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Accessibility and Equity Analysis of Transit Facility Sites for Common Carrier Parcel Lockers

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Abstract

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 facilities. The implementation of an unmanned, secure, common carrier parcel locker system could have benefits for non-transit users as well. This research presents a multiple-criteria approach for analyzing the potential of public transportation facilities as hosts for a common carrier locker system. Several accessibility and equity metrics, including ridership, mode of transportation, spatial distribution, and sociodemographic profiles of coverage areas are utilized. A case study utilizing real-word data from the Portland, OR region and its transit facilities is used to illustrate accessibility and equity tradeoffs. The results demonstrate that multiple facility types have the potential to host a locker system but there are complex accessibility and equity tradeoffs to be considered by stakeholders and policy makers when prioritizing locations.

E-commerce activity continues to grow worldwide, and business-to-consumer (B2C) sales in the U.S.A. are predicted to reach over $550 billion by 2024, up from $360 billion in 2019 (*1*). Consumer demand has generated growing parcel volumes and demanded the perception of low shipping costs, and many retailers mask the true cost of shipping to promote sales. Retailers rely on competitive logistic strategies to offer increasingly short delivery lead times, high traceability, and reliability. Although logistical operations have become streamlined in early supply chain phases, the final segment of delivery—"the last mile"—remains the most expensive and least efficient segment (*2*, *3*). The operational costs of the last mile swell because of order fragmentation, which precludes economies of scale; many delivery tour stops deliver only one parcel per stop (*4*). Looking even further than the last mile, research on "the last 800 feet" finds the fragmentation of delivery tours to be rife with distinct challenges, such as locating parking (*7*, *8*) and the operations performed outside the freight vehicle (*5*).

As last mile challenges are not easily overcome, some recent innovations look to alternatives to home delivery destinations. European markets introduced parcel lockers as early as 2002, but parcel lockers were not implemented in the U.S.A. until the introduction of Amazon Hub Locker service in 2011. Subsequently, United States Postal Service (USPS) launched a gopost® locker pilot in select cities, and UPS developed the 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. USPS and Amazon lockers can receive and hold freight from UPS and FedEx, which offers some flexibility to their users, but UPS and FedEx lockers only accept in-network parcels. Under these restrictions, consumers are expected to travel to multiple collection points to receive parcels from non-cooperating carriers.

To offer a locker solution that can compete with the convenience of home deliveries, the alternative of a common carrier parcel locker system has been conceived to maximize the consolidation benefits to consumers (*6*). Since U.S. consumers are likely to have incoming parcels from multiple couriers, the purpose of a common carrier system reduces consumer pickup travel by offering a

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one-stop location for packages from different couriers. Ideally, a common carrier locker program is independent of any singular courier, because of the proprietary nature of logistics data and courier operations. Moreover, an automatic/unmanned parcel locker system can offer consumers more security and privacy than porch drop-offs, and expanded hours of locker access compared with the lockers that are located within private businesses (*7*).

This paper presents a multiple-criteria approach for reviewing the potential of public transportation facilities as a host for a common carrier locker system. Special attention is given to (a) accessibility and (b) equity in comparing possible locker sites. In the accessibility analysis, special consideration is given to ridership and geometric design criteria. In the equity analysis, special consideration is given to the spatial coverage areas of the potential locker sites and their socioeconomic attributes related to income, race, education level, and internet access. The service area of TriMet, the transit agency for the Portland, OR metropolitan region, is used as a case study for discussing the results of this approach.

In this research, the term "transit facility" is used as an umbrella term to describe a location that includes any one or a combination of the following: bus station, light rail (MAX) station, transit center, park-and-ride facility, and the segments of the downtown transit mall (Figure 1). More connections and higher ridership are seen in facility types illustrated toward the right and/or bottom of Figure 1. This analysis focuses on the three types of facilities demonstrating the highest ridership in the Portland metropolitan region: (a) the *downtown* transit mall with light rail and bus service, (b) *urban* and *suburban* transit centers with light rail and bus service, and (c) *suburban* park-and-ride facilities with large *auto parking* capacity in addition to light rail and/or bus services.

Literature Review

There is a wide range of issues related to freight lockers. To facilitate the review of key findings, the literature review has been organized into five subsections. The contributions of this paper are summarized at the of this section.

Advantages of Freight Lockers over Conventional Collection Points

In spite of the popularity of home delivery, many residences do not have a secure means for package reception. Requiring a signature for package delivery is a traditional means documenting successful package reception. Not only are these signatures inefficient for the courier, but they may also inconvenience the consumer and may cause the delivery to "fail" if the resident is away or cannot hear or respond to the doorbell. The development of a publicly accessible, self-serve, 24/7 parcel locker system does not require a signature for security; rather, the use of the temporary access code on the electronic locker can provide proof of pickup.

In the U.S.A., collection point pickups often serve as an undesirable routing solution after home delivery fails, typically utilized only after time and labor are wasted on unsuccessful home deliveries, and the last mile connection is shifted to a consumer pickup trip (*6–8*). If the collection point operates inside a private business (such as convenience or box stores), staff labor may be required to provide the necessary customer service for the package pickup. This arrangement limits pickup availability to the operating hours of the hosting business (*9–11*). Freight lockers can uncouple package pickup from the constraints of in-store collection points.

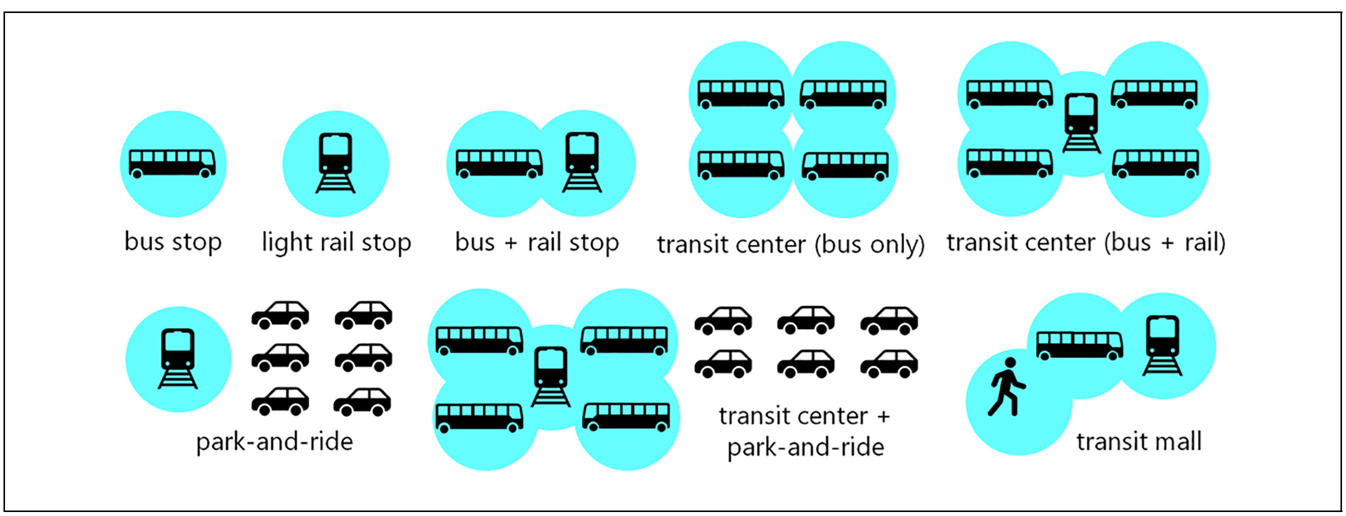

Figure 1. Defining "transit facility" to include different kinds of transit locations.

Market Viability

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 (*12*) and Chinese surveys find that only 22% of consumers prefer collection points and parcel lockers (*13*). Even in countries with established locker programs, actual usage rates of collection points or parcel lockers range from about 10% to 20% (*14*, *15*). Low adoption rates may be partly explained by a lack of familiarity with parcel lockers as a delivery option (*16*), or because the option is not yet offered by many online stores (*17*). The initial audit of the USPS gopost® pilot identified that its foremost need for success was increased locker utilization (*18*). Ultimately, Iwan et al. found the biggest barrier in the adoption of locker use is that consumers are required to make the final leg of the journey themselves (*9*).

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 U.S. online shoppers would consider delivery alternatives if it meant avoiding delivery charges (*19*). Additionally, as consumers become more reliant on e-commerce for sensitive or costly goods, the value of secure delivery increases. In 2016, a U.S. home security company nationwide study 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 (6). Similarly, nearly a quarter of survey respondents in Brussels preferred parcel pickup at transit-oriented locations (25).

Among Polish consumers already using collection points, the majority (up to 79%) of users preferred lockers located close to home or to their employment (9, 17). 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 (20).

Locker Accessibility: Mode Choice and Convenience of Access

When studying vehicle miles traveled (VMT) and carbon emission tradeoffs between home delivery and consumer travel it is key to consider modes and vehicle engine type and efficiency (*21*). Utilizing a personal automobile to access a locker will increase VMT, but locker pickup trips made via active travel (walking, biking, transit) are more energy efficient and produce lower demands on the street network.

Kedia et al. asked consumers about their willingness to use active transport modes to access collection points (*20*). Over half of 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 (*6*). 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 (Belgium) 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 (*14*). Moroz and Polkowski found that 44% of Polish millennials using parcel machines collect their parcels on foot (*8*).

Based on survey responses in the cited literature, the accessibility of 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 (France), 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 (*10*). InPost prefers to locate its parcel lockers in areas of high population density, high traffic pedestrian areas, and near local commuting hubs (*9*). Lee et al. agreed that access to the parcel lockers is an important factor to consider when selecting an optimal location (*22*). 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 (*6*). High foot traffic also promotes an "eyes on the street" effect, giving pedestrians a greater perception of security (*23*). 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 U.S. market, high visibility may be advantageous to promote utilization of this delivery alternative.

Pandemic and Resiliency Considerations for Parcel Access

At the time of writing, 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 the workplace will evolve. Evidence is growing that transit is highly utilized by essential workers and those who cannot work from home (*24*, *25*), justifying a prioritization of systems that serve such workers. Moreover, self-service lockers are compatible with social distancing measures and an efficient, contactless method of delivery. Technological changes and the pandemic are also fostering the development of autonomous delivery vehicles (*26*, *27*) that could efficiently complement unmanned lockers.

Other disasters—earthquakes, hurricanes, wildfires, landslides—can strain the normal transportation operations and home deliveries. In an emergency situation, e-commerce deliveries may be hindered, but resiliency planning also plans for a recovery period, the time in between crisis and the return to normality. Resiliency planners realize that consolidated distribution systems may be particularly advantageous to a recovering transportation system. A transit-oriented locker system offers an additional layer of logistical infrastructure, and any investments in a transit facility's pedestrian and bicycle access will be advantageous for access to the lockers.

Lockers as a More Equitable Approach to On-Demand Home Delivery

The literature on lockers has not yet addressed equity considerations. However, 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 (*28*). Research into the adoption of e-commerce by disadvantaged groups finds that they are less likely to adopt home delivery, indicating a strong correlation between low home delivery rates, transit use, low-income households, low education levels, and non-white populations in the Portland region (*29*). Existing home delivery options have apparent barriers to disadvantaged and transit-using populations. For these reasons, this research presents an equity analysis, to demonstrate that the selection of locker sites should be linked with equity goals, particularly in light of racial, educational, e-commerce adoption, and income disparities.

Overall, much of the reviewed literature has relied on consumer surveys to gauge potential usage or mode of access for parcel lockers. In contrast, this research focuses on evaluating transit sites as potential common carrier locker sites with a novel emphasis on equity (there is a growing discussion around transportation equity that is absent from the locker literature). Both performance metrics and a quantitative assessment of accessibility and equity are provided. A further contribution of the research is to utilize real-world data to highlight the complex tradeoffs between potential locker utilization, equity metrics, user convenience, and spatial coverage. The analysis and findings are useful for future policy makers and transportation practitioners in evaluating common carrier parcel locker locations as an alternative for last mile logistic solutions. In this research a freight locker system at transit facilities is discussed with the assumption that the lockers would be primarily used as the intended delivery destination, and secondarily utilized as a collection point for failed home deliveries.

Accessibility Analysis

This section describes and presents the results of the accessibility analysis where special consideration is given to ridership, connectivity, and geometric design.

Connectivity and Ridership Criteria

Ridership is an important consideration when evaluating transit sites for their potential in hosting a common carrier locker system. Locker systems located at transit stops with higher ridership levels (i.e., more boardings, alightings, tranfers, and/or foot traffic) have the potential to serve more people and therefore locations with higher transit raidership are preferred when considering site alternatives.

TriMet publishes public ridership reports with the number of ons/offs at the stop-level, by route, and aggregated by transit centers. The data used in this research was from the fall quarter of 2019 (*30*), before normal traffic patterns were altered by the Covid-19 pandemic. It is worth noting that, at the time of writing, 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.

For this analysis, ridership totals were tabulated for transit centers (TC) and park-and-ride (PaR) facilities (which may serve multiple stops) and for segments of the downtown transit mall to identify facilities with the greatest activity.

The transit mall requires a different type of analysis. The transit mall runs along two adjacent one-way streets and has rail stops positioned four to five blocks apart with multiple bus stops located in the blocks between the rail stops. Given the proximity of stops, aggregation of ridership by segments was performed to capture more accurately the high levels of activity occurring in the area. To create a contextually relevant aggregation level of passenger boardings and alightings, the transit mall was partitioned into directional segments so that most segments included one rail stop at their origin and terminated just before the following downstream rail stop

Table 1. Transit Facilities with the 20 Highest Ridership Volumes, Fall 2019, Weekday Only

Location	Connections		Facility type			Ons/offs	Land use
	Rail	Bus	TC	Mall	PaR		
Pioneer Sq.—Madison on 6th	4	13	na	×	na	18,291	Downtown
Beaverton TC	3	11	×	na	na	18,253	Residential
Gateway/NE 99th	3	7	×	na	×	16,470	Residential
Pine—Pioneer Court on 6th	4	12	na	×	na	14,433	Downtown
Oak—Pioneer Place on 5th	4	17	na	×	na	14,378	Downtown
Rose Quarter	4	8	×	na	na	14,213	Arena
Pioneer Place—Jefferson on 5th	4	12	na	×	na	13,526	Downtown
Clackamas town center	1	12	×	na	×	9,937	Shopping
Madison—Montgomery on 6th	2	14	na	×	na	8,939	Downtown
City Hall—Mill on 5th	2	13	na	×	na	8,324	Downtown
Sunset TC	2	9	×	na	×	8,046	Residential
Mill—Jackson on 5th	2	12	na	×	na	7,972	University
Lloyd center	3	2	na	na	×	7,903	Business
Davis—Pine on 6th	2	15	na	×	na	7,271	Downtown
Hollywood TC	3	4	×	na	na	6,536	Shop + Res.
Glisan—Couch on 5th	2	9	na	×	na	5,460	Downtown
Willow creek	1	5	×	na	×	5,301	Downtown
Lombard TC	1	2	×	na	na	5,243	Residential
Couch—Oak on 5th	2	14	na	×	na	4,886	Downtown
Montgomery—College on 6th	2	12	na	×	na	4,406	University

Note: TC = transit center; PaR = park-and-ride facility; na = not applicable.

Figure 2. Segments of the downtown transit mall.

(segments on the ends of the transit mall included a rail stop at both their origin and terminus). Figure 2 illustrates these transit mall segments.

Table 1 lists the top 20 transit facilities by ridership volumes, as ranked by total ons and offs in fall 2019. Observations about the connectedness of these locations and facility types are provided, as well as data about the size of the parking facilities at PaR stations. There is a direct relationship between connectivity and ridership. Locations with four rail connections (the maximum possible) tended to have the highest ridership volumes. Lombard is the least connected TC of the high-volume list, with only one rail connection and two bus route connections. The 13th highest ridership location is the Lloyd Center MAX (light rail) station, whose ons/offs quantity reflects the aggregation of one rail stop and two connecting bus stops that are no more than a block away. This indicates that the ridership activity of a transit facility may be undervalued if one only looks at ridership level data in the transit facility itself. A transit facility that connects several high-volume bus routes can have foot traffic on par with or greater than other TCs, such as Hollywood Transit Center with the 15th highest ridership. Thus, attention should be paid to the number of connections and coverage of the routes that feed into the transit facility area in addition to ridership numbers. Spatial coverage of the transit facilities is discussed in more detail in the Equity Analysis section.

Ultimately, the numbers of the case study indicate that most of the high-ridership transit facilties are within the city center, where PaR facilties are absent. In fact, over half of the 20 highest ridership locations are segments of the downtown transit mall.

Geometric Design Criteria

The accessibility of transit facilities for the distribution and retrieval of parcels should also be discussed with

Figure 3. Street view of the covered parking facility at Clackamas Transit Center (Google Earth).

Figure 4. Street view of transit mall: bus stop, bus bay, and sightlines of upstream light rail cars (Google Earth).

reference to their geometric design. A common carrier locker system should enhance the utility of the transit facility and not impede the transit services. Consideration should be given to a loading/unloading zone that could accommodate parcel delivery vehicles without interfering with transit activities. Furthermore, turning radii and sight lines should be conducive to these delivery vehicles.

Fortunately, TCs are designed for heavy vehicles (i.e., buses), so delivery trucks or vans would be able to maneuver through them easily. 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. Compared with TCs in denser areas, the PaR facilities in the suburbs generally have more flexible space to accommodate freight or parcel delivery vehicles (Figure 3).

At transit facilities, there could be dedicated loading/unloading zones for delivery vehicles serving the lockers, placed at locations that minimize conflicts with transit vehicles. If an agreement were made such that locker-loading deliveries occurred outside of peak transit service hours, delivery vehicles could potentially use empty bus bays for speedy loading and unloading.

Along the transit mall, situating lockers at one of the bus stops between light rail stations is preferable for staging needs, given the curbside placement of rails at rail stations. Bus stops between rail stations have bays that can accommodate multiple 40 ft buses. Figure 4 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 parcels 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 urban design of downtown.

Geometric design is also important for people with mobility impairments and/or and wheelchair users. There

Figure 5. Street view of light rail stations at the Rose Quarter transit center.

is a correlation between the number of wheelchair lifts, overall ridership, and comfort and accessible design at transit facilities (*31*).

Finally, the overall design of each facility and its urban context may be also relevant. For example, the Rose Quarter TC (Figure 5) has high ridership and connectivity but also some areas with geometric constraints, such as narrow sidewalks, bridges and columns, traffic infrastructure, and rails. This is an inflexible setting that presents major design challenges for siting and orienting the locker for accessibility by both consumers and freight vehicles.

Equity Analysis

This section describes and presents the results of the equity analysis. Equity metrics related to population coverage areas by transportation mode, population, and employment distribution, and key socioeconomic characteristics (income, race, education level, and internet access) of the covered areas are presented and compared among high-ridership facilities. Access to basic goods, services, and activities is a key component in accessibility-based transportation equity evaluations and mail and package distribution is considered a basic service. An example of the importance of mail and package delivery is that the USPS is mandated with a universal service obligation, provided in many places at great cost (*32*).

To process spatial data and to visualize and quantify equity metrics, the open source R environment, version 4.0.2, and the SF package, version 0.9-8, were utilized.

Mode of Transportation

The mode of transportation by which travelers access transit facilities is an important equity consideration. Riders from lower income households have been linked with lower rates of vehicle ownership, access to jobs, and other opportunities (*33*). Thus, transit sites with higher walking/bicycling accessibility may be particularly beneficial to transportation disadvantaged populations.

To determine the mode-specific accessibility of transit facilities, modal buffers of Euclidean distances were created around the high-ridership facilities to estimate the population living within reasonable walking, biking, and driving distances. Population data provided by the American Community Survey (ACS) 2018 five-year estimates (*34*) at the U.S. Census block group level (the smallest level of detail publicly available) was assumed to be uniformly distributed throughout the enumeration unit. The population within the modal buffers was then estimated using simple areal proportioning.

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 in Portland the average bicycle trip to access light rail was 2.1 km (1.3 mi) long (*35*). 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 mi. 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 min 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 mi, and taking 26 min (*36*). From these averages, a peak travel speed of 16.4 mph was derived. Thus, the catchment assumption of a 10 min drive translates into a 2.73 mi range.

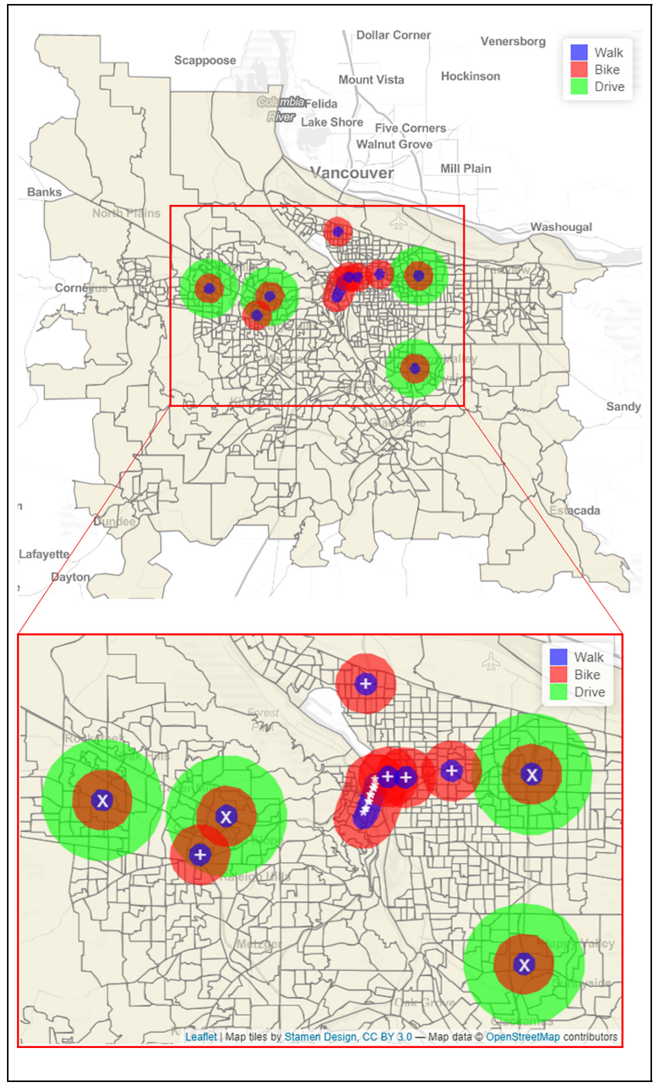

Figure 6. Modal buffers at top TriMet facilities by ridership: regional map (*top*), detail of the downtown area (*bottom*).
Note: × = park-and-ride, + = transit center, * = transit mall.

Because multimodal access was estimated through buffers of Euclidean distances, correction factors based on the mean circuitry of Portland's driving and walking networks were applied to the expected driving and walking distances (*37*). Additionally, although cyclists can legally travel on any of the streets in Portland except the intracity freeways, Portland cyclists chose more comfortable routes with lower stress levels than using the shortest route possible (*38*). Based on the literature 0.24 miles of extra distance for cyclists was considered. 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. The locations of the top 20 TriMet facilities by ridership and their modal buffers are shown in Figure 6 where the bottom map

Table 2. Population within Walking and Biking Modal Buffers for Transit Mall and Transit Center Facilities in the Top 20 Locations by Ridership

	Total population	
Transit mall	Walk	Bike
Madison—Montgomery on 6th	10,746	30,636
Mill—Jackson on 5th	10,491	30,365
Montgomery—College on 6th	8,840	27,854
City Hall—Mill on 5th	8,516	34,726
Pioneer Sq.—Madison on 6th	8,214	36,079
Glisan—Couch on 5th	5,779	34,132
Pine—Pioneer Court on 6th	5,237	39,061
Pioneer Place—Jefferson on 5th	5,186	37,933
Couch—Oak on 5th	4,748	37,438
Davis—Pine on 6th	4,413	40,297
Oak—Pioneer Place on 5th	4,055	39,478
	Total population	
Transit center	Walk	Bike
Hollywood/NE 42nd Ave Transit Center	4,141	31,203
N Lombard Transit Center	3,567	23,271
Beaverton Transit Center	3,017	18,149
Lloyd Center/NE 11th Ave MAX Station	2,841	26,957
Rose Quarter Transit Center	2,352	23,886

Table 3. Population within Walking, Biking, and Driving Modal Buffers for Park and Ride Facilities in the Top 20 Locations by Ridership

	Total population		
Park and ride facility	Walk	Bike	Drive
Willow Creek/SW 185th Ave TC Park & Ride	3,124	25,895	87,841
Gateway/NE 99th Ave TC Park & Ride	2,643	22,598	91,139
Clackamas Town Center Parking Garage	2,540	14,335	55,260
Sunset Transit Center Park & Ride	1,854	14,494	58,492

provides location of the facilities in the TriMet service region and the top map more detail for the downtown area.

Note that the bottom map contains the boundaries of U.S. Census block groups. Block groups are statistical divisions of census tracts and generally defined to contain between 600 and 3,000 people. In addition, note that driving buffers were not constructed for facilities without a PaR facility, that is, without automobile parking. The proximity of the transit mall facilities causes the overlapping modal buffers to appear as an oblong area covering the central portion of the city. Figure 6 illustrates how the different facility types (transit mall, TC, and PaR) generally serve spatially different regions of the metropolitan area with the PaR serving suburban neighborhoods, the transit mall serving the downtown core, and the TCs primarily serving urban neighborhoods.

Table 2 displays the estimated population within the walking and biking modal buffers for the transit mall and TC facilities with the highest ridership (refer to Table 1). The high population density in the central city core results in more than double the estimated population within walking distance at some of the transit mall facilities compared with any of the TCs. The magnitude of differences is smaller when considering biking distance, however.

The population within the walking, biking, and driving modal buffers is given in Table 3 for the four PaR facilities found within the top 20 locations by ridership. The population estimates within walking and biking distances are generally lower for the PaRs than for the TCs, because of the lower population density in the suburban coverage areas. However, it appears that a sizable population is estimated within the driving buffers and the suburban locations of potential PaR locker sites could complement more centrally located locker sites on the transit mall or other facilities with high ridership and/or equity priority in the urban core.

Geographic Coverage and Convenience

The distribution of population and employment activities throughout the region is an important element to consider when evaluating transit facilities as potential locker sites. As shown in the map in Figure 7, the population density (per square mile) throughout the Portland region varies considerably, with the highest densities occurring in the downtown area. More heavily populated areas tend to have smaller block groups, as shown in Figure 7, since each block group contains between 600 and 3,000 people as previously mentioned.

Similarly, the employment density (per square mile), calculated from the U.S. Census Bureau's ZIP Codes Business Patterns data from 2018, is displayed by ZIP code tabulation area (ZCTA) in Figure 8. Again, the density is greatest in the downtown core. These high population and employment density areas generally correspond to the location of the transit mall.

Figures 7 and 8 should be compared with Figure 6 to understand the strong connection between population density, employment, and the location of high-ridership transit facilities. It is also evident, however, that focusing only on the top facilities by ridership provides a somewhat small coverage in the metropolitan region.

The distinction between employment and population areas is also relevant to user convenience and trip origin-and-destination pairs. For example, a common carrier

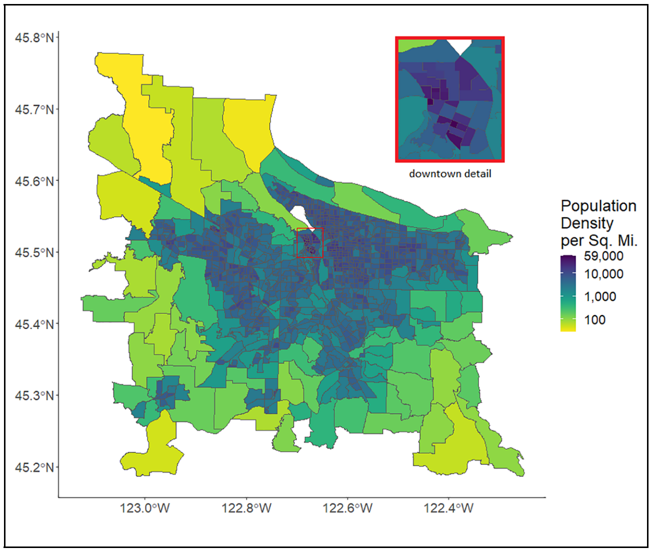

Figure 7. Population density by census block group in the Portland region.

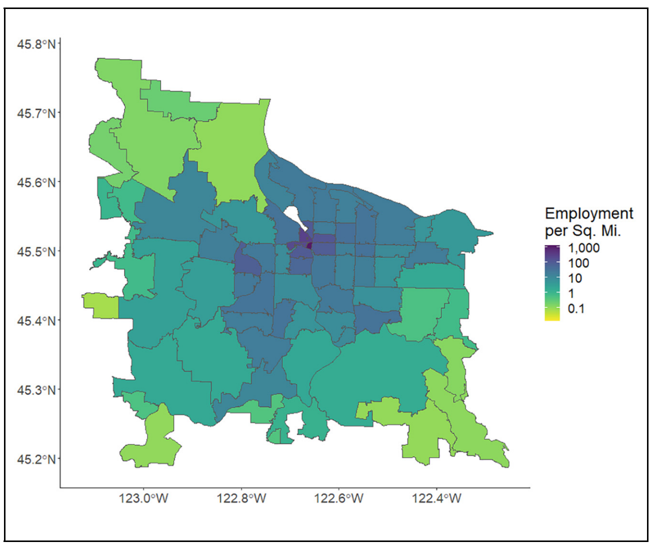

Figure 8. Employment density by ZIP code tabulation area (ZCTA) in the Portland region.

locker system located along the downtown transit mall may be accessible by the greatest number of people because of the high concentration of workers in the area, but it is not known whether this would directly translate to increased usage of the lockers. Workers who commute by public transit may find discomfort in transporting a package received at the origin of their commute home, particularly during peak hours when buses and trains are most crowded. These workers may find it more convenient to complete the transit portion of their commute first and retrieve their package from a locker located where they alight. Additionally, if the alighting stop were at a PaR facility, the minimization of distance the package would need to be carried could encourage more usage of the locker services.

Sociodemographic Equity Metrics

While there is no one prescribed method for evaluating equity, Litman (*39*) describes various methods and measures of evaluation and Di Ciommo and Shiftan (*40*) discuss criteria for differentiating population groups in equity analyses. Among those criteria are race or ethnicity, income, education level, and access to technology. These criteria are also highly relevant to study equity in relation to home deliveries (*29*).

For this equity analysis, demographic data for the TriMet service area was again sourced from the ACS 2018 five-year estimates (*34*) at the block group level and assumed to be uniformly distributed throughout the block groups. Demographic variables were chosen to represent the non-white population (any person who did not identify as "white only"), the population with lower education levels (high school degree, general educational development (GED), or less), and the number of households without a broadband internet subscription. The modal distances described in the previous section (Mode of Transportation) were applied to the top 20 transit facilities by ridership and areal proportioning was used to calculate the demographic profiles within each modal buffer. Walking and biking buffers were applied to all top 20 transit facilities, but driving buffers were only applied to PaR facilities. The median household income corresponding to each facility was assessed based on the location of the transit facility as opposed to the buffer areas.

As this equity analysis is informational only and not meant as a final recommendation for site selection, and because of the vastly different attributes of the transit mall, facilities were evaluated within their respective types (PaR, TC, and transit mall) to elicit further discussion from stakeholders or policy makers.

A priority score was assigned to each facility by creating a method that utilized quintile breakpoints for the ridership and for each demographic variable and modal buffer combination. Once the quintile breakpoints were established for each group of facilities, a score of 1 through 5 was assigned to each facility for each variable and buffer distance combination. Higher scores were assigned for facilities with higher ridership, higher non-white or lower educated population, more households without broadband internet, and lower median income. Thus, higher scores indicated a greater equity priority. The scores for each variable were averaged and compared among the facilities, with 1 being the lowest equity priority score and 5 the highest.

Results of the equity analysis for the PaR facilities in the top 20 locations by ridership are presented in

Table 4. Equity Analysis Results for the PaR Facilities in the Top 20 Locations by Ridership

		Non-white			Low education			No broadband			
Park and ride	Median household income	Walk	Bike	Drive	Walk	Bike	Drive	Walk	Bike	Drive	Equity Score
Gateway/NE 99th Ave TC Park & Ride	$30,675	853	6,948	24,719	624	5,700	21,631	185	1,538	5,403	3.6
Clackamas Town Center Parking Garage	$45,278	568	3,523	10,387	552	3,075	11,846	190	1,202	2,968	2.6
Willow Creek/SW 185th Ave TC Park & Ride	$53,713	1,311	9,923	30,519	568	4,426	15,411	112	798	2,825	2.6
Sunset Transit Center Park & Ride	$83,328	333	2,477	11,629	170	1,349	7,971	80	523	2,477	1.1

Table 5. Equity Analysis Results for the Transit Mall and Transit Center Facilities in the Top 20 Locations by Ridership

		Non-white		Low education		No broadband		
Transit mall	Median household income	Walk	Bike	Walk	Bike	Walk	Bike	Equity score
Pine—Pioneer Court on 6th	$10,640	1,080	8,745	1,175	4,503	1,219	5,032	4.0
Pioneer Sq—Madison on 6th	$15,972	1,941	8,189	1,150	4,223	1,311	4,630	3.8
Oak—Pioneer Place on 5th	$10,640	865	8,920	1,009	4,588	1,012	5,214	3.8
Pioneer Place—Jefferson on 5th	$10,640	1,084	8,599	1,144	4,440	1,139	4,910	3.8
Davis—Pine on 6th	$10,640	927	8,987	989	4,624	1,034	5,288	3.6
City Hall—Mill on 5th	$15,972	2,020	7,957	1,132	4,089	1,299	4,502	3.1
Madison—Montgomery on 6th	NA	2,888	7,122	881	3,445	1,303	4,013	2.9*
Mill—Jackson on 5th	NA	2,794	7,106	859	3,445	1,277	4,010	2.4*
Couch—Oak on 5th	$31,875	988	8,245	987	4,432	968	5,025	2.4
Glisan—Couch on 5th	$27,917	1,139	7,102	936	4,205	952	4,704	2.1
Montgomery—College on 6th	$23,487	2,477	6,613	494	2,968	909	3,514	1.5
Beaverton Transit Center	$36,857	740	3,970	893	4,890	274	1,295	3.8
Rose Quarter Transit Center	$37,727	559	4,700	324	3,085	415	2,957	3.5
Hollywood/NE 42nd Ave Transit Center	$45,284	682	4,125	420	2,637	379	1,356	2.8
Lloyd Center/NE 11th Ave MAX station	$59,107	574	4,385	251	2,808	292	2,069	2.5
N Lombard Transit Center	$80,469	581	5,141	476	3,788	190	1,264	2.5

Note: *Scores were averaged without median household income; NA = not available.

Table 4. Of the four PaR facilities, the Gateway/NE 99th Ave Transit Center PaR has the highest equity priority score (= 3.6). The lowest equity priority score of the group (= 1.1) is assigned to the Sunset Transit Center PaR, which has the highest median household income and the lowest populations that are non-white, with low-educational attainment, and without broadband internet service.

Table 5 presents the equity results for the transit mall and TC facilities in the top 20 locations by ridership. For facilities along the transit mall, the Pine—Pioneer Court segment on 6th received a score of 4.0, the highest of the group with a low median household income and the highest populations that are non-white, with low-educational attainment, and without broadband internet service. Three additional segments, Pioneer Sq.—Madison on 6th, Oak—Pioneer Place on 5th, and Pioneer Place—Jefferson on 5th, also received relatively high priority scores of 3.8. Since the locations along the transit mall are only a short distance from each other, there is considerable overlap in the modal buffer areas, leading to less variability among the demographic measures. The median household incomes associated with the transit mall facilities appear to be, on average, the lowest of the top 20 locations. However, it is important to mention that there is a high level of variability among incomes throughout the downtown core, as it is home to both low-income and luxury housing, and the areas of the block groups are quite small (less than 0.02 mi^2 in some cases) so one or two large, high-rise apartment buildings could significantly alter the income metrics in a block group.

Out of the five TCs presented, the Beaverton Transit Center received the highest equity priority score of 3.8. The Lloyd Center/NE 11th Ave MAX Station and the N Lombard Transit Center both received scores of 2.5—the lowest of the group—yet compared with the lowest scoring transit mall facility, these locations would appear to serve a less disadvantaged population.

Discussion and Conclusion

Accessibility and equity approaches are presented for their complementary value. Transit data and ACS data were gathered and processed to quantify and map several accessibility and equity metrics. The ridership evaluation identified transit facilities with high levels of potential locker users. The accessibility by mode was extended not only to study equity issues but also because most research on transit-oriented lockers assumes that the catchment area for transit riders is constrained by the distance they are willing to walk with a parcel. However, transit riders that drive their personal vehicle to PaR facilities will not be inhibited by "willing to walk" estimates, and similarly, those who access transit via bicycle are not best represented by "willing to walk" estimates.

Based on the data collected, a common carrier parcel locker system leveraging the transit mall ridership is reasonable 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 transit 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. The transit mall has also a high amount of foot traffic that provides a sense of safety for those retrieving potentially valuable parcels.

Locating common carrier parcel locker systems at suburban PaR facilities not only improves spatial equity and coverage but also has the potential to serve a much greater population because of the convenience of personal vehicle access. Spatial constraints for locker placement and loading zones would be reduced or eliminated at many suburban locations. In addition, transit users' comfort preferences in transporting a parcel via bus or train are an important consideration for locating lockers at the origin or destination of the traveler. The transit mall is a transfer area and is the origin of many return-to-home evening trips, whereas the suburban locations may be preferable for users that would like to pick up a parcel after ending their transit journey.

The equity analysis uses demographic data from the area surrounding a transit facility to gauge which locations would be compatible with regional equity goals for development and investments. The results of the research show that there are complex tradeoffs between spatial coverage, type of facility, and equity metrics. Budget constraints are always present; though outside the scope of this research, they must be considered. The real-world application of equity analysis highlights equity and accessibility tradeoffs but it is not intended to determine final site selections, which should include budget considerations and site design.

If a transit-based common carrier locker pilot is successfully adopted by consumers and delivery companies, there is potential to establish them at any transit facility with suitable space and qualifying demand. Like any reasonable pilot, a common carrier locker system could start with a smaller number of locations, and the equity analysis would ensure that the incremental growth of the locker program is cost efficient by reaching many users but also covering areas serving disadvantaged populations. Cities and transit agencies can be proactive in attracting public-private partnerships with interested delivery companies.

A future area of research includes locker site design, to incorporate the safety of parcel carriers during unloading as well as the security of consumers retrieving parcels. Other design-related research should ensure that the lockers are suitable for users of all ages and all abilities. On a macroscopic design scale, transit-oriented locker systems are relevant to ongoing conversations guiding the evolution of transit-oriented development. For this review, only the PaR facilities owned by TriMet were considered; other parking lots owned by local businesses and/or churches were not reviewed for ridership, equity, or parcel locker suitability but could be incorporated in a future study. Additionally, the impact of delivery vehicle automatization on locker operations and design, VMT, and carbon emission reductions, and an overall cost and benefit analysis of transit locker facilities would be interesting extensions of this research.

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The authors confirm contribution to the paper as follows: study conception and design: J. S. Schaefer, M. A. Figliozzi; analysis and interpretation of results: J. S. Schaefer, K. L. Keeling, M. A. Figliozzi; manuscript preparation: K. L. Keeling, J. S. Schaefer, M. A. Figliozzi.

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