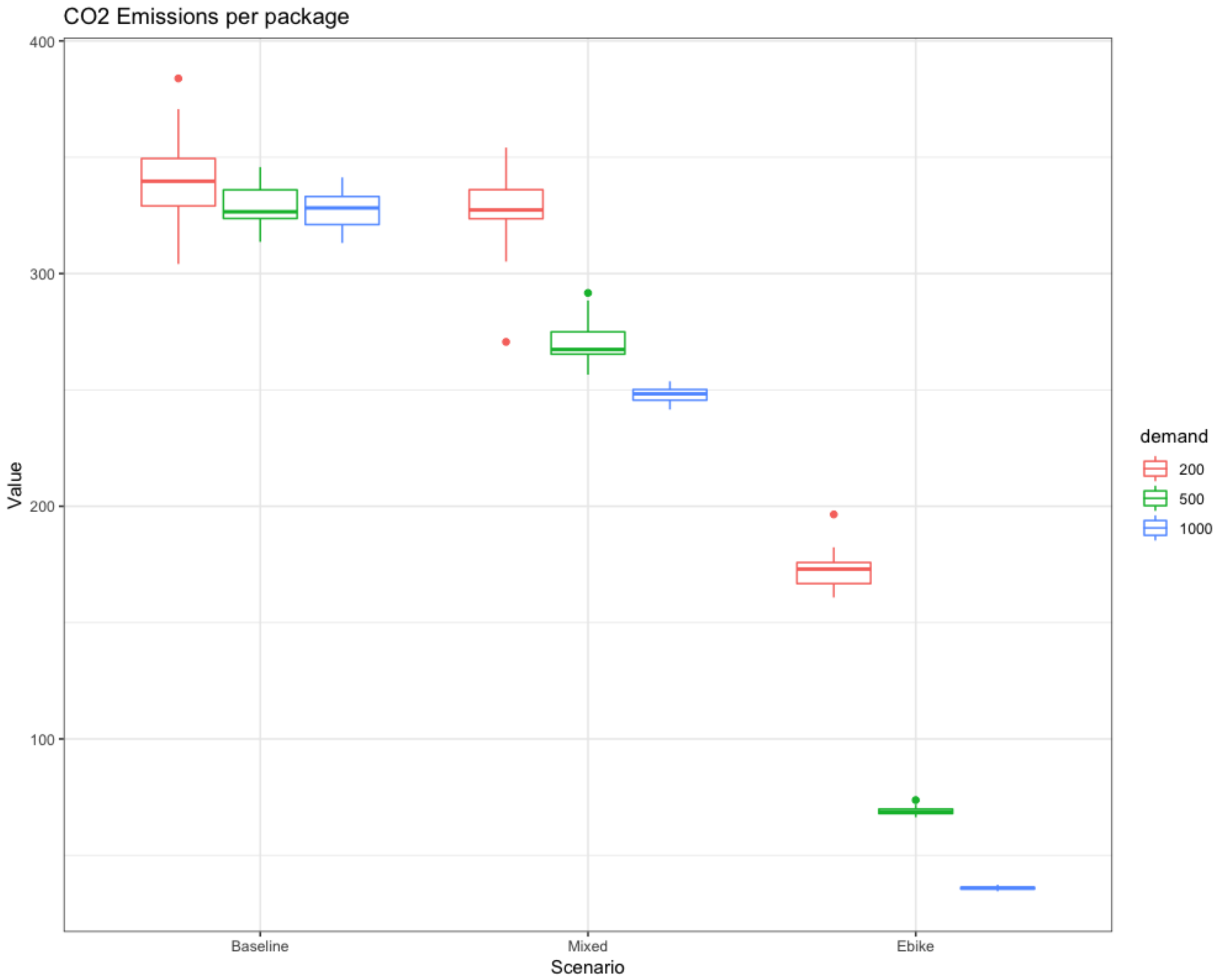

Figure A-2: Boxplot for the performance metric tailpipe CO_2 emissions per package

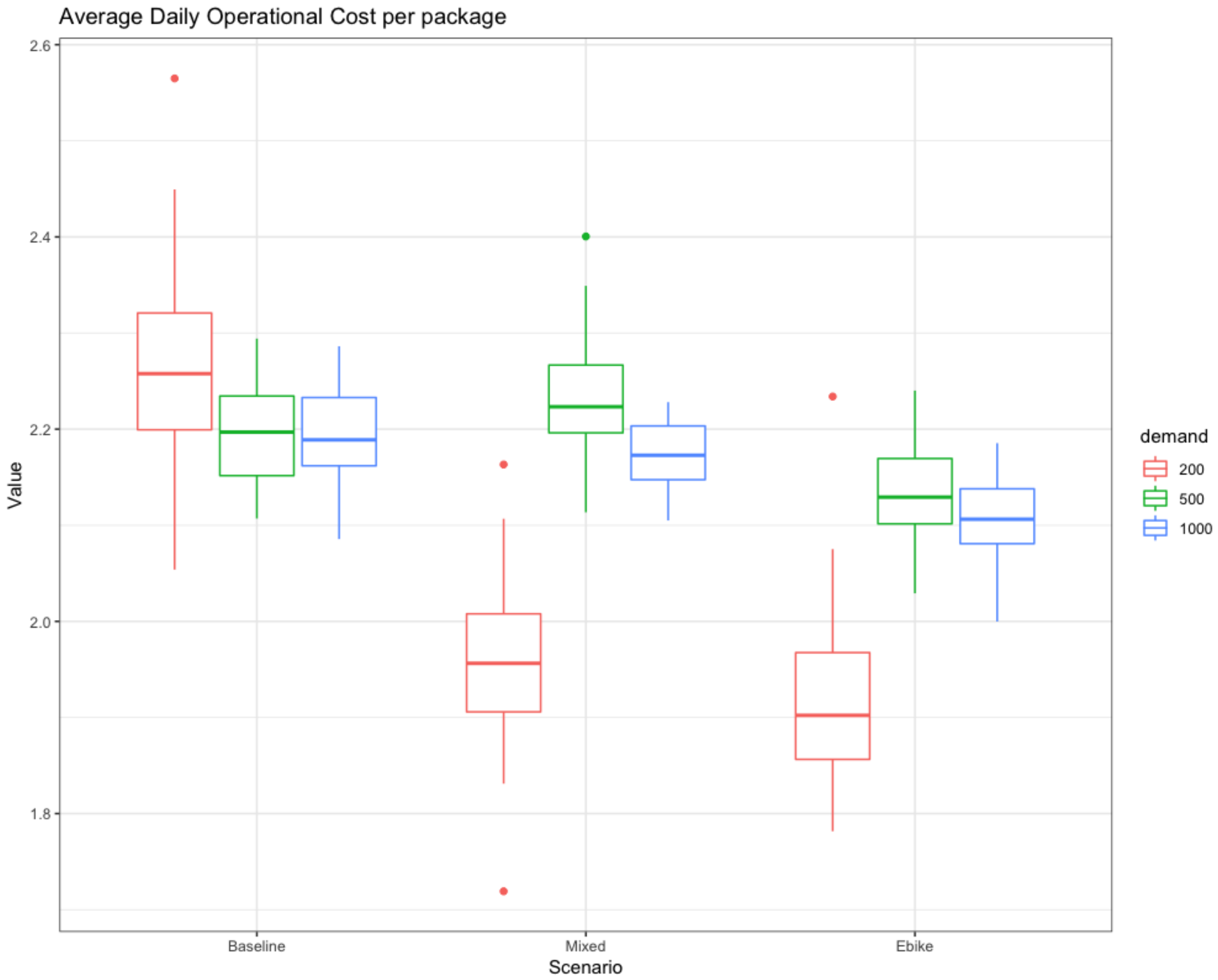

Figure A-3: Boxplot for the performance metric average daily cost per package

Appendix B: Results of Paired t-tests

Table B-1: Results of paired t-tests between groups for the performance metric VMT per package

Scenario	Performance metric	group1	group2	n1	n2	statistic	df	p	p.adj	p.adj.signif
Baseline	VMT per package	200	500	30	30	3.32	29	2.00E-03	7.00E-03	**
Baseline	VMT per package	200	1000	30	30	3.49	29	2.00E-03	5.00E-03	**
Baseline	VMT per package	500	1000	30	30	1.05	29	3.01E-01	9.03E-01	ns
Mixed	VMT per package	200	500	30	30	15	29	3.30E-15	9.90E-15	****
Mixed	VMT per package	200	1000	30	30	21.7	29	1.77E-19	5.31E-19	****
Mixed	VMT per package	500	1000	30	30	11.1	29	6.04E-12	1.81E-11	****
Ebike	VMT per package	200	500	30	30	21.3	29	3.11E-19	9.33E-19	****
Ebike	VMT per package	200	1000	30	30	27.8	29	1.78E-22	5.34E-22	****
Ebike	VMT per package	500	1000	30	30	12.8	29	1.90E-13	5.70E-13	****

Customer Demand	Performance metric	group1	group2	n1	n2	statistic	df	p	p.adj	p.adj.signif
200	VMT per package	Baseline	Mixed	30	30	-1.28E+01	29	1.85E-13	5.55E-13	****
200	VMT per package	Baseline	Ebike	30	30	-1.39E+01	29	2.40E-14	7.20E-14	****
200	VMT per package	Mixed	Ebike	30	30	-5.08E+00	29	2.02E-05	6.06E-05	****
500	VMT per package	Baseline	Mixed	30	30	-8.03E+00	29	7.37E-09	2.21E-08	****
500	VMT per package	Baseline	Ebike	30	30	-1.86E-02	29	9.85E-01	1.00E+00	ns
500	VMT per package	Mixed	Ebike	30	30	6.86E+00	29	1.55E-07	4.65E-07	****
1000	VMT per package	Baseline	Mixed	30	30	1.71	29	9.80E-02	2.94E-01	ns
1000	VMT per package	Baseline	Ebike	30	30	12.7	29	2.36E-13	7.08E-13	****

Table B-2: Results of paired t-tests between groups for the performance metric tailpipe CO_2 emissions per package

Scenario	Performance metric	group1	group2	n1	n2	statistic	df	p	p.adj	p.adj.signif
Baseline	Tailpipe CO2 emissions per package	200	500	30	30	2.71	29	1.10E-02	3.40E-02	*
Baseline	Tailpipe CO2 emissions per package	200	1000	30	30	3.07	29	5.00E-03	1.40E-02	*
Baseline	Tailpipe CO2 emissions per package	500	1000	30	30	1.02	29	3.14E-01	9.42E-01	ns
Mixed	Tailpipe CO2 emissions per package	200	500	30	30	18.5	29	1.38E-17	4.14E-17	****
Mixed	Tailpipe CO2 emissions per package	200	1000	30	30	26.1	29	1.03E-21	3.09E-21	****
Mixed	Tailpipe CO2 emissions per package	500	1000	30	30	13	29	1.37E-13	4.11E-13	****
Ebike	Tailpipe CO2 emissions per package	200	500	30	30	72.8	29	2.19E-34	6.57E-34	****
Ebike	Tailpipe CO2 emissions per package	200	1000	30	30	99	29	3.00E-38	9.00E-38	****
Ebike	Tailpipe CO2 emissions per package	500	1000	30	30	102	29	1.18E-38	3.54E-38	****

Customer Demand	Performance metric	group1	group2	n1	n2	statistic	df	p	p.adj	p.adj.signif
200	Tailpipe CO2 emissions per package	Baseline	Mixed	30	30	2.77	29	1.00E-02	2.90E-02	*
200	Tailpipe CO2 emissions per package	Baseline	Ebike	30	30	44.8	29	2.55E-28	7.65E-28	****
200	Tailpipe CO2 emissions per package	Mixed	Ebike	30	30	48.4	29	2.79E-29	8.37E-29	****
500	Tailpipe CO2 emissions per package	Baseline	Mixed	30	30	27.4	29	2.78E-22	8.34E-22	****

500	Tailpipe CO2 emissions per package	Baseline	Ebike	30	30	169	29	5.87E-45	1.76E-44	****
500	Tailpipe CO2 emissions per package	Mixed	Ebike	30	30	127	29	2.51E-41	7.53E-41	****
1000	Tailpipe CO2 emissions per package	Baseline	Mixed	30	30	44.2	29	3.70E-28	1.11E-27	****
1000	Tailpipe CO2 emissions per package	Baseline	Ebike	30	30	192	29	1.36E-46	4.08E-46	****
1000	Tailpipe CO2 emissions per package	Mixed	Ebike	30	30	335	29	1.39E-53	4.17E-53	****

Table B-3: Results of paired t-tests between groups for the performance metric average daily cost per package

Scenario	**Performance metric**	**group1**	**group2**	**n1**	**n2**	**statistic**	**df**	**p**	**p.adj**	**p.adj.signif**
Baseline	Average daily cost per package	200	500	30	30	3.36	29	2.00E-03	7.00E-03	**
Baseline	Average daily cost per package	200	1000	30	30	3.16	29	4.00E-03	1.10E-02	*
Baseline	Average daily cost per package	500	1000	30	30	0.534	29	5.97E-01	1.00E+00	ns
Mixed	Average daily cost per package	200	500	30	30	-15.2	29	2.56E-15	7.68E-15	****
Mixed	Average daily cost per package	200	1000	30	30	-11.6	29	2.11E-12	6.33E-12	****
Mixed	Average daily cost per package	500	1000	30	30	4.22	29	2.16E-04	6.48E-04	***
Ebike	Average daily cost per package	200	500	30	30	-10.6	29	1.56E-11	4.68E-11	****
Ebike	Average daily cost per package	200	1000	30	30	-8.79	29	1.13E-09	3.39E-09	****
Ebike	Average daily cost per package	500	1000	30	30	2.61	29	1.40E-02	4.20E-02	*

Customer Demand	Performance metric	group1	group2	n1	n2	statistic	df	p	p.adj	p.adj.signif
200	Average daily cost per package	Baseline	Mixed	30	30	13.9	29	2.31E-14	6.93E-14	****
200	Average daily cost per package	Baseline	Ebike	30	30	11.5	29	2.32E-12	6.96E-12	****
200	Average daily cost per package	Mixed	Ebike	30	30	1.4	29	1.71E-01	5.13E-01	ns
500	Average daily cost per package	Baseline	Mixed	30	30	-2.35	29	2.50E-02	7.60E-02	ns
500	Average daily cost per package	Baseline	Ebike	30	30	4.47	29	1.12E-04	3.36E-04	***
500	Average daily cost per package	Mixed	Ebike	30	30	5.7	29	3.63E-06	1.09E-05	****
1000	Average daily cost per package	Baseline	Mixed	30	30	1.63	29	1.14E-01	3.42E-01	ns
1000	Average daily cost per package	Baseline	Ebike	30	30	6.52	29	3.90E-07	1.17E-06	****
1000	Average daily cost per package	Mixed	Ebike	30	30	6.59	29	3.19E-07	9.57E-07	****

ProQuest LLC
789 East Eisenhower Parkway
P.O. Box 1346
Ann Arbor, MI 48106 - 1346 USA