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# EVALUATING THE GROWTH OF LAST-MILE DELIVERIES AND INNOVATIONS TO REDUCE FREIGHT CURB SPACE DEMAND

## Draft Report

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# DISCLAIMER

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# EXCUTIVE SUMMARY

This reports studies potential benefits of locker delivery systems. The literature review indicates that e-commerce growth is clearly outpacing brick-and-mortar's growth globally and in the US. Besides huge package delivery demand, the desire for alternative and faster delivery methods, increasing regulatory restrictions on freight deliveries, and the adoption of new technologies challenge current urban logistics system. As a sustainable and efficient emerging delivery method, parcel lockers do possess potentials of reducing carbon emissions, improving logistics efficiency, serving customers' need needs, and gaining more popularity and economic viability. Lockers are expected to benefit courier companies by allowing operations at increasingly competitive rates, and retailers and consumers benefit from convenience and low shipping rates.

This research evaluated the consolidation of deliveries utilizing a case study based on light rail stations, transit centers, and transit malls in the greater Portland, OR area. The potential of hosting transit sites is reviewed based on ridership (the number of ons/offs at transit facilities), the number of residents in influence areas (whether transit users or not), and a framework for prioritizing locations based on best-practice equity metrics. Mode-specific accessibility of park-and-ride facilities outside the urban core, as well as the potential of consolidated distribution points in city resiliency plan are discussed. Locker service adoption is related to high volumes of foot traffic. TriMet's validated ons/offs data was used as a measure of expected foot traffic at transit stops. The data used was from the fall quarter of 2019 before normal traffic patterns were altered by the Covid-19 pandemic.

Transit agencies can be proactive in developing public-private partnerships with interested couriers. Portland's transit network has high ridership volumes and overall foot traffic along Portland's transit mall. In contrast, suburban park-and-rides generally have more space to install automated parcel locker facilities with high security and 24-hour operations that can attract consumers who do not utilize transit. The development of a locker program is amenable to incremental expansion that involves iterative review of the changes in consumer needs, travel pattern changes, and consumption. A locker system at transit facilities is also congruent with the interest in transit-oriented development (TOD), which has typically centered on developing housing near transit facilities.

Finally, a mathematical optimization program that jointly minimizes the total cost of locating shared parcel lockers and resulted delivery routes was proposed. By minimizing the total system cost, the optimal solution determines where to open shared locker facilities and through these facilities how routes should be planned so that selected shared locker locations and home sites of customers that are not assigned to any shared lockers are both visited by delivery vehicles. Total cost savings (including capital investment and operational cost) ranged between 19% to 28% compared to the traditional all-home deliveries. With even greater reduced freight VMT, urban residents benefit from improved traffic safety and better air quality.

# 1.0 INTRODUCTION

According to the United States Census Bureau's Quarterly E-Commerce Report, E-Commerce sales in the United States (US) have increased at double digits rate in the past two decades and this rapid growth of e-commerce and package/service deliveries is creating new challenges in urban areas.

Nowadays, most national retailers in the USA are selling online and in order to utilize their existing facilities, retailers adopt the omnichannel delivery strategy (Lim et al., 2018). Among these delivery methods, attended home delivery (AHD), reception or delivery box (RB or DB), shared parcel lockers, collection-and-delivery points (CDPs), and crowd-sourcing delivery are the most commonly used last-mile delivery methods. Delivery to shared parcel lockers, an unattended delivery method, receives more and more attention in practice and research.

An innovative idea is the utilization of parcel lockers at transit stations where it may be more convenient to transit and non-transit users. Presently, most parcel lockers operate out of private businesses, but consumer surveys have found that transit users may be interested in locker facilities at transit connections. The implementation of an unmanned, secure, common carrier parcel locker system could have benefits for non-transit users as well. Consolidation of deliveries is expected to benefit courier companies by allowing operations at increasingly competitive rates, and retailers and consumers benefit from convenience and low shipping rates.

This report answers the following two main research questions: (1) Given that most parcel lockers operate out of private businesses, what is the potential of utilizing parcel lockers at transit stations?

To answer this question this report utilizes a case study of the light rail stations, transit centers, and transit malls in the greater Portland, OR area. The potential of hosting transit sites is reviewed based on ridership (the number of ons/offs at transit facilities), the number of residents in influence areas (whether transit users or not), and a framework for prioritizing locations based on best-practice equity metrics. Mode-specific accessibility of park-and-ride facilities outside the urban core, as well as the potential of consolidated distribution points in city resiliency plan are discussed.

(2) Given the increasing usage of shared parcel lockers, how much last-mile delivery operation efficiency is gained by adopting the new delivery method and how the total delivery cost can be minimized?

To answer this question this report develops a mathematical optimization problem that jointly optimizes the delivery routes (operational decision) and the locations of the shared parcel lockers (planning decision) for the innovative delivery system adopting shared parcel lockers. By conducting numerical experiments with real network data, the efficiency gain of the innovative delivery method is quantified. Metrics such as the total system cost is particularly employed to quantify the potential efficiency gains and the impacts to transportation system and environmental cost.

The report is organized as follows. Section 2 reviews the general trend of e-commerce and package delivery demand. Section 3 summarizes the challenges of the last-mile delivery in the e-commerce era and presents several alternative delivery methods to traditional home-attended delivery means. Specific to shared parcel lockers, research findings on the potential environmental impacts, its economic viability, and the ability to serve people's needs of the are presented in section 4. In section 5, we analyze the potential of parcel lockers at transit stations in terms of how they can improve efficient logistic operations, provide competitive services, and improve social equity. A mathematical optimization program of minimizing the total cost of locating shared lockers and the resulted delivery cost is proposed in section 6, and computational experiments illustrating the efficiency gain with the introduction of the parcel locker system are documented. The report is concluded by section 7 with some discussions on

# 2.0 E-COMMERCE AND PACKAGE DELIVERY REVIEW

Last mile logistics are highly context specific as infrastructure, travel demand, and land use patterns vary greatly. Yet an overarching goal crosses borders: namely, finding the optimal balance between efficient logistic operations and the most competitive service to consumers. This review presents a collection of research findings aimed at e-commerce trends and package delivery trends.

## 2.1 E-COMMERCE TRENDS

According to the United States Quarterly E-Commerce Report, e-commerce sales in the United States (US) have increased at double digit rates for the past two decades (USDC, 2020). During this time, e-commerce has outpaced brick-and-mortar retail growth, both in the United States and globally. Some online stores promote an in-store pickup service, but the large majority of online customers have products delivered to their residence, their work, or another location of their choice. Though some authors distinguish between retailers (sales revenue is primarily generated offline) and e-tailers (sales revenue is primarily generated online), this section will use the term retailer to refer broadly to sellers, and the specifiers "in-store," "brick-and-mortar," "online," and "e-commerce" will be used as necessary.

E-commerce activity continues to grow worldwide, and business-to-consumer (B2C) sales in the US are predicted to reach over $500B by 2024, up from $365 billion in 2019 (Statista Digital Market Outlook, 2020). Market competition pressures businesses to meet these growing volumes with increasingly short delivery lead times, low shipping costs, and high reliability. Operations have become streamlined in early supply chain phases, but the final segment of delivery–"the last mile"–is often the most expensive and least efficient segment (Capgemini Research Institute, n.d.; Gevaers et al., 2011). The operational costs of the last mile swell due to order fragmentation, which precludes economies of scale; many delivery tour stops deliver only one parcel per stop (Deutsch and Golany, 2018; Iwan et al., 2016). Recent research examining the granular nuances of "the last 800 feet" finds it rife with distinct challenges to tour efficiency, such as locating parking and the operations performed outside the freight vehicle (Butrina et al., 2017).

## 2.2 PACKAGE DELIVERY TRENDS

Between 2015–2019, US major couriers FedEx, UPS, and United States Postal Service (USPS) all exhibited growth in the number of packages shipped (FedEx, 2020; UPS, 2019; USPS, 2020). By the end of fiscal year 2019, 1.52 billion packages were shipped domestically, a +27.5% increase from 2015. By company, FedEx package volumes grew +23.5% and UPS's grew +19.3% over the same period. USPS package volume–which includes Priority Mail, Priority Mail Express, First-Class Package, Parcel Return Service, and Parcel Select–increased by +37.8%, from 4.5B to 6.2B pieces. Conversely, USPS's volume of first-class (flat) mail declined from 62.6B to 54.9B pieces. This signals the shift in mail streams from postage stamps to shipping labels, as can be attributed to e-commerce demand.

FedEx Ground grew dramatically (+29.5%) but their air cargo service, FedEx Express, saw relatively modest growth (+8.1%). Unlike FedEx Express, UPS's Next Day Air dramatically increased by +43.0%. UPS Deferred (a service slower than Next Day Air but faster than Ground) and UPS Ground services saw moderate increases but were relatively less than the growth of FedEx Ground. The increase in package circulation correlates with the increase in e-commerce sales, but it should be noted that the figures in Table 1 represent total packages shipped, whether associated with e-commerce or not.

**Table 1 Number of packages annually*, US domestic (in millions).**

| Courier | 2015 | 2016 | 2017 | 2018 | 2019 | Vol. change 2015-2019 | % Change 2015-2019 |
|---|---|---|---|---|---|---|---|
| FedEx Express | 979 | 990 | 995 | 996 | 1,059 | 80 | 8.1% |
| FedEx Ground | 2,523 | 2,747 | 2,882 | 3,043 | 3,267 | 745 | 29.5% |
| UPS Next Day Air | 334 | 352 | 371 | 390 | 478 | 144 | 43.0% |
| UPS Deferred | 334 | 345 | 356 | 362 | 410 | 77 | 23.0% |
| UPS Ground | 3,294 | 3,446 | 3,571 | 3,668 | 3,840 | 545 | 16.56% |
| USPS | 4,500 | 5,200 | 5,700 | 6,200 | 6,200 | 1,700 | 37.80% |
| TOTAL | 11,964 | 13,080 | 13,875 | 14,659 | 15,254 | 3,290 | 27.5% |

**Fiscal year ends Dec 31st for UPS and USPS; fiscal year ends Mar 31st for FedEx.*
(FedEx, 2018; 2019) (UPS, 2018; 2020) (USPS, 2020)

With all three major US couriers showing strong growth in recent years, the overall momentum of package circulation is apparent. It is no longer unusual to see parcels on residential doorsteps, with many consumers receiving shipments almost daily. The logistics of transporting the package to final delivery must be reliable and efficient. As more producers and retailers deliver directly to the end user, it is critical to understand timeframes, operations, and product destinations, as they will shape future delivery modes and receiving technologies.

FedEx expected US parcel delivery to increase to 100 million packages per day by 2026 but the COVID-19 pandemic has accelerated parcel delivery growth and now it projects that this number of parcels will be shipped daily in the U.S. across all carriers sometime in 2023 (Ziobro, 2020).

## 2.3 PARKING IMPLICATIONS

In commercial/mixed-use zones, rising volumes of B2C deliveries have exacerbated a shortage of loading zones; illegal parking has increased (Figliozzi and Tipagornwong, 2017) as trucks and vans simply cannot find enough suitable places for unloading parcels (Jaller et al., 2013). Freight trip generation at residential destinations is now on par with that of business destinations (Chen et al., 2017); however, residential areas are not designed for efficient parcel delivery. Neighborhoods may have insufficient road signage, and multi-unit complexes can be difficult to navigate (Deutsch and Golany, 2018). Moreover, where signed receipt of delivery is required, resident absence–coined the "not-at-home" problem–further multiplies last mile costs. Unfortunately, porch piracy has sustained consumer demand for signed parcel reception. If multiple delivery attempts fail to garner a signature, parcels are diverted to a retail center, post office, or freight locker for customer reception (Deutsch and Golany, 2018; Moroz and Polkowski, 2016; University of Washington Urban Freight Lab, 2018).

# 3.0 LAST-MILE DELIVERY CHALLENGES AND ALTERNATIVE DELIVERY METHODS

This review presents some research findings on the challenges of last-mile deliveries in the e-commerce era and summarizes alternative delivery methods to the traditional home-attended delivery method.

## 3.1 CHALLENGES IN LAST-MILE PACKAGE DELIVERIES

Last-mile logistics is continually facing challenges as the urban population grows and the sales of e-commerce boost. According to the report by the United Nations Department of Economic and Social Affairs (UN DESA), the urban population accounts for 55% of the world's population today and this proportion is projected to be 68% by 2050 (The United Nations Department of Economic and Social Affairs, 2019). The steady growth of the business-to-customer e-commerce sales, which in 2019 almost doubled its turnover five years ago reaching $2.3 trillion (Lone and Quaglieri, 2019), results in a significant increase in *to-home* delivery demand in urban areas. The growth in population and the demand for home deliveries in high-density urban areas presents great challenges to last-mile logistics in addressing problems related to congestion, safety, and environment (Savelsbergh and Van Woensel, 2016).

It goes without saying that the root of urban logistics problems is the growing quantity and density of population concentrated in urban areas. In the following, we summarize four specific challenges that create layers of complexity to the urban last-mile delivery system. The contradiction between the increasing demand for better delivery services and the arising expectation of reducing the negative impacts of delivery activities brings new challenges for delivery service providers, as well as customers.

### 3.1.1 Huge Demand in Home Deliveries

Enabled by the advancement of information technology and the increasing penetration of the Internet and mobile phones, the e-shopping gains popularity around the world. Shopping and paying become much easier thanks to technology development. In the US, people are buying digitally more than ever—more than 82% of Americans are e-shoppers (Lone and Quaglieri, 2019). The online spending of 2019 reached $602 billion accounting for 16% of the total retail sale (Statista Digital Market Outlook, 2020) in the US. At the same time of generating huge revenue, the thriving e-commerce generates tons of packages and parcels whose annual total number was predicted to be over 16 billion in the US by 2020 (Laseter et al., 2018). They need transportation from e-tailers to the end consumers, and the reverse when necessary. The enormous delivery need is therefore generated.

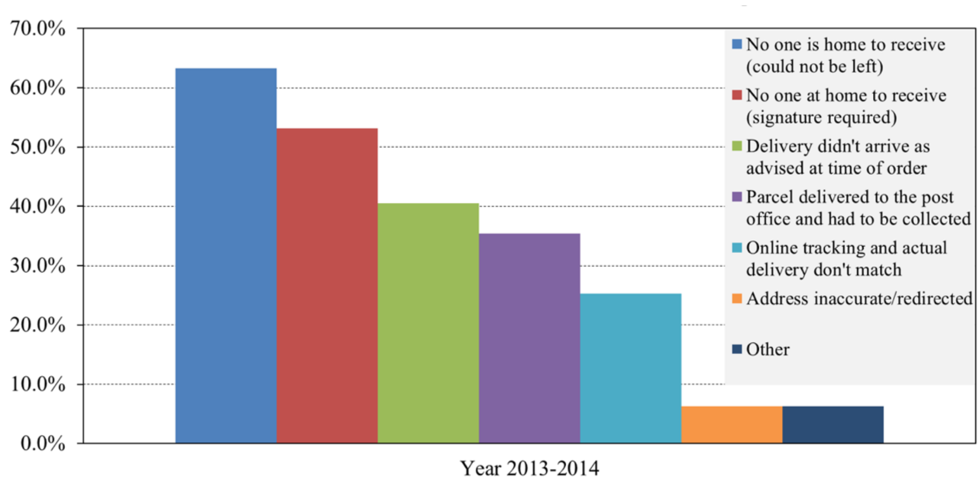



**Figure 1** Perceived reasons for unsuccessful parcel deliveries on a first attempt in the UK (Statista Research Department)

Among the huge delivery need, the direct delivery to home addresses accounts for the largest share. Globally, 80% of online shoppers prefer home deliveries to other alternative delivery locations (ADLs) according to UPS (UPS, 2019). Even in countries like China and Poland, where ADLs are more often used nowadays, home delivery is still the most chosen delivery option making up 58% and 60% of the total requests, respectively. Convenient as it is for customers, the home delivery, however, is expensive for delivery service companies. Apart from the labor and transportation cost, home deliveries suffer great efficiency loss due to the high rate of first delivery failure. A tracking record from 2008 to 2014 for UK parcel deliveries shows that the top reason for an unsuccessful package delivery had always been related to “no one at home to receive” (Statista Research Department). See Figure 1 for the data for year 2013-2014. The home delivery, especially the attended-home deliveries (AHD) which require customers to wait at home for their packages, significantly increases the operational cost for delivery companies. In the UK, the cost of failed delivery amounted to $ 1.1 Billion meaning that 1% of the market opportunity is lost (Abarza, 2016). Due to the huge demand for home deliveries and inevitable re-deliveries, the last-mile delivery portion accounts for 50% or more of total package delivery costs (Joerss et al., 2016).

Direct transportation to the end customers is going to increase the number of freight movements. Besides, the increase in freight movement will be exacerbated because the size of the deliveries is typically small. Therefore, the increase in home deliveries is believed to present a significant challenge to urban logistics and is described as “a curse rather than a blessing” (Savelsbergh and Van Woensel, 2016).

### 3.1.2 Rising Demand for Flexible and Alternative Delivery Options

Probably as important as the bulk demand for home deliveries, we note that flexible and alternative delivery options are gaining popularity among e-shoppers as well. A report by UPS shows that quite a large portion of customers are interested and have chosen alternative delivery locations(UPS, 2019) (see Figure 2). What’s more, e-shoppers now have more power to dictate how the delivery services should be provided to them. As is stated by Savelsbergh and Van Woensel (2016) “the consumer is allowed, more and more, to take part in defining the e-logistics that suits her, in terms of price, quality, time, green and/or fair”. The alternative delivery options certainly enhance customers' shopping experience but meanwhile, they require the reconfiguration of the logistics systems. Instead of the conventional delivery service to bricks-and-mortar retail stores, logistics companies and retailers need to provide various options for alternative delivery locations besides home addresses and stores.

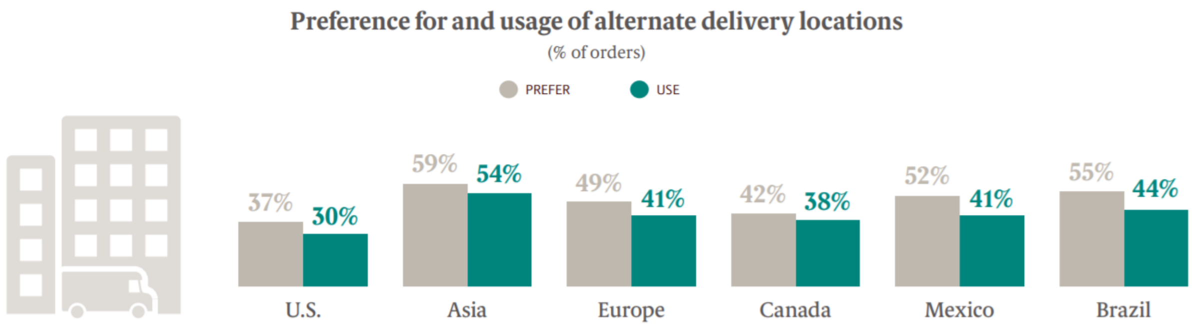



**Figure 2** Preference and usage of ADLs (United Parcel Service of America, Inc., 2018)

The UPS survey also shows that the e-shoppers want “a choice in the place and manner of delivery” (UPS, 2019). Customers want the delivery service to fit their schedules and lifestyles instead of the retailers’, especially the choice in the time of delivery with flexibility. To accommodate this emerging need, new delivery locations such as workplace, pick-up and delivery points (CDPs), and shared locker system (SLS) are adopted by more and more retailers and logistics companies. To enable such a variety of delivery options, both logistics companies and retailers are transforming their logistics systems. Examples of such transformations include multi-echelon transportation networks and omnichannel distribution system.

To cope with the potential increase in delivery vehicle movement within urban areas, one common design is to consolidate fragmented volumes of packages in the distribution centers (DCs) on the outskirts of the city (Cattaruzza et al., 2017; Crainic et al., 2009; Grangier et al., 2016; Savelsbergh and Van Woensel, 2016; Zhou et al., 2018). Instead of having many delivery vehicles carrying out separate and uncoordinated delivery services into the city directly, consolidated goods can be transported into the inner part of the city with fewer vehicles. These vehicles are usually more energy cleaner and efficiently utilized. Another layer of satellite facilities (SFs) can be added to this multi-echelon system when needed. In terms of the retailers, the omnichannel distribution system is often implemented to meet the various delivery demand of customers (Arslan et al., 2020; Hübner et al., 2016). In addition to reaching their customers through conventional distribution centers, e-tailers can satisfy the demand of e-shoppers through retail store inventories. Implementing these strategies to offer alternative delivery options can mitigate the negative impacts brought in by home deliveries. However, both the multi-echelon network and the omnichannel distribution system add fulfillment complexities. More efficient operation and management strategies are certainly needed to make the most of these systems, which are some challenges logistics companies and retailers face.

### 3.1.3 Speed in Delivery Services

In addition to the flexibility of delivery locations and delivery time, customers are generally expecting faster delivery services. Next-day delivery and same-day delivery begin to emerge. Some services can be even faster as 1-hour and 2-hour deliveries. An example is Amazon Prime Same-Day Delivery, which was first tested in 2009 and by the year 2014 customers already ordered 10 times more items than the previous year during the Christmas holiday (Chang, 2015). Amazon is not alone, Walmart, Home Depot, Alibaba and JD, two e-commerce giants in China, all provide same-day delivery services. It was estimated that 20% - 25% of the parcels will be same-day delivered in the future (Joerss et al., 2016).

From a customer's perspective, same-day delivery "combines the convenience of online shopping with the immediate product access of stationary retail" (Thomas Netzer et al., 2017); From an e-tailer's perspective, the speedy delivery service makes them more competitive against traditional bricks-and-mortar stores where customers gain instant access to the products they purchased. However, same-day and instant delivery is a scale game. Only when the delivery density is high enough, an e-tailer with a small number of distribution centers can make profits from the services. In this regard, Amazon keeps investing in its own decentralized warehouses to establish the same/next-day services available to many. On the other hand, bricks-and-mortar stores have natural advantages over their competitors. That is, they can use their physical stores as distribution centers to satisfy their online customers. Unsurprisingly, these stores are already close enough to their customers and this makes same-day deliveries much easier for them. Consolidation is the key to the success of same-day delivery services. Parcel logistics providers, courier service providers, and the retailers all have potentials in establishing the affordable same-day delivery network. Figure 3 shows the variable cost per shipment changes with respect to the total shipment amount for the aforementioned service providers.

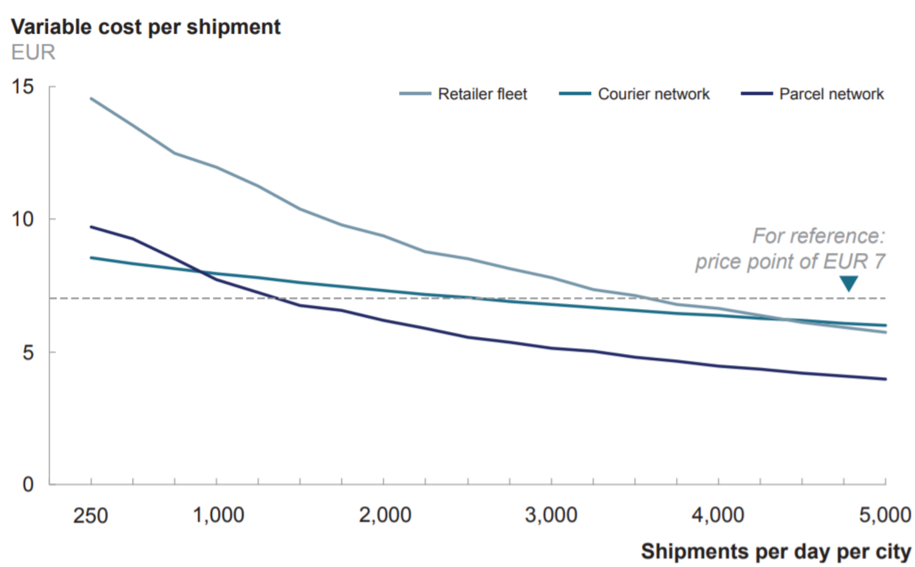



**Figure 3** The relations between variable costs per shipment and the total shipment amount for same-day delivery service providers

According to Savelsbergh and Van Woensel (2016), these speedy delivery services will "increase the number of freight movements as it will make the coordination and consolidation of direct-to-consumer deliveries even more challenging".

### 3.1.4 Increasing Regulatory Restrictions on Freight Deliveries

Freight transportation brings negative externalities including congestion, greenhouse gases, air pollution, water pollution, noise pollution, accidents, and land use to the people and society(Demir et al., 2015). As people becoming more and more aware of these problems related to last-mile delivery, many cities have set up regulatory restrictions on the operation of freight vehicles inside the city areas. For example, London has rolled out a plan to reduce the number of lorries and vans entering the central city by 10% by 2026(Transport for London, 2019). Currently across London, a broad range of restrictions exists regulating what freight vehicles can be used, when and where they can go and park.

On one hand, freight deliveries exert negative impacts on traffic congestion, safety, and environmental problems. A case study of the UK pointed out that light and heavy goods vehicles have increased by 70% and 15% from 1995 to 2015. Also, good collection and delivery account for 30% of total vehicle kilometers which has been steadily increasing since 1993(Allen et al., 2018). It is a well-known problem that delivery vehicles have great disturbance to the general traffic and pedestrians due to the stop-and-go. An interview and observation-based study carried out in Germany show that the delivery truck's stop duration and disturbances caused varies across district types (Schocke et al., 2019). Depending on district types, vehicles carrying out delivery services stop for various lengths of time and disturb other road users to different extents. Downtown generally sees longer stop duration and exceptional long duration (>30 minutes) (see Figure 4) and accordingly delivery activities within the downtown area create significant disturbances to traffic, pedestrians, bikers, and public transit (Figure 5). Due to these facts, restrictions have been set to regulate the operation activities of delivery vehicles.

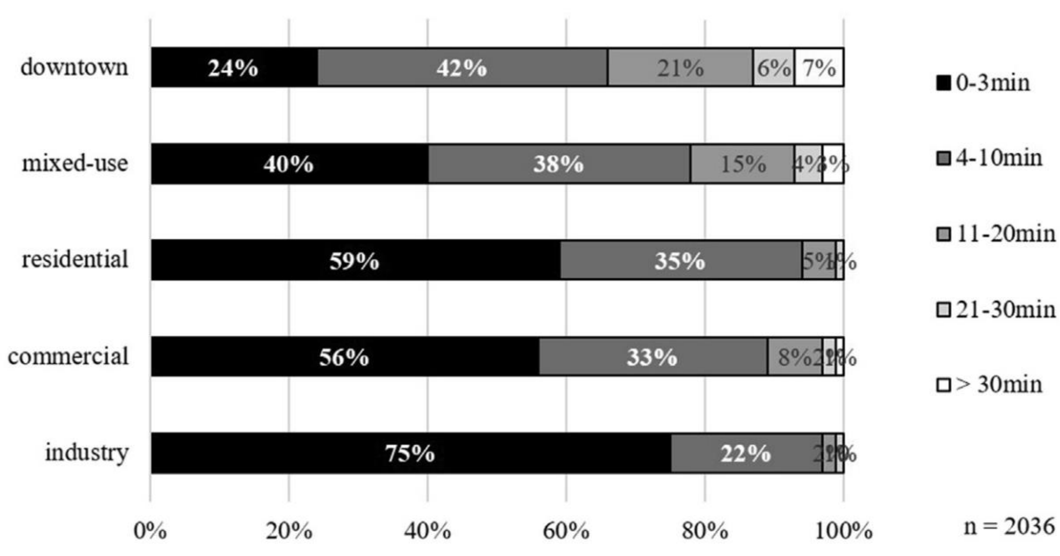



**Figure 4** Delivery vehicle's stop duration depending on district types (Schocke et al., 2019)

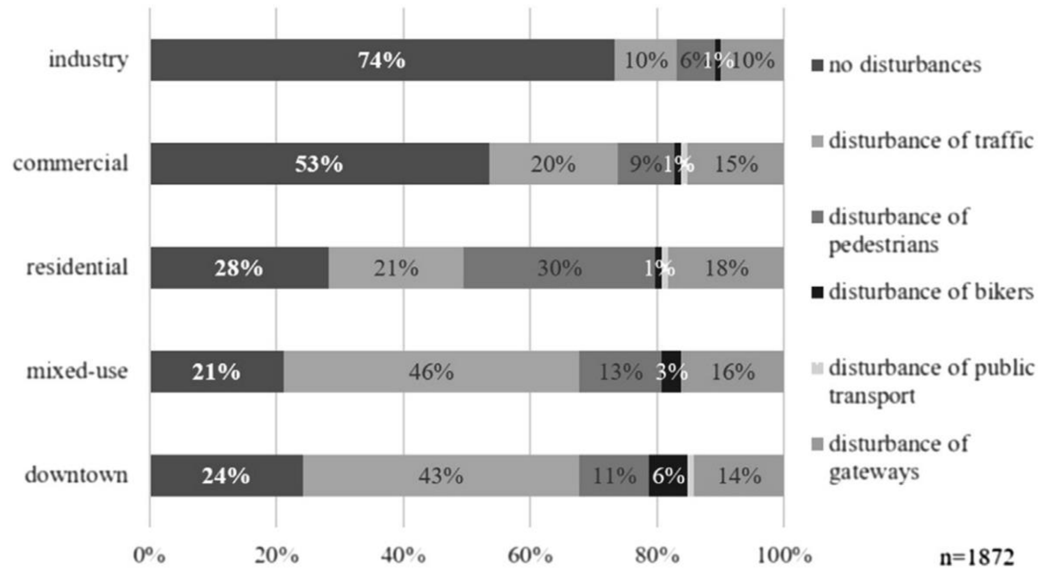



**Figure 5** Delivery vehicle's disturbance depending on district types (Schocke et al., 2019)

On the other hand, the urban infrastructure design has made the delivery operations even harder. Allen et al. (2018) pointed out in the case of London, there are conflicts between last-mile delivery operations and urban infrastructure design, which challenges and pressures the last-mile delivery system. Road space reallocation has made it difficult to find suitable curbside parking space and travel time reliability becomes another major issue due to congestion. Schocke et al., (2019) 's study also showed that lack of loading zones and restrictions on the road infrastructure decreases the performance delivery vehicle drivers and thus the delivery services.

To sum up, on one hand the increase in last-mile delivery services in response to the increasing demand worsens traffic conditions and brings other related problems, which makes cities regulate the operation activities of delivery companies. On the other hand, due to the restrictions imposed by the cities, it becomes a challenge for last-mile delivery services. Actions to make the urban logistics system more efficient and innovative are needed.

### 3.1.5 New Technologies and the Trend of Sharing Economy

Besides the increasing demand and the regulatory restrictions, new technologies and the trend for sharing economy present challenges to the current urban logistics system. Fortunately, new technologies and the propensity for sharing are more likely to be opportunities for delivery service providers if they are well adopted.

Information technologies make it possible to transfer data in large volume and higher speed, to understand the data better. Accurate and timely decisions made by current and future delivery service providers based on received data is key to improve the urban logistics system.

Automation technologies that support the operation of autonomous vehicles (AVs), unmanned aerial vehicles (UAVs), and robots set the foundation for the automated and connected delivery system. Coordination and cooperation between delivery vehicles, delivery service providers are becoming a reality.

In addition, new energies, such as natural gas, non-petroleum-based fuels, and rechargeable batteries, make it possible towards the zero-emission delivery services.

## 3.2 ALTERNATIVE LAST-MILE PACKAGE DELIVERY METHODS

In this section, we present some last-mile delivery methods that exist or are emerging in recent years. We will introduce the following four methods of last-mile package deliveries. Categorizing by delivery locations, these methods include collection and delivery points (CDPs), shared locker system (SLS), and reception boxes (RBs) and delivery boxes (DBs). Because these new services generally do not deliver packages directly to customers' homes, they are collectively referred to delivery service with alternative delivery locations (ADLs). Other delivery methods include crowd-sourcing based methods.

### 3.2.1 Collection-and-delivery Points (CDPs)

Collection and delivery points (CDPs) are locations packages and parcels of online order can be delivered to and collected from (Weltevreden, 2008). They are usually implemented in an attended form, which can only be accessed during certain operating hours. Typical CDP locations are chosen to be supermarkets, grocery stores, and shopping centers.

For example, FedEx started its CDP services in alliance with Walgreens in 2017. FedEx provides access to its package pick-up drop-off services at Walgreens locations across the US (Steiner, 2018).This last-mile package delivery solution, handling a group of packages, lowers the costs for FedEx compared to the door-to-door residential solutions.

Weltevreden (2008) summarized the rationales of the CDPs from the perspective of logistics service providers, retailers where CDPs are located, and customers, respectively. For the logistics service provider, "delivering a package to a CDP after a first-time delivery failure may save time and fuel, as they need not anymore visit a home for a second or a third time to make a successful delivery". In addition, it reduces the possibility of the good theft which would have otherwise been left unattended at the neighbors or outside the home. For the customers, this service does not necessarily mean additional travel compared to home-deliveries. Because when CDPs are located near residential locations or at areas, such as gas stations, that already generate consumer trips, little additional travel is needed to fetch a package by the shoppers. For the retailers where CDPs are located, it means more attractiveness to their own business as well. This is also supported by the UPS annual survey (UPS, 2018), it shows that even it varies across regions, more than 20% of the customers have used CDPs already in all surveyed regions with the U.S. being the highest with 50% share (Figure 6). More importantly, at least about 40% of customers made additional purchases in stores where CDPs are located.

**Ship-to-store**

| | U.S. | Asia | Europe | Canada | Mexico | Brazil |
|---|---|---|---|---|---|---|
| Have items shipped to store for pickup | 50% | 37% | 24% | 34% | 42% | 44% |
| Made additional purchases while in store | 44% | 60% | 44% | 38% | 65% | 58% |
| Plan to use it more often next year | 41% | 59% | 57% | 43% | 58% | 67% |

**Figure 6** Online shopper's CDP usage (UPS, 2018)

### 3.2.2 Shared Locker/Parcel System (SLS)

Shared locker systems, sometimes referred to as "locker bank" or "parcel lockers", are a group of individual lockers installed at fixed locations. Customers are provided with digital codes or keys when their packages are delivered to a locker. They are unattended facilities. Typical locations for shared lockers are residential areas, shopping centers, and convenience stores.

An example of the shared locker system is the Amazon Locker Hub. It was launched in 2011 and now with 900 locations across towns and cities in the US (Holsenbeck, 2018). The lockers not only service online orders for Amazon but also accept packages from any sender shipped via any logistics service provider. After the purchase of Whole Foods, Amazon has its locker network expanded into Whole Foods locations as well (Steiner, 2018).

The advantages of the shared locker system differ slightly from the CDPs. They both consolidate spatially spread-out delivery demand into concentrated locations which saves operational cost for delivery companies. As shared lockers can be installed inside retail stores, these stores are also potential beneficiaries of the system. Since the shared locker system is an unattended facility, it is much likely to further reduce the labor cost compared with CDPs. Besides, as each locker is provided with a dynamic and unique key/code, the security is well ensured. On top of that, because of the compactness of these facilities, they are also suited for installation in metro stations which can become even more convenient for commuters. For example, Singapore recently proposed an initiative of such a shared locker system that will be installed in train stations and residential areas (Lyu and Teo, 2019). Taking a further step, the concept of the mobile shared locker has been brought up (Schwerdfeger and Boysen, 2020). Instead of being fixed at static locations, these shared lockers are mobile to meet the temporally dynamic change of the demand. It was shown that a significantly smaller number of lockers are needed when they can move to meet pick-up demand.


(a) (b)

**Figure 7** Shared locker system: (a) static shared locker system and (b) mobile shared locker system (concept) (Schwerdfeger and Boysen, 2020)

### 3.2.3 Reception Boxes (RBs) and Delivery Boxes (DBs)

Reception boxes and delivery boxes are two other alternative delivery locations. Reception boxes are usually installed outside customers' home and delivery companies can put parcels and packages into these facilities by accessing them with keys or codes. A delivery box is usually temporarily attached to a locking device outside a customer's home when there is a package to be delivered to the customer. They are owned by delivery companies. These methods are not newly emerged and can date back to the late 90s.

These methods were once used for grocery deliveries since grocery orders are more time-sensitive and sometimes they even require refrigeration during transportation, where the reception and delivery boxes can be designed with such a feature(Punakivi et al., 2001). However, due to the high investment in the equipment and commitment from customers, these methods are not widely used nowadays.

### 3.2.4 Crowd-sourcing Delivery Methods

The crowd-sourcing logistics get its name from outsourcing delivery services to a crowd. Facilitated by the information technologies, a package can be co-transported by a group of non-professional people whose trip purposes are not for delivery (Sampaio et al., 2019). As an alternative to traditional delivery methods, crowd-sourcing delivery is believed to be sustainable.

An example of crowd-sourcing delivery was given in Sampaio et al. (2019). A distribution center on the outskirts of the city have goods to be delivered into the intercity, and in addition to utilizing their own fleet and staff to make the deliveries, individuals who live in the outer city can participate to handle partial flow of goods on their way to work. (Wang et al., 2016)proposed a similar crowd-sourcing delivery method where crowd-workers deliver parcels from parcel stations to final customers. Another example currently implemented in Paris was studied by (Akeb et al., 2018). In this "neighbor relay" method, an individual is paid to deliver parcels to customers within his/her neighborhood, which are delivered to him/her due to unsuccessful first delivery. This significantly reduces the cost stemmed from failed first home attended delivery.

The biggest motivation for crowd-sourcing delivery methods lies in its promptness. An online order can be delivered to the customer within hours. For the retailers, the crowd-sourcing is potentially beneficial because it is a “tech-heavy and asset-light” delivery method (Dolan, 2018). Contracted individual carriers utilize their own transportation tools to make deliveries, oftentimes from a retailer’s store. Therefore, it saves retailers operational costs in managing warehouse inventory, fleet, and staff. On the customers’ side, the service is speedy and respects the schedules of customers. Customers have more control over this on-demand service.

# 4.0 PARCEL LOCKER REVIEW

This review presents a collection of research findings aimed at fully sustainable locker solutions: their advantages including potential environmental impacts, its economic viability, and its ability to serve people's needs.

## 4.1 LOCKER ADVANTAGES

Parcel delivery and parking challenges have driven innovative mitigation strategies, each of which have benefits and limitations. Porch piracy and the not-at-home problem can be alleviated by permanent reception boxes at homes or carrier- or retailer-owned secure delivery but these solutions fail to address the larger issue of fragmentation, and are not appropriate for all delivery destinations.

Fragmentation can be reduced by developing collection points, which reduce delivery vehicle dwell time, decrease first-delivery failures, prevent theft of parcels, and provide consumers with flexibility in electing a suitable retrieval time. Many collection points operate inside private businesses such as convenience or box stores, with staff available for customer service. This arrangement limits pick-up availability to the operating hours of the hosting business (Iwan et al., 2016; Lachapelle et al., 2018; Morganti et al., 2014a).

European parcel lockers date back to 2002, but US parcel lockers were not implemented until Amazon began offering Amazon Hub Locker service in 2011. Soon after, the United States Postal Service (USPS) launched a gopost® locker pilot in select cities, and UPS developed their Access Point Locker™ network. FedEx has a limited network of Ship&Get® lockers in Texas, but primarily promotes in-store shipping centers and on-street drop boxes. UPS and FedEx lockers only accept in-network parcels, so consumers must travel to multiple collection points when receiving from different carriers. USPS and Amazon lockers can receive and hold freight from UPS and FedEx, which offers some flexibility to their users.

The appeal of a common carrier parcel locker system is its extension of consolidation benefits to consumers; instead of multiple trips to courier-owned lockers, common carrier systems offer consumers a one-stop pickup location for packages from different couriers. This reduces the travel burden to consumers. Publicly accessible, unmanned parcel lockers are secured via electronic locks with variable codes to offer consumers the convenience of 24/7 access (Deutsch and Golany, 2018). Though USPS's gopost and Amazon Hub Lockers will receive UPS- and FedEx-shipped parcels, a common carrier locker program ideally is independent from any singular courier in the highly competitive market of delivery logistics. The proprietary nature of logistics data and courier operations undermines the development of a common parcel locker systems, particularly in the US.

The development of a publicly accessible, self-serve, 24/7 parcel locker system can uncouple the operation of locker reception from the constraints of in-store retailers. During the Covid-19 pandemic, many businesses reduced their occupancy limits and/or hours of business, affecting the accessibility of parcel lockers hosted within. Self-service lockers are compatible with social distancing measures and an efficient, contactless method of delivery. Still there are other disasters—earthquakes, hurricanes, wildfires, landslides—than can preclude the normal operations of residential delivery; a system of freight lockers could be incorporated into civic and state emergency response plans, as disasters often require the expeditious distribution of resources at consolidated points (*Basic emergency operations plan*, 2016; Oregon Siesmic Safety Policy Advisory Commission, 2013).

At the time of authorship, Covid-19 has altered many aspects of travel and day-to-day activities, including transit volume and e-commerce volume. At this point it is uncertain how transit ridership, the economy, and workplace will evolve. However, a transit-oriented locker system offers an additional layer of infrastructure, and can be developed within existing, underutilized assets. Evidence is growing that transit is highly utilized by essential workers and those who cannot work from home (Sy et al., 2020), justifying a prioritization of systems that serve such workers.

## 4.2 ENVIRONMENTAL EXTERNALITIES

One of the highest priorities of environmental stewardship is to reduce carbon emissions; transportation practitioners can most urgently reduce emissions by minimizing vehicle miles traveled (VMT). Researchers exploring VMT-reduction strategies have modeled the benefits of stricter limits on home-delivery attempts. Edwards et al. compared the carbon impacts of the three-attempt allowance for home delivery, to that of more limited delivery allowances (Edwards et al., 2009). The baseline scenario assumed a tour of 120 home deliveries within 50 km (31 mi), and 100% success rate of first-attempt deliveries. Alternative scenarios included (i) three failed delivery attempts and a 15 km (9 mi) car trip by the consumer to a local depot for retrieval, and (ii) one failed delivery attempt, after which the parcel is taken to a collection point at a railway station and retrieved via a 3.2 km (2 mi) car trip by the consumer. Alternatives (i) and (ii) were applied to 10% and 50% of deliveries. The model predicted that alternative (ii) would only generate 26% of the emissions of alternative (i). The model's alternatives assume that private vehicles are used for recovering failed deliveries, but the authors note that trips to collection points made via active travel and transit modes have the potential to further reduce emissions (Kedia et al., 2019; Verlinde et al., 2019).

Giuffria et al. modeled direct delivery to parcel lockers, instead of any home delivery convention. In an urban context, direct locker delivery reduced carbon emissions by almost two-thirds (Giuffrida et al., 2016). For suburban contexts, lockers have an even greater potential to reduce emissions, because residence-based delivery trips in low-density areas are very resource-intensive. So long as a suburban consumer's locker-bound trip is either shorter than 6 kms (3.7 mi) or deviates from a regular driving trip less than that distance, their trip to a locker is expected to produce less emissions than conventional home delivery. In Belgium–where the collection point network is quite dense–consumer pick-up trips are easily completed as part of everyday errands, and trip-chaining has been demonstrated to produce less carbon emissions than home delivery, regardless of mode choice (Verlinde et al., 2019).

## 4.3 LOGISTICS EFFICIENCIES AND MARKET DEMAND

The potential benefits of the aforementioned collection point/locker models were qualified based on the amount of driving a consumer incurred to in the pick-up process, but environmental impacts are also mitigated from the increased efficiency of freight tours. In general, consolidation and higher delivery density increases the efficiency of urban logistics (Figliozzi, 2007). Delivery consolidation allows couriers to deliver more of their freight volume on shorter routes. Iwan et al. provides figures from the Polish courier InPost (Iwan et al., 2016), contrasting typical courier operations of 60 parcel deliveries per 150 km (93 mi) tour, to the delivery of 600 parcels to parcel lockers in just 70 km (43 mi). In Belgium's urban areas, conventional courier stops average a delivery of 1.2 parcels, but stops at parcel lockers average 25 parcel deliveries (Verlinde et al., 2019).

Though parcel locker service can reduce emissions and repeat-failed deliveries, most e-commerce consumers prefer home delivery. Belgian surveys find that 75% of respondents prefer home delivery (Beckers and Sanchez-Diaz, 2019) and Chinese surveys find that only 22% of consumers prefer collection points and parcel lockers (Xiao et al., 2018). Even in countries with established locker programs, actual usage rates of collection points or parcel lockers to range from about 10% to 20% (Morganti et al., 2014b; Verlinde et al., 2019). Low adoption rates may be partly due to a lack of familiarity of parcel lockers as a delivery option (Vikingson and Bengtsson, 2015), or because the option is not yet offered by many online stores (Lemke et al., 2016). The initial audit of the USPS gopost pilot identified their foremost need of increasing locker utilization (Office of Inspector General, 2013). Ultimately, Iwan et al. found the biggest barrier to adopting locker use is that consumers are required to make the final leg of the journey themselves (Iwan et al., 2016).

Despite low adoption rates, consumer interest in parcel lockers or collection points may be growing. Consumers are highly motivated by free delivery options; 52% of US online shoppers would consider delivery alternatives if it meant avoiding delivery charges (United Parcel Service of America, Inc., 2018). Additionally, as consumers become more reliant on e-commerce for sensitive or costly goods, the value of secure delivery increases. In 2016, a US home security company commissioned a nationwide study by Research Now, which found that 45% of the 2,000 survey respondents have had a parcel stolen or known someone who has (10). These negative experiences may also increase interest in freight lockers.

Multimodal travelers may be distinctly amenable to locker use. Among light rail passengers who shop online, 14% of survey respondents claimed a parcel locker or collection point was one of their top preferred locations to pick up parcels, and 40% to 67% respondents stated a willingness to use a common carrier locker system at a light rail station (University of Washington Urban Freight Lab, 2018). Similarly, nearly a quarter of survey respondents in Brussels prefer parcel pick-up at transit-oriented locations (25).

Among Polish consumers already using collection points, the majority (up to 79%) of users prefer lockers located close to home or to their employment (Iwan et al., 2016; Lemke et al., 2016). Almost 15% of the users surveyed indicated they would use the parcel lockers more often if they were "better located", particularly in proximity to public transport, shops, or supermarkets. New

Zealand consumers echoed a desire for lockers at supermarkets, likely because they are a frequent destination, and amenable to trip-chaining (Kedia et al., 2019).

## 4.4 LOCKER ACCESSIBILITY: MODE CHOICE AND CONVENIENCE OF ACCESS

Replacing automobile trips in favor of active travel (walking, biking, transit) increases the environmental benefits. Kedia et al. asked consumers about their willingness to use active transport modes to access collection points (Kedia et al., 2019). Over half the respondents (54%) were willing to walk or cycle to the collection point. The mean maximum tolerable distances to walk and cycle were 1.7 km (1 mi) and 2.33 km (1.4 mi), respectively. Light rail riders surveyed by the University of Washington Urban Freight Lab gave a three to six block range as the most common answer to the question of how far they were willing to walk with a parcel (University of Washington Urban Freight Lab, 2018). Researchers also noted that a relatively high proportion (24% to 42%) of riders said they were willing to walk seven or more blocks with a parcel. Survey results of parcel locker users in Brussels found that 12% to 15% of users accessed the parcel lockers via public transport, as many as one-third of users traveled on foot, and 18% to 23% of users traveled by bicycle (Verlinde et al., 2019). Moroz and Polkowski found that 44% of Polish millennials using parcel machines collect their parcels on foot (Moroz and Polkowski, 2016).

Based on survey responses in the cited literature, the accessibility to a parcel locker is likely to influence the utilization of such a delivery service. For urban areas in the Eastern part of the Paris region, the population is, on average, only 1.6 km (1 mi) in Euclidean distance from the nearest pickup point. Additionally, half of the pickup points in this region are located within 300 m (less than 1,000 ft) of a commuter railway station (Morganti et al., 2014a). InPost prefers to locate their parcel lockers in areas of high population density, high traffic pedestrian areas, and near local commuting hubs (Iwan et al., 2016). Lee et al. agrees that accessibility to the parcel lockers is an important factor to consider when selecting an optimal location (Lee et al., 2019). Placing them along the daily life path of consumers or near public transportation is believed to enhance their utilization. When discussing evaluation criteria for light rail-locker sites, residential density and walkability were paramount to the majority of the stakeholders involved in the project (University of Washington Urban Freight Lab, 2018). High foot traffic also promotes an “eyes on the street” effect, giving pedestrians a greater perception of security (Painter, 1996). Perceived and actual security supports the use of lockers for receiving items of value, as opposed to a conventional front door drop-off. Additionally, since parcel lockers have not yet saturated the US market, high visibility may be advantageous to promote utilization of this delivery alternative.

Most of the research on transit-based locker systems focus on light rail stations as the facility of choice. In Portland, several transit centers also have substantial foot traffic, even if they do not include light rail access. The presence of park-and-rides at transit centers and rail stations is noted because most research on the customer experience assumes that the catchment area for transit riders is constrained by the distance they are willing to walk with a parcel, and do not consider the riders that access transit via car or bicycle. Previous research in Portland has already shown that package delivery can provide access to goods and services for many groups that are mobility impaired or face other accessibility barriers (Keeling and Figliozzi, 2019). Hence, this research presents an equity analysis, to demonstrate that the selection of locker sites can help a city reach its equity goals, particularly in light of racial and income disparities.

# 5.0 PARCEL LOCKERS AT TRANSIT FACILITIES

Last mile logistics are highly context specific as infrastructure, travel demand, and land use patterns vary greatly. The goal of this section is to analyze the potential of locker facilities at transit stations and how they can meet multiple demands in terms of efficient logistic operations, competitive service to consumers, and equity.

## 5.1 INTRODUCTION

Transit goals have typically focused on commuter trips but facilitating urban last-mile freight logistics is a potential strategy to increase transit ridership and mitigate the demands of parcel distribution on the transportation network. Presently, most parcel lockers operate out of private businesses, but consumer surveys have found that transit users may be interested in locker facilities at transit connections. The implementation of an unmanned, secure, common carrier parcel locker system could have benefits for non-transit users as well.

Consolidation of deliveries is expected to benefit courier companies by allowing operations at increasingly competitive rates, and retailers and consumers benefit from convenience and low shipping rates. This evaluation includes a case study of the light rail stations, transit centers, and transit malls in the greater Portland, OR area. The potential of hosting transit sites is reviewed based on ridership (the number of ons/offs at transit facilities), the number of residents in influence areas (whether transit users or not), and a framework for prioritizing locations based on best-practice equity metrics. Mode-specific accessibility of park-and-ride facilities outside the urban core, as well as the potential of consolidated distribution points in city resiliency plan are discussed.

## 5.2 METHODOLOGY

This evaluation synthesizes Portland, Oregon's transportation policy goals, transit data and demographic data from the 2018 American Community Survey 5-yr estimates (United States Census Bureau, 2019). Transit facilities included in this analysis include light rail stations (MAX), transit centers (TCs), park-and-ride facilities (PaR), and the downtown transit mall.

### 5.2.1 Ridership Analysis

Based on the examples in the literature review, locker service adoption is related to high volumes of foot traffic. TriMet's validated ons/offs data was used as a measure of expected foot traffic at transit stops. The data used was from the fall quarter of 2019 (TriMet, 2020), before normal traffic patterns were altered by the Covid-19 pandemic. It is worth noting that at the time of authorship, the pandemic response is not yet resolved, and ridership patterns may not return to the same pre-pandemic pattern. Future review should evaluate this approach after transportation patterns have re-stabilized.

Estimating the foot traffic at transit centers, park-and-rides, and rail stations is relatively straightforward; the amount of boarding and alighting passengers ("ons/offs") most directly reflects foot traffic. From stop-level data, bus/light rail stops occurring at the same transit facility are aggregated as to reflect the potential catchment of a locker site.

The transit mall differs from other transit facilities. It runs the length of two one-way streets, SW $5^{th}$ and SW $6^{th}$ avenues, through downtown Portland. Rail stations are located about a quarter mile apart, with multiple bus stops located between rail stops. Unlike the rest of the transit network, it is reasonable to bound catchment areas based on the qualitative aspects of the mall's design and operational flow. To this end, catchment area bounds were formed by aggregating foot traffic at and between rail stops (**Error! Reference source not found.**Figure 8). This aggregation is different than typical association of same-route stops serving travel in opposite directions. The transit mall generally orients travel along the one-way streets with trip planning/navigation apps generally suggesting passengers to alight at the nearest stop upstream of their destination. In accordance with the findings in the literature review, it is assumed that transit users would be willing to walk up to 6 blocks to access a locker; Portland blocks are about 200 feet long.

Situating transit mall lockers between MAX stations is also amenable to courier needs. Staging will be easier when not at MAX stations, because the rail lines at MAX stations occupy the curbside lane at these stations. Bus stops between MAX stations have bays that can accommodate multiple 40-ft. buses. If an agreement was made such that locker-loading deliveries occur outside of peak transit service hours, freight vehicles could potentially use empty bus bays for speedy loading/and unloading. For lockers located at bus stops between MAX stations, out-of-direction walking can be minimized if lockers are situated closer to the upstream MAX station. **Error! Reference source not found.** Figure 9 shows the layout of a bus station between rail stops on the transit mall. The bus bay is clearly visible, and the sightlines would allow multi-tasking transit riders to pick up their parcel while keeping an eye on the advancing buses and rail cars while retrieving their parcel. These stations already have trash cans, electrical wiring, and an established presence in the fabric of downtown.


**Figure 8** Defining transit mall locker catchment areas

**Figure 9** Mall qualities: Bus stop, bus bay, and sightlines of light rail (Google Earth)

### 5.2.2 Locker Accessibility to Areas Surrounding Transit Facilities

Transit facilities are typically designed to be accessible 24-hours a day and to operate unmanned. These arrangements befit a common carrier locker program; unmanned lockers offer more flexibility in retrieval than lockers located inside private businesses with limited operating hours. Therefore, a successful common carrier locker program may even attract customers who do not use transit facilities, especially those who work, commute, and run errands during non-traditional work hours, and live in suburban areas, where there tend to be fewer 24-hour or late night businesses. A special focus was placed on suburban park and ride (PaR) and transit center (TC) facilities, as studies discussed in the literature review found consolidated package options in the suburbs to have extra efficiency and environmental benefits.

TriMet has an extensive network of PaRs in the suburbs. To determine potential service populations for PaRs and TCs, a spatial analysis was performed to estimate the population within reach of a locker program based on mode choice. TriMet's support of pedestrian- and bike-friendly development has been grounded in concerted efforts and reports such as 2011 Pedestrian Network Analysis Report (TriMet, 2011), and the 2016 TriMet Bike Plan (TriMet, 2016). All the TCs and TriMet-owned PaRs provide some form of bicycle parking accommodation, whether by covered racks, bike lockers, or a keycard secured bicycle storage facility.

For this spatial analysis, a half-mile walking distance was assumed as the threshold of a comfortable pedestrian trip to access transit facilities. This threshold is congruent with the default walk limits in the TriMet Trip Planner tool. For commutes chaining a bicycle trip to a transit trip, a 2005 survey found that Portland's average bicycle trip to access light rail was 2.1 km (1.3 mi) long (Lasky, 2005). Though the study's sample size was small (n = 36), the trip lengths are based on actual commuter trips, and are similar to findings in other studies. This threshold is more conservative than the default bicycle limit in the TriMet Trip Planner tool, which is set at 3 miles. Lastly, a driving threshold was defined for users accessing PaR connections. A 2011 TriMet memo detailing the expected use as justification for new PaRs assumed a catchment area around PaRs based on a 10-minute drive. Since driving speeds vary greatly based on street type, an estimated average travel speed was based on the region's average commute length of 7.1 miles, and taking 26 minutes (Small, n.d.). From these averages, a peak travel speed of 16.4 mph was derived. Thus, the catchment assumption of a 10-minute drive translates into a 2.73-mile range.

Though several studies use network distances through the ArcGIS Network Analyst Service Area problem solver (Kedia et al., 2019; Morganti et al., 2014b; University of Washington Urban Freight Lab, 2018), Euclidian distances were used for the purposes of this multimodal analysis. Correction factors were applied to these distances based on the mean circuitry of Portland's driving and walking networks (Boeing, 2019). Although cyclists can legally travel on any of the streets in Portland except the intracity freeways, Portland cyclists chose more comfortable routes averaging 0.24 miles longer than the shortest route possible (Portland State University et al., 2008). The Euclidian buffer for bicycle trips was adjusted for this average routing cost in addition to the network circuitry for the drivable/bikeable street network.

These buffer distances represent the areas of influence around TCs and PaRs. Demographic data was uniformly proportioned at the Zip Code Tabulation Area (ZCTA) level. Spatial analysis packages in R estimated the population with acess to the transit facilities according to travel mode. **Error! Reference source not found.** Figure 10 and **Error! Reference source not found.** Figure 11 show maps (generated with MapView package in R) of PaR and TC buffers by mode, respectively. For this review, only the PaRs owned by TriMet were considered; other lots are generously shared by local businesses and churches but are not reviewed for parcel locker suitability.

Finally, accessibility for delivery vehicles should also be considered. Presently, cargo bicycles operate in downtown Portland successfully and they can easily access the wide sidewalk areas (Tipagornwong and Figliozzi, 2014) or gain other access that traditional freight trucks cannot. Cargo bicycles  can contribute to important GHG reductions (Figliozzi et al., 2020). In addition, small sidewalk autonomous delivery robots (Jennings and Figliozzi, 2019) could be utilized to increase the efficiency and resiliency of the locker system.

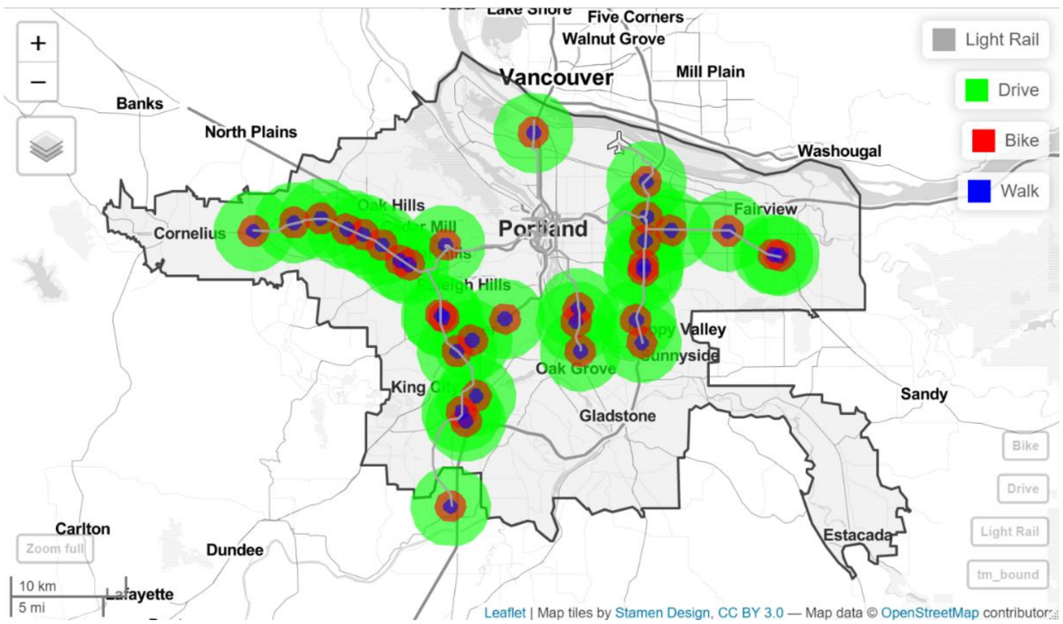


**Figure 10** Service area and modal buffers around TriMet-owned PaR facilities

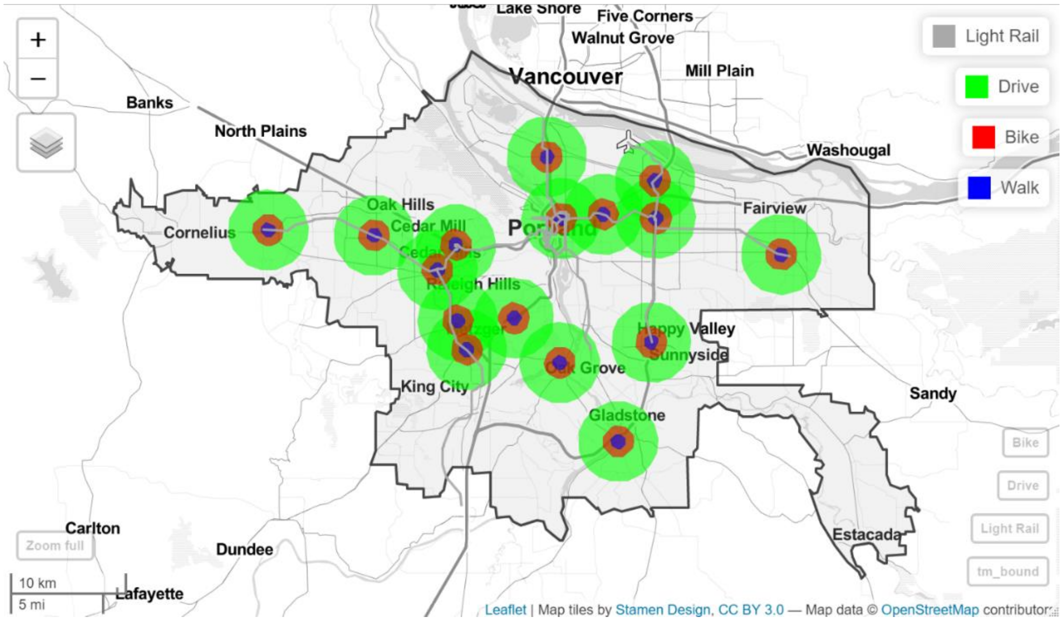



**Figure 11** Service area and modal buffers around TC facilities

## 5.3 RESULTS

Table 2 lists the top 20 transit facilities by ridership volumes, as ranked by total ons and offs in fall 2019. Figures about the connectedness of these locations and facility types are provided. Locations with four rail connections tended to have the highest ridership volumes. Lloyd Center MAX station is the only high-ranking transit facility that is neither a PaR or a TC. Lombard TC is the least connected location of the high-volume list, with only one rail connection and two bus route connections.

Most of the high-ridership transit facilities are within the central city, including along the the transit mall, where PaR facilities are absent. However, the spatial analysis measured the total populations within convenient walking, biking, and driving distances. When ranked by population access, the top 15 locations are all located in the central city. But the next ten highest-reaching transit facilities all have a PaR amenity. Figure 12 displays these highly-accessible transit facilities outside the central city, with population reach shown by mode. Although these facilities are outside the central city where the population is less dense, a significant population would be able to reach a parcel at these locations with only a ten-minute drive. The walking reach is much less, but this suburban ring of potential locker sites can complement a centrally-located network of pedestrian-friendly locker sites downtown.

Furthermore, if suburban locker site locations are leveraged as part of a civic resiliency plan, the accessibility shown below further quantifies the civilian reach of a PaR as consolidated distribution centers. Locating distribution centers where there are lockers would streamline a civilian's trip burden to retrieve privately-ordered parcels and publicly distributed emergency supplies. Large parking lots in the Portland metro were utilized during the summer 2020 wildfires for distribution to wildfire evacuees as well as for drive-in Covid testing (Foden-Vencil, 2020; Metro News, 2020).

However, for an emergency that damages the road network, such as a large earthquake, having more, smaller distribution centers within walking/cycling distance will be helpful.

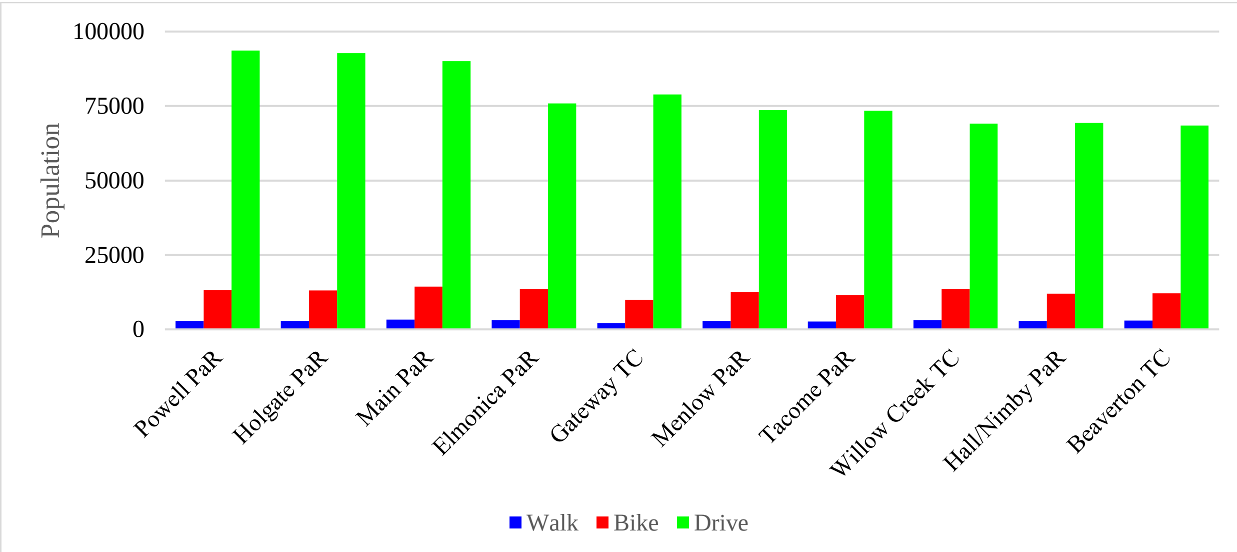



**Figure 12** Reach by mode of park-and-ride facilities outside the central city

## 5.4 EQUITY ANALYSIS

Lastly, analyzing the socioeconomic makeup of the population and prioritizing equity goals is strongly promoted by the City of Portland and Portland Bureau of Transportation (PBOT). Household income levels and employment are not uniformly distributed across the city, so the selection of locker sites should consider how the services offered will benefit some groups more than others.

**Table 2** Transit facilities with the 20 highest ridership volumes, fall 2019, weekday only

| | | Connections | | Facility type | | | PaR | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Rank** | **Location** | **Rail** | **Bus** | **TC** | **Mall** | **Stop** | **Spaces** | **Full by:** | **Ons/off** | **Land Use** |
| 1 | Pioneer Sq.—Madison on 6th | 4 | 13 | | x | | — | — | 18,291 | Downtown |
| 2 | Beaverton TC | 3 | 11 | x | | | — | — | 18,253 | Residential |
| 3 | Gateway/NE 99th | 3 | 7 | x | | | 690 | 7:30a | 16,470 | Residential |
| 4 | Pine—Pioneer Court on 6th | 4 | 12 | | x | | — | — | 14,433 | Downtown |
| 5 | Oak—Pioneer Place on 5th | 4 | 17 | | x | | — | — | 14,378 | Downtown |
| 6 | Rose Quarter | 4 | 8 | x | | | — | — | 14,213 | Arena |
| 7 | Pioneer Place—Jefferson on 5th | 4 | 12 | | x | | — | — | 13,526 | Downtown |
| 8 | Clackamas Town Center | 1 | 12 | x | | | 750 | not full | 9,937 | Shopping |
| 9 | Madison—Montgomery on 6th | 2 | 14 | | x | | — | — | 8,939 | Downtown |
| 10 | City Hall—Mill on 5th | 2 | 13 | | x | | — | — | 8,324 | Downtown |
| 11 | Sunset TC | 0 | 9 | x | | | 630 | 7:30a | 8,046 | Residential |
| 12 | Mill—Jackson on 5th | 2 | 12 | | x | | — | — | 7,972 | University |
| 13 | Lloyd Center | 3 | 2 | | | x | — | — | 7,903 | Business |
| 14 | Davis—Pine on 6th | 2 | 15 | | x | | — | — | 7,271 | Downtown |
| 15 | Hollywood TC | 3 | 4 | x | | | — | — | 6,536 | Shop+Res. |
| 16 | Glisan—Couch on 5th | 2 | 9 | | x | | — | — | 5,460 | Downtown |
| 17 | Willow Creek | 1 | 5 | x | | | — | — | 5,301 | Downtown |
| 18 | Lombard TC | 1 | 2 | x | | | — | — | 5,243 | Residential |
| 19 | Couch—Oak on 5th | 2 | 14 | | x | | — | — | 4,886 | Downtown |
| 20 | Montgomery—College on 6th | 2 | 12 | | x | | — | — | 4,406 | University |

PBOT has reviewed national best practices to present a simplified approach to calculating a race+income equity score, as these two factors include many intersectional determinants of opportunity (37). Race and income data are gathered for the contextual area of interest, and quintile breakpoints are established for assigning 1-5 scores for both race and income factors. The lowest possible equity score is 2, and the highest possible equity score is 10.

For this evaluation, the area of interest is all ZCTAs intersecting and included in the TriMet service boundary, and the previously established walking thresholds provide the basis for estimating the demographic profile associated with transit facilities. Demographic data is provided by the ACS 2018 5-year estimates (United States Census Bureau, 2019).

To acknowledge the opportunity disadvantages for non-white racial groups, the percentage of white-only residents was used to figure the race subscore, with white-only prevalence being assigned a lower equity point value. Income levels were similarly weighted to assign lower subscores to higher median household incomes. The transit facilities with the highest equity score should receive priority in locker site selection. See Table 3 for an abridged table of the equity analysis results.

**Table 3** Equity Evaluation for Residents Within 1/2 Mile Walk to Transit Facilities (abridged)

| **Facility** | **% of white-only residents** | **% of median household income** | **Subscore, race** | **Subscore, income** | **PBOT equity matrix score** |
|---|---|---|---|---|---|
| SE Powell Blvd Park & Ride | 65% | 69% | 5 | 5 | 10 |
| E 122nd/Menlo Park Park & Ride | 69% | 67% | 4 | 5 | 9 |
| Gateway/NE 99th Ave TC Park & Ride | 68% | 74% | 4 | 4 | 8 |
| Elmonica/SW 170th Ave Park & Ride | 67% | 106% | 5 | 2 | 7 |
| Hall/Nimbus Park & Ride | 83% | 103% | 2 | 3 | 5 |
| SE Tacoma/Johnson Creek Park & Ride | 87% | 95% | 1 | 3 | 4 |
| Tigard TC Park & Ride | 85% | 113% | 1 | 2 | 3 |
| Barbur Blvd Park & Ride | 86% | 139% | 1 | 1 | 2 |

## 5.5 DISCUSSION

Based on the data collected, a parcel locker system leveraging the transit mall's ridership is strategic based on ridership volumes; it offers consolidated parcel collection points at the densest area of the city's employment and transit networks. Not only does the transit mall define the nexus of transit use, but the mall's well-designed pedestrian facilities may even attract non-transit riders; workers may elect to take a mid-shift short walk to send or pick up parcels at transit mall facilities. As mentioned in the methodology, the transit mall has environmental characteristics that are suitable for a locker site, such as the sightlines necessary for riders to remain watchful for their desired transit vehicle, and also a high amount of foot traffic to promote a sense of safety in numbers. Further research could model the ramifications of allowing freight vehicles to temporarily unload in bus bays; as assistive devices and automation in logistics handling increases, the dwell time of locker operations may become increasingly succinct.

Regarding GHG reductions, the literature review indicates that utilization of lockers generate GHG emissions reductions of up to two thirds. However, if packages are picked up as part of a transit trip there is potentially larger reduction in GHG emissions given the increased efficiency of delivery vehicles and the reduction in delivery vehicle-miles. When customers drive to the transit station to access a locker, other variables must be included in the analysis like type of vehicle driven. For example, the GHG reduction potential can still be significant if the user drives an electric car but less significant (or even negative) if a vehicle with below average fuel efficiency is utilized (Figliozzi, 2020). The estimation of GHG reductions is beyond the scope of the paper and should be explored in future research endeavors.

Three-quarters of the high foot traffic locations are in the central city, and the street network in Portland is already a host of many different uses. Although Rose Quarter TC has high ridership and connectivity, the rail that dominates its landscape is inflexible, should a cargo vehicle happen on a conflict. Rose Quarter TC generally has good sightlines and often has transit security attendants. However, Rose Quarter TC has extreme variations in traffic activity—it is the arena home of the Portland Trailblazers and the city's largest music venue. The reliability needed by couriers and the unpredictability of large crowds should be preemptively addressed. Again, cargo bicycles or sidewalk autonomous delivery vehicles or robots may be needed for their advantages in maneuverability.

Compared to the granular detail of establishing a locker system into the inner city's maturing streets, the peripheral park-and-rides generally have more space (Figure 13). Ultimately, careful consideration should be given to the staging needs of the delivery driver. TriMet's transit centers are designed for heavy vehicles (i.e. buses) so turning radii and sight lines would be conducive to commercial vehicles. However, careful design development is needed to orient the locker facility such that the number of bus/truck and truck/pedestrian/bicyclist conflicts is minimized. Lastly, further analysis can recommend a routing framework such that different courier companies have staggered appointments for loading lockers, hopefully in line with their freight products and not conflicting with peak ridership times. Transit hourly data shows that many stops experience their PM peaks of ons/offs as early as the 3-4pm hour, which presents challenges for afternoon delivery tours that want to avoid the PM rush.

**Figure 13** Street view of the Clackamas TC covered parking facility (Google Earth)

It should be pointed out that although calculations were made for up to a half-mile walking distance, a more realistic approach would be to model the parcel locker usage as a function of distance, with the rate decreasing past a set distance band, e.g., a half of a mile. Future research could consider this approach once more insight into consumer travel pattern preferences is collected. Further application of network analysis could create more precise figures of accessibility. Similarly, detailed questions about behavior (e.g. choosing different pickup options) are outside the scope of this paper and better addressed by future studies that analyze tradeoffs utilizing revealed preference data or stated choice surveys.

Transit agencies could be more proactive in developing public-private partnerships with interested couriers. Portland's transit network has high ridership volumes and overall foot traffic along Portland's transit mall. Other central locations such as the Rose Quarter TC demonstrate the relationship between a high number of rail lines and high ridership volumes, but they also carry constraints such as the spatial bounds of existing infrastructure. In contrast, suburban park-and-rides generally have more space to install automated parcel locker facilities, but to compensate for lower transit foot traffic, the flexibility and security of 24-hour operations should be highlighted to attract consumers who do not otherwise utilize transit. Including suburban locations in a network-approach to parcel lockers can also add a layer of distribution infrastructure that makes the suburbs more resilient to emergencies. The Covid-19 pandemic is still highlighting the different impacts of disaster between low-density and high-density areas. The development of a locker program is amenable to incremental expansion that involves iterative review of the changes in consumer needs, travel pattern changes, and consumption.

Lockers are congruent with the interest in transit-oriented development (TOD), which has typically centered on developing housing near transit facilities. A transit-oriented common carrier parcel locker system is a suitable complement to existing TOD plans, as it offers a relevant service and potentially a win-win-win solution: couriers can operate more efficiently, consumers can retrieve parcels securely and conveniently, and the environment can benefit from reduced congestion and air pollution from fewer courier and consumer miles traveled. Since locker adoption in the US is still in nascent phases, transportation practitioners can widen the evaluation of existing transit infrastructure to better negotiate public-private partnerships towards the sustainability goals of economic prosperity, environmental benefit, and equitable service to people.

# 6.0 LAST-MILE DELIVERY ROUTE AND SHARED LOCKER LAOCATION OPTIMIZATION

## 6.1 INTRODUTION

E-commerce challenges urban logistic systems. On one hand, the rising and compelling transportation demand creates traffic congestion and related environmental problems. On the other hand, the further worsened traffic condition impairs the last-mile delivery operation efficiency. As an innovative, cost-effective, and efficient last-mile delivery method, adopting shared parcel lockers has great potentials for improving the operation efficiency of last-mile delivery. However, very few studies have been devoted to the design of a shared parcel locker system in urban areas (Savelsbergh and Van Woensel, 2016).

In this section, a mathematical model jointly optimizing delivery vehicles' routes and the locations of shared parcel lockers is presented first. The delivery vehicles visit both conventional home addresses and shared locker locations, which is referred to as "mixed-route". The mathematical model specifically solves the conditional relations that if a package is chosen to be delivered to a shared locker location, then the original home address should not be visited by a delivery vehicle. Computational experiments with real network input are carried out and the efficiency gains are quantified through the use of metrics such as vehicle miles travelled (VMT) and total system cost.

## 6.2 MATHEMATICAL OPTIMIZATION PROBLEM

The mathematical optimization problem jointly minimizing the cost of mixed delivery routes and the cost of location shared lockers is presented below.

$$\min f(x,y,z) = \sum_{i \in \mathcal{E}\cup\mathcal{D}} \sum_{j\in\mathcal{E}\cup\mathcal{D}} c_{ij}x_{ij} + (\gamma - 1)\sum_{i\in\mathcal{C}} \sum_{j\in\mathcal{S}} (c_{ij} + c_{ji})y_{ij} + \sum_{k\in\mathcal{S}} z_k I_k \tag{1}$$

$$s.t. \sum_{j\in\mathcal{E}\cup\mathcal{D}} x_{ij} = 1, \qquad \forall i \in \mathcal{C} \tag{2}$$

$$\sum_{i\in\mathcal{E}\cup\mathcal{D}} x_{di} = |\mathcal{V}| \tag{3}$$

$$\sum_{i\in\mathcal{E}\cup\mathcal{D}} x_{id} = |\mathcal{V}| \tag{4}$$

$$\sum_{i\in\mathcal{E}\cup\mathcal{D}} x_{ij} - \sum_{i\in\mathcal{E}\cup\mathcal{D}} x_{ji} = 0, \qquad \forall\, j \in \mathcal{E}, \tag{5}$$

$$y_{ij} \geq x_{ij} + x_{ji} - 1, \qquad \forall\, i \in \mathcal{C}, j \in \mathcal{S} \tag{6}$$

$$y_{ij} \leq x_{ij}, \qquad \forall\, i \in \mathcal{C}, j \in \mathcal{S} \tag{7}$$

$$y_{ij} \leq x_{ji}, \qquad \forall\, i \in \mathcal{C}, j \in \mathcal{S} \tag{8}$$

$$\sum_{i \in \mathcal{C}} x_{ij} + \sum_{i \in \mathcal{C}} x_{ji} > 2 \sum_{i \in \mathcal{C}} y_{ij}\,, \qquad \forall\, j \in \mathcal{S} \tag{9}$$

$$l_i - l_j + Q x_{ij} \leq Q - D_j, \qquad \forall\, i, j \in \mathcal{C} \cup \mathcal{D} \tag{10}$$

$$0 \leq l_i \leq Q, \qquad \forall j \in \mathcal{E} \cup \mathcal{D} \tag{11}$$

$$l_i - l_j + Q\big(x_{ij} - y_{ij}\big) \leq Q - \sum_{k \in \mathcal{C}} D_k y_{jk}\,, \qquad \forall\, i \in \mathcal{C}, j \in \mathcal{S} \tag{12}$$

$$l_i - l_j + Q\big(x_{ij} - y_{ji}\big) \leq Q - \big(x_{ij} - y_{ji}\big) D_i, \qquad \forall\, i \in \mathcal{S}, j \in \mathcal{C} \tag{13}$$

$$l_i - l_j + Q x_{ij} \leq Q - \sum_{k \in \mathcal{C}} D_k y_{jk}\,, \qquad \forall\, i \in \mathcal{S} \cup \mathcal{D}, j \in \mathcal{S}, i \neq j \tag{14}$$

$$l_i - l_j + Q x_{ij} \leq Q, \qquad \forall\, i \in \mathcal{S}, j \in \mathcal{D} \tag{15}$$

$$\sum_{i \in \mathcal{C}} \sum_{v \in \mathcal{V}} D_i\, y_{ikv} \leq Q_k z_k, \qquad \forall\, k \in \mathcal{S} \tag{16}$$

$$x_{ijv} \in \{0,1\}, \qquad \forall\, i, j \in \mathcal{E} \cup \{d\}, v \in \mathcal{V} \tag{17}$$

$$y_{jiv} \in \{0,1\}, \qquad \forall\, i \in \mathcal{C}, j \in \mathcal{S}, v \in \mathcal{V} \tag{18}$$

$$z_k \in \{0,1\}, \qquad \forall\, k \in \mathcal{S} \tag{19}$$

$$l_i \in R^+, \qquad \forall\, i \in \mathcal{E} \cup \mathcal{D} \tag{20}$$

Notations used in the mathematical program is listed in Table 4. There are two sets of decision variables for the model. Variables $\boldsymbol{x}$ determine the sequence of the visits by delivery trucks, and the variable $\boldsymbol{y}$ determines whether a customer is assigned to a shared locker so that no delivery trucks are needed for visiting it. We refer to the $\boldsymbol{y}$ variables as (locker-customer) assignment variables hereinafter. The formulation adopts the three-index formulation in the vehicle routing literature. We note that the problem is not simply a capacitated vehicle routing problem but has some additional decisions involved.

The objective function is comprised of four terms. The first term is related to delivery truck routing variables $\boldsymbol{x}$. The first term adds up the travel costs for traveling between the nodes in the extended set $\mathcal{E}$ and the depot set $\mathcal{D}$. Note that the first term also includes extra travel costs for delivery trucks for visiting demand sites that are assigned to a shared locker, which should be excluded and computed as customer pick-up cost. This is realized by the second term. It is related to assignment variables between demand sites and shared lockers. When there is an active assignment ($y_{ij} = 1$ for instance), it incurs the travel cost equal $\gamma(c_{ij} + c_{ji})$ for the customer pick-up trip. In addition, the extra cost added by the first term, $c_{ij} + c_{ji}$, should be subtracted for delivery trucks, which gives the simplified form as is shown in the second term. Note that the travel cost between locations $i$ and $j$ are not necessarily symmetric. We also note the difference in the summation domain for these terms in the objective and claim that the first three terms set the actual total travel cost for both delivery trucks and customer pick-ups. The third term computes the capital investment of the selected shared locker facilities. Hence, the objective function of the proposed model minimizes the actual total travel costs for both delivery trucks and customer pick-up trips, and the capital investment on the selected shared lockers.

Constraints (2) – (5) are flow conservation constraints for delivery vehicles. Constraints (6) – (8) set the relationship between the vehicle routing variables and customer assignment variables. They ensure that a customer is assigned to a shared locker location only if a delivery truck visits the demand site directly from the shared locker location and returns to the shared locker after the visit. That is, a customer effectively switches from home delivery to a shared locker delivery. (9) – (15) are subtour elimination constraints. Note that subtours are eliminate with the use of an additional node label variable, $l_i$, which is a type of MTZ formulation (Miller et al., 1960). Also, constraints (11) set the delivery vehicle capacity. Constraints (16) stipulate that the total capacity of a candidate shared locker location is not exceeded. (17) – (20) are variable definition constraints.

**Table 4** Notation Glossary

| Symbol | Definition |
|---|---|
| $i, j$ | Indices for demand sites and shared locker locations |
| $k$ | Index for shared locker locations |
| $d, d'$ | Index for the depot |
| $\mathcal{C}$ | Set of customers |
| $\mathcal{S}$ | Set of potential shared locker locations |
| $\mathcal{D}$ | Set of the depot, $\mathcal{D} = \{d, d'\}, \mathcal{D} \cap \mathcal{E} = \emptyset$ |
| $\mathcal{E}$ | Set of extended customers including customers and candidate shared locker locations, $\mathcal{E} = \mathcal{S} \cup \mathcal{C}$ |
| $\mathcal{V}$ | Set of delivery trucks |
| $d_{ij}$ | Distance between location $i$ to location $j$ |
| $\rho$ | Mileage-based travel cost parameter for delivery trucks |
| $c_{ij}$ | Travel cost from location $i$ to location $j$, $c_{ij} = \rho\, d_{ij}$ |
| $\gamma$ | Travel cost reduction parameter |

| | |
|---|---|
| $Q$ | Capacity of a delivery vehicle |
| $Q_k$ | Total shared locker capacity at location $k$ |
| $D_i$ | Demand for customer $i$ |
| $I_k$ | Capital investment on opening a shared locker bank |
| $x_{ij}$ | Whether a delivery vehicle travels directly from location $i$ to location $j$ |
| $y_{ij}$ | Whether demand site $i$ is assigned to the shared locker location $j$ |
| $z_k$ | Whether the shared locker $k$ should be opened or not |
| $l_j$ | Node labels (representing visiting sequence of a delivery vehicle) |

## 6.3 COMPUATIONAL EXPERIMENTS

In this subsection, we carry out some experiments on three networks with different parameter settings to show the cost savings with the shared lockers in the last-mile delivery problem.

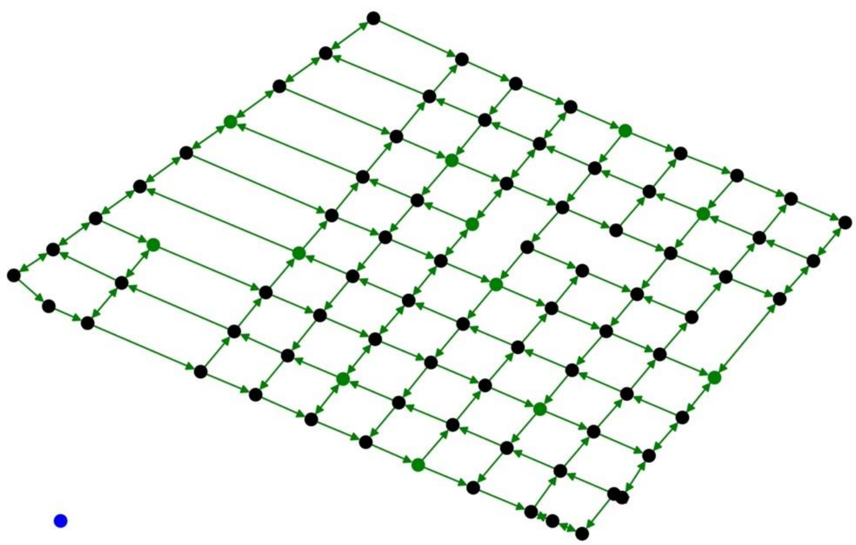
### 6.3.1 Test Networks and Parameter Settings

The three networks used for these experiments are as follows. The first network is adopted from the literature on vehicle routing problems (VRP) (Fisher, 1994), which serves as a general network. The data set is referred to as F-n045-k4. The network has 44 demand sites with heterogeneous delivery requests. Besides, we randomly generated 7 candidate locations of shared lockers. Two trucks are used for the delivery and with the same capacity of 3800. With the same data set, we randomized demand sites' locations and regenerated another instance named "F-n045-k4-2" as the second network. 15 candidate SLs are regenerated for this instance. The third network serves as a case study. We selected the area of downtown Minneapolis as the subject. The land use of the study area is commercial retail, office, and mixed. The road network is gridiron with many one-way roads. This instance is suitable to show the application of the shared locker system in high-density areas with some traffic restrictions. All-to-all shortest path is computed to obtain the distances between points of delivery. Figure 14 shows the study area and road network sketch. Table 5 summarizes the network information.

**Table 5** Test network information

| Index | Network | # of demand sites | # of candidate SLs | # of delivery trucks | Truck capacity | Depot index |
|---|---|---|---|---|---|---|
| 1 | F-n045-k4 | 44 | 7 | 2 | 3800, 3800 | 0 |
| 2 | F-n045-k4-2 | 44 | 15 | 2 | 3800, 3800 | 3 |
| 3 | Minneapolis | 74 | 12 | 2 | 500, 500 | 0 |

(a) The study area is shaded in green.



(b) Single arrow lines indicate one-way streets. Black and green node represents demand sites and shared locker locations, respectively. The blue node represents the truck depot.

**Figure 14** Downtown Minneapolis Network

The truck delivery cost parameter $\rho$ is estimated to be \$3.0/mile. According to the American Transportation Research Institute's report, the average cost of operating a truck is \$1.8 per mile in 2018 (ATRI, 2019) (including fuel cost, maintenance cost, insurance, driver wage, etc.), and considering that last-mile delivery trucks mostly drive on local roads and have frequent stop-and-go's (a stop cost was estimated to be \$0.4 per delivery by Campbell et al. (2018) and the driver also need to deliver packages to the end customers. We, therefore, estimate the delivery truck mileage-based operational cost as above. The fixed cost for installing shared lockers was estimated to be \$300 per unit and is converted to daily cost with a 5-year amortization period. All computational experiments were executed on a personal laptop with Intel CORE-i7 @ 1.8GHz and 16 GB RAM, and the optimization solver Gurobi 9.0 was used to solve the resulting optimization problems.

### 6.3.2 Sensitivity on the Customer Pick-up Cost Discounting Factor

The proposed last-mile delivery method with shared lockers relies on the collaborative cooperation between delivery companies and customers. The cheaper the customer pick-up travels are, the greater the total cost the system can save. In this section, therefore, we carry out the sensitivity analysis on the customer pick-up cost discounting factor $\gamma$ to showcase the total cost trend for different values of $\gamma$. In Table 6, we record the total cost and other solutions and computational details.

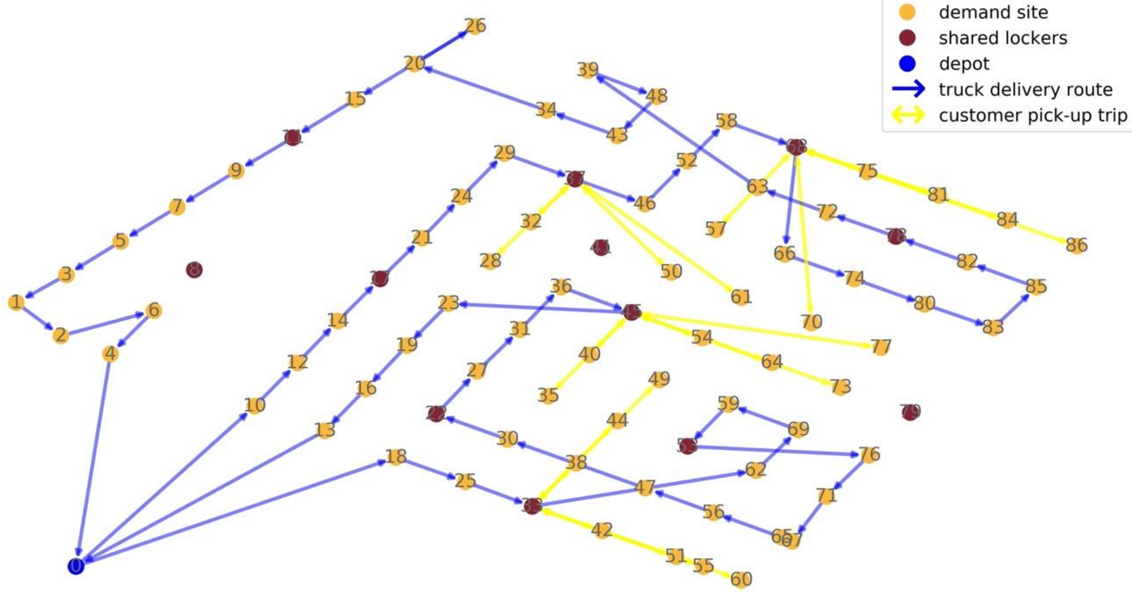
**Table 6** Sensitivity on the pick-up cost discounting factor

| Network Index | $2\gamma$ | Objective Value | Gap (%)* | Selected shared locker facilities |
|---|---|---|---|---|
| 1 | 0.5 | 1632.6 | 9.9 | 2,4 |
| | 0.6 | 1652.3 | 9.9 | 2,3 |
| | 0.7 | 1681.6 | 9.9 | 3 |
| | 0.8 | 1699.4 | 9.8 | 3 |
| | 0.9 | 1754.0 | 9.9 | 3 |
| | 1.0 | 1743.5 | 9.9 | 3 |
| 2 | 0.5 | 3798.5 | 9.9 | 6, 9, 11,13 |
| | 0.6 | 3851.5 | 9.9 | 6,11,15 |
| | 0.7 | 3938.0 | 9.1 | 6,15 |
| | 0.8 | 4056.2 | 9.8 | 6 |
| | 0.9 | 3989.9 | 8.3 | 6 |
| | 1.0 | 4092.2 | 9.9 | 6 |
| 3 | 0.5 | 22.1 | 2.83 | 33,37,45,68 |
| | 0.6 | 25.0 | 0.77 | 45,68 |
| | 0.7 | 26.2 | 0.83 | 68 |
| | 0.8 | 26.9 | 0.81 | 68 |
| | 0.9 | 27.2 | 0.58 | - |
| | 1.0 | 27.2 | 0.11 | - |

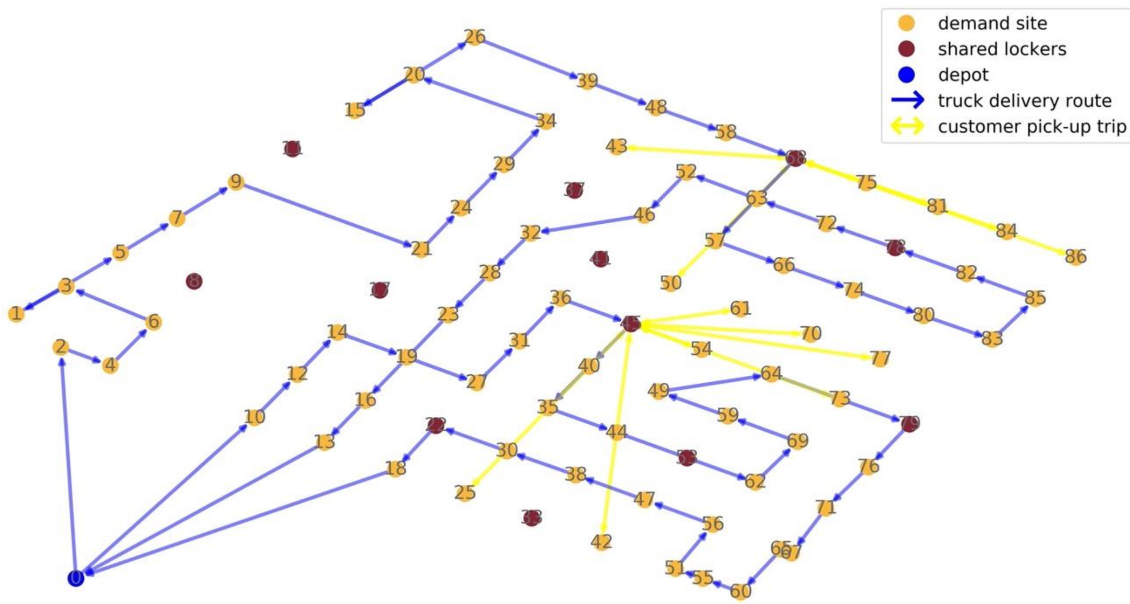
*The instances of the network 1 and 2 were solved with a 10% gap threshold, and those of the network 3 were with a 3% threshold.

We observe that, in general, with the increase of the discounting factor, the total system cost increases. When $\gamma$ increases, the benefit of customer pick-ups shrinks, and thus we see the increase in the total system cost. In terms of the number of the opened shared locker facility, it decreases with the parameter. That is, the more benefits the customer pick-up trips bring, the more shared locker can be opened. Because of the capital investment on the shared lockers, a shared locker facility can only open when the benefit it brings outweighs its capital investment. The notion of economies of scale in the customer pick-ups plays a role here.

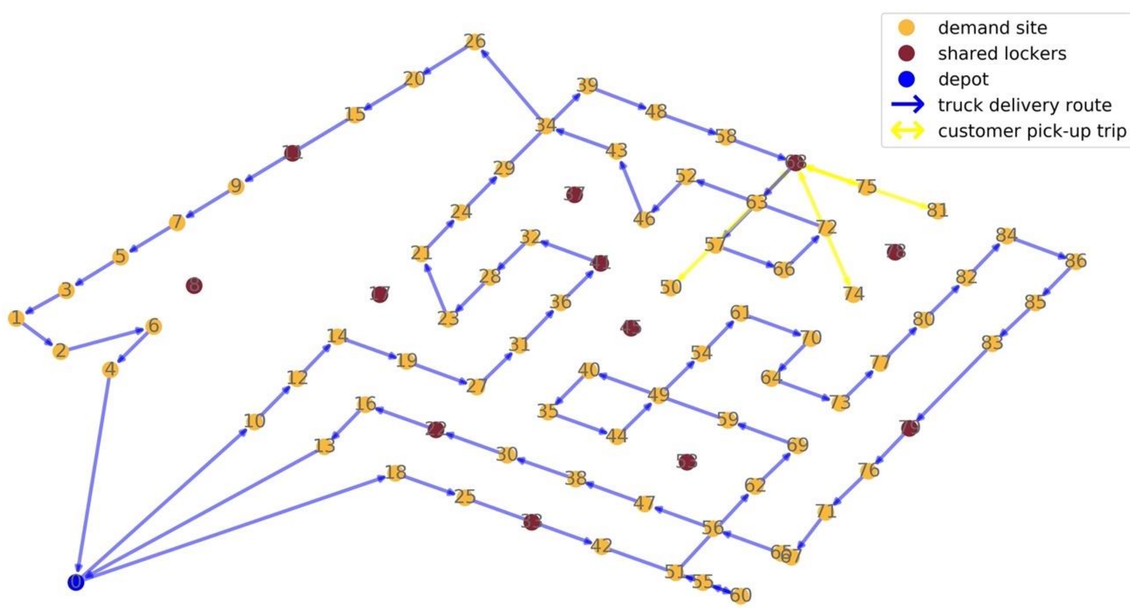
Specific for the network 3, when the parameter $2\gamma$ ranges below 0.9, some shared lockers are selected. When it reaches 0.9 and above, having any shared locker opened does not benefit the system any longer, and for these instances, the problem becomes a traditional all home delivery problem (a standard VRP). The total cost for the VRP is 27.21. In Figure 15, we present the routing and customer assignment solutions for selected $\gamma$ of the network 3, where Figure 15 (d) shows the truck routes for the VRP. Remember that the road in network 3 replicates the real network in downtown Minneapolis where one-way streets exist. This partially explains, for example, in Figure 15 (a) a delivery truck visits the shared locker 53 between its visits to the demand sites 59 and 76, because the shortest path from 59 to 76 passes the shared locker 53 due to the network restriction. The more important reason is that the nodes are selected as road intersections, which making some visits to unnecessary shared lockers inevitable.



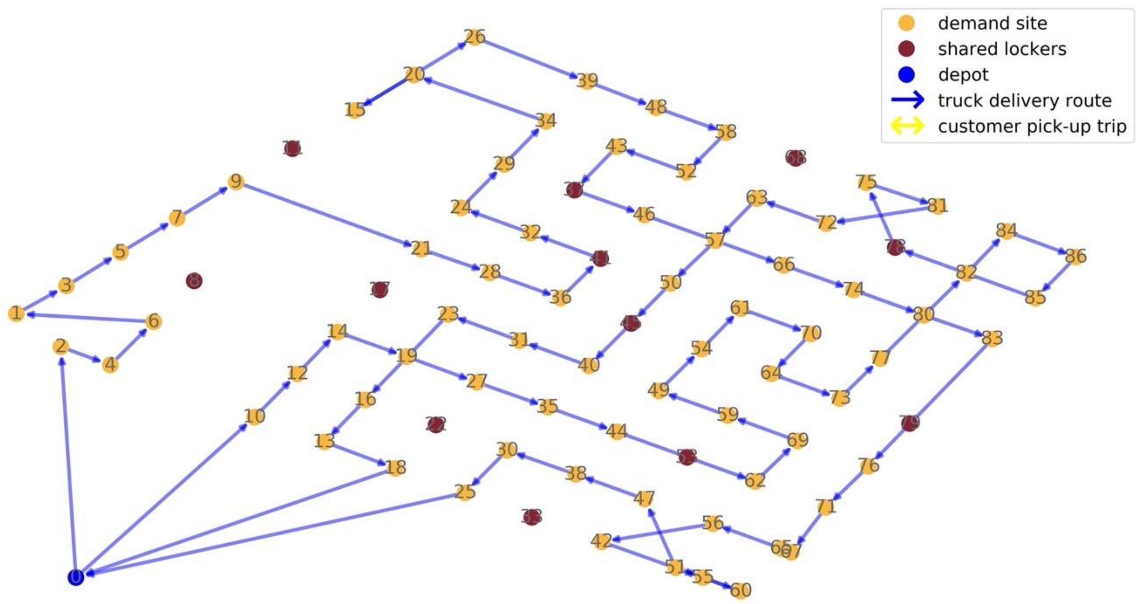

(a) $2\gamma = 0.5$




(b) $2\gamma = 0.6$




(c) $2\gamma = 0.8$




(d) $2\gamma = 1.0$

**Figure 15** Routing and customer assignment solutions for the network three with varied pick-up cost discounting parameter

### 6.3.3 Sensitivity on the Capital Investment of Shared Lockers

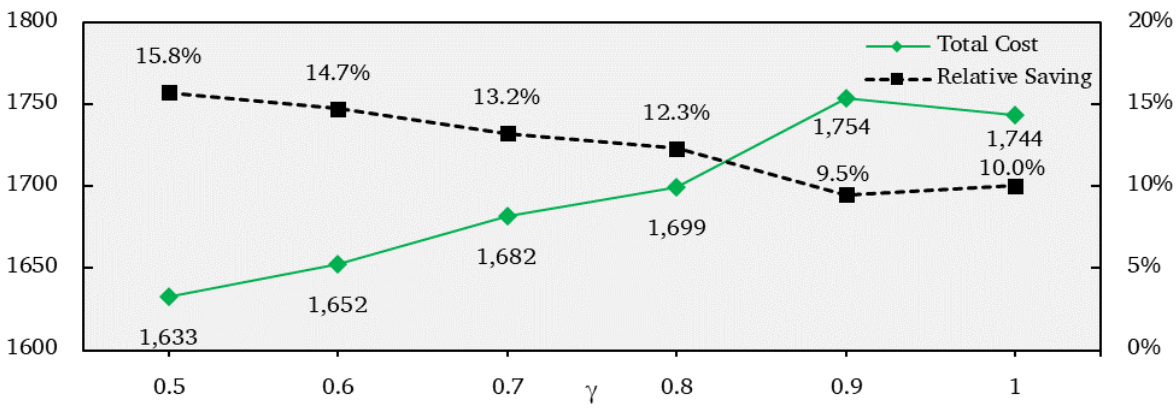
In addition to the sensitivity analysis on the customer pick-up cost, we tested the system performance with varied capital investment on the shared lockers. With $2\gamma$ equal 0.5, the results on network 3 with the unit capital cost ranging in {200, 250, 300, 350, 400} are documented in Table 7. All instances were solved within a 5% gap. It is intuitive that with the increase of unit capital investment on shared lockers, the number of shared locker facilities decreases and so does the number of customer pick-ups.

**Table 7** Sensitivity on the unit capital investment

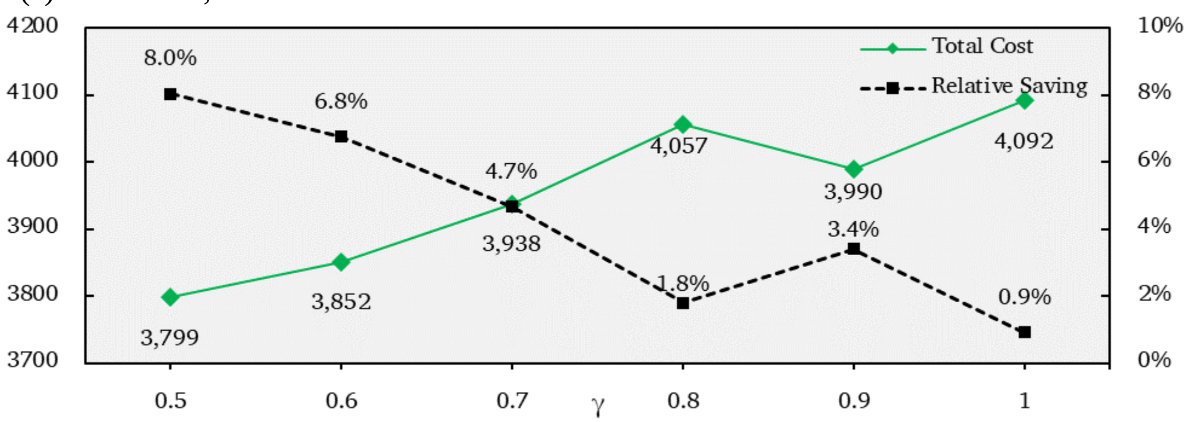
| **Network Index** | **Unit capital investment** | **Objective value** | **Gap (%)** | **Selected shared locker locations** | **# of customer pick-ups** |
|---|---|---|---|---|---|
| 3 | 200 | 19.64 | 3.6 | 33, 37, 45, 53, 68, 78 | 31 |
| | 250 | 21.52 | 4.7 | 33, 37, 45, 68, 78 | 27 |
| | 300 | 22.27 | 4.9 | 33, 37, 45, 68 | 23 |
| | 350 | 23.07 | 4.5 | 33, 37, 45, 68 | 22 |
| | 400 | 24.24 | 4.1 | 33, 37, 45, 68 | 22 |

### 6.3.4 Total System Cost Reduction with the Shared Locker System

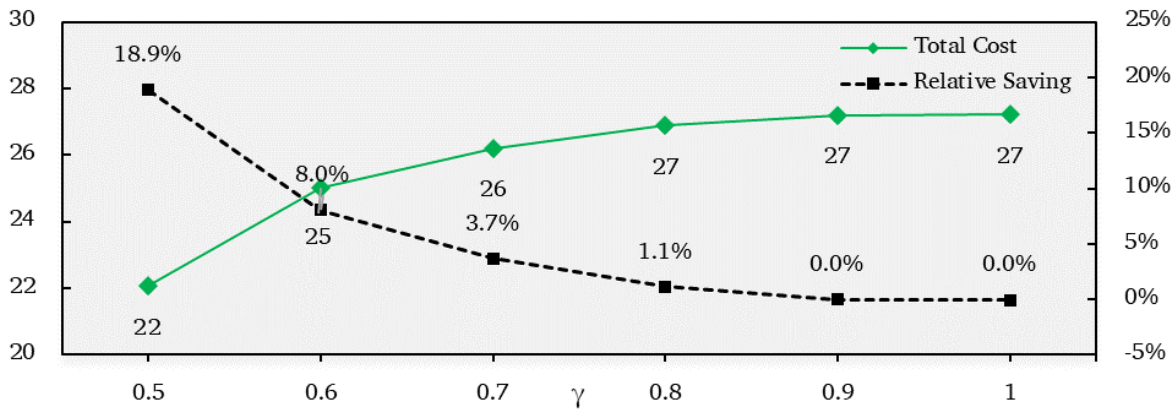
In this sub-section, we address the question of how much total cost can be saved with the collaborative shared-locker last-mile delivery method. To gain a deep insight into this problem, we varied both the customer pick-up cost parameter and the capital cost for setting up shared lockers. In Figure 16, the total cost savings relative to the traditional all-home deliveries for each problem instance are presented, where the capital cost for the shared lockers is fixed at $300 per unit except for the last sub-figure where unit capital investment varies. Depending on the values of the related parameters used and network structure, the total cost saving relative to the traditional all home delivery varies from case to case. The case study on the Minneapolis downtown network shows that the shared locker last-mile delivery system can save up to 18.9% - 27.8% of the total system cost compared to the traditional all home deliveries.



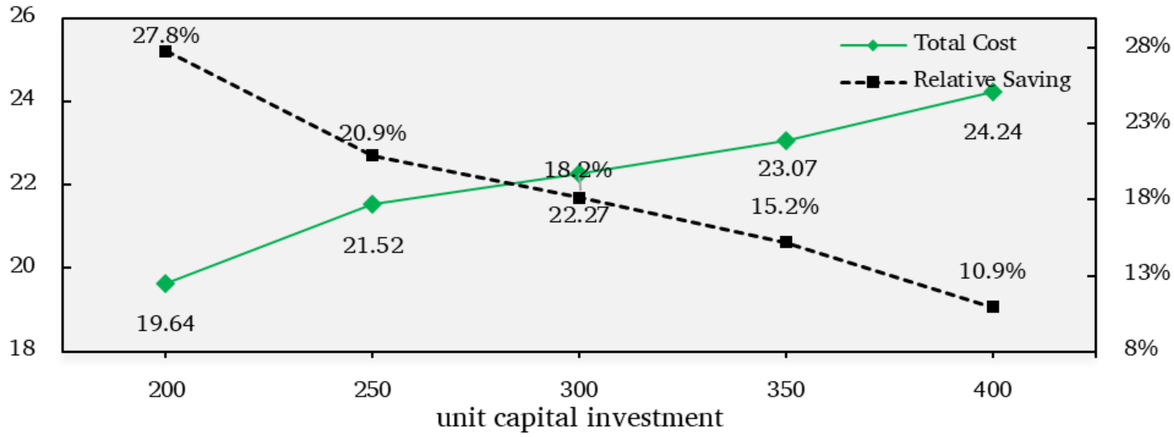

(a) Network 1, base cost 1938




(b) Network 2, base cost 4130




(c) Network 2, base cost 27.21




(d) Network 3, base cost 27.21

**Figure 16** Total system cost saving with the shared locker system

# 7.0 CONCLUSIONS

The growth of e-commerce and retailers' adoption of omni-channel distribution system put significant pressure on urban freight logistics system, especially the last-mile package deliveries. In addition to the induced large package delivery demand, factors such as limited curb and parking space, increasing regulatory restrictions on freight vehicles, and the desire for speedy and reliable package deliveries, further challenge the current urban freight logistics. Foreseeing the trend, cities and are actively rethinking and revising their city freight plans so as to not only improve delivery service efficiency, but also address issues related to congestion, environment, and social equity. In this project, we specifically examine an innovative delivery method – shared parcel lockers – that is potentially a sustainable and effective solution to the last-mile delivery.

First, we answered three key background questions through literature and policy review and summarized main findings. The trending of e-commerce is apparent with its growth outpacing brick-and-mortar's globally, and e-commerce induces drastic increase in package and parcel deliveries around the world. Besides huge package delivery demand, the desire for alternative and faster delivery methods, increasing regulatory restrictions on freight deliveries, and the adoption of new technologies challenge current urban logistics system. As a sustainable and efficient emerging delivery method, parcel lockers do possess potentials of reducing carbon emissions, improving logistics efficiency, serving customers' need needs, and gaining more popularity and economic viability.

Second, we conclude that parcel lockers have potential in different transportation facility types, including transit malls, transit centers, rail stations, and park-and-rides. In addition, transit practitioners should consider the socioeconomic ramifications of locker investments as part of overarching equity goals in addition to the typical focus on consumer attitudes and level of interest. Transit agencies could be more proactive in developing public-private partnerships with interested couriers regarding the installation of lockers on stations with high ridership and foot traffic as well as suburban park-and-ride facilitiess that generally have more space to install automated parcel locker facilities but provide the flexibility and security of 24-hour operations for non-transit users. Lockers are also congruent with the interest in transit-oriented development (TOD), which has typically centered on developing housing near transit facilities.

Third, we concentrated on the strategic and operational planning of the shared parcel lockers in the urban environment. A mathematical optimization program that jointly minimizes the total cost of locating shared parcel lockers and resulted delivery routes was proposed. By minimizing the total system cost, the optimal solutions determines where to open shared locker facilities and through these facilities how routes should be planned so that selected shared locker locations and home sites of customers that are not assigned to any shared lockers are both visited by delivery vehicles. The solution to the mathematical problem also helps to quantify the benefit of using this delivery method in terms of transportation efficiency. Experiments with Minneapolis downtown road network were carried out and it showed that the total cost savings (including capital investment and operational cost) ranged between 19% to 28% compared to the traditional all-home deliveries. With even greater reduced freight VMT, urban residents benefit from improved traffic safety and better air quality. In the future work, we will consider package demand uncertainties in the optimization problem and propose more reliable facility location and routing decisions.

The research outcomes will better inform cities regarding implementing alternative last-mile delivery options and policies to manage parking and curb space. Lessons learned from this project can be utilized by these planning agencies in the near-term, and other agencies in the future, to update their policies and design appropriate infrastructure to accommodate upcoming demand changes.

# 8.0 ACKNOWLEDGEMENTS

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