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# Spatial Accessibility and Equity Analysis of Amazon Parcel Lockers Facilities

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1                   **Spatial Accessibility and Equity Analysis of**  
2                   **Amazon Parcel Lockers Facilities**

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24  Parcel Lockers Facilities". *Journal of Transport Geography*, Forthcoming.

25

26 **Spatial Accessibility and Equity Analysis of Amazon Parcel Lockers Facilities**

27

28

29 **Abstract**

30

31 The onset of the COVID-19 pandemic has accelerated the growth of e-commerce and home  
32 deliveries. Automated parcel lockers are a way to improve delivery efficiency, but despite their  
33 rapid growth, little is known about their accessibility and equity impacts. Among e-commerce  
34 players in the U.S., Amazon stands out by its large market share. This research studies the  
35 location of Amazon lockers in Portland, Oregon utilizing highway, land use, employment, and  
36 sociodemographic datasets. Geographical tools and cluster analysis are utilized to estimate  
37 accessibility and equity metrics. Lockers tend to be located in mixed-use areas and can be  
38 utilized by a large percentage of the population. However, the equity metrics indicate that the  
39 current distribution of lockers could be improved to reach traditionally underserved populations.  
40 Given the environmental and economic advantages of lockers, policymakers should encourage  
41 the expansion of this type of last mile solution to avoid market failures in areas that are currently  
42 underserved.

43

44 **Keywords:** E-commerce, parcel lockers, last mile and urban logistics, accessibility, equity,  
45 market failure

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# 1. INTRODUCTION AND MOTIVATION

The last mile is often said to be the most expensive and least efficient segment of the supply chain. The high costs of the last mile are in part driven by a lack of economies of scale due to increasingly fragmented orders. One strategy suggested for mitigating the high costs and inefficiencies in the last mile of business to consumer (B2C) deliveries is the implementation of parcel lockers that operate as unmanned pick-up or collection points, where a consumer uses a variable electronic code to open the locker and retrieve a shipment. Lockers are typically offered in various sizes, and some may also serve as drop-off points for consumer returns or to send parcels from locker to locker as well as from locker to home (or vice versa). Cost reductions gained by using lockers are significant. For example, in Poland – a country leader in the adoption of lockers – the cost of sending a parcel from locker to locker is 15% to 30% less than sending from locker to home, depending on the package size (INPOST, 2021).

Lockers have been successfully used by Amazon, the largest e-commerce company in the U.S. Amazon has a complex logistics network with a recent push towards vertical integration of e-commerce activities that includes lockers where customers can pick up parcels (Rodrigue, 2020). Amazon started implementing locker stations in 2011 and as of 2018, was the majority provider of public access lockers, located in over 900 cities in the U.S. (Holsenbeck, 2018). Its share of the U.S. e-retail market also takes a staggering lead against its competitors (Lunden, 2018). Due to Amazon’s great influence on U.S. e-commerce and its rapidly expanding logistics services, the current study focuses only on Amazon lockers.

Data from the U.S. indicate that during the COVID-19 pandemic, home deliveries disproportionately benefit higher-income, more educated sectors of the population (Figliozi & Unnikrishnan, 2021). But, even before COVID, results from the 2017 NHTS (National Household Travel Survey) indicate that in the U.S., households above the poverty line are twice as likely to make online purchases than households below the poverty line (FHWA, 2018). In this context, and since parcel lockers reduce delivery costs, it is relevant to study the distribution of lockers in relation to equity metrics.

77 This research studies the distribution of 176 Amazon locker locations in the Portland, OR  
78 metropolitan area to answer two research questions: (a) How are lockers distributed with respect  
79 to accessibility measures such as population coverage and employment by mode of  
80 transportation? and (b) What are the equity implications of the current distribution of lockers? To  
81 answer these questions, several datasets are analyzed utilizing geographic tools and cluster  
82 analysis. The lockers studied in this research are a closed system (i.e. only used by Amazon) but  
83 with public access. Other types of locker types can be utilized to improve transportation,  
84 accessibility and equity goals as discussed in Section 7.

85  
86 Although parcel lockers are widely used in countries like Poland (Iwan et al., 2016), they are still  
87 a relatively recent phenomenon in the U.S. and to the best of the authors' knowledge no previous  
88 research effort has attempted to analyze accessibility metrics for parcel locker locations in whole  
89 urban areas of the U.S or by utilizing cluster analysis. In addition, the focus on equity and market  
90 failure utilizing multiple variable groups (income, internet access, transportation, built  
91 environment, socio-demographic, and land use variables) is novel and has not been found in the  
92 literature review.

93  
94 The research is organized as follows: Section 2 reviews relevant literature. Section 3 details the  
95 data and Section 4 describes methods employed in this analysis. Section 5 presents the results of  
96 the accessibility analysis. Section 6 provides the equity analysis results. Section 7 discusses the  
97 results, mainly focusing on the potential role of government to avoid market failures in terms of  
98 parcel locker accessibility and equity. Finally, Section 8 summarizes main findings and  
99 conclusions.

## 100 **2. LITERATURE REVIEW**

101 The literature related to parcel lockers has been growing more rapidly in the last few years and  
102 clearly indicates that parcel lockers have many advantages (Viu-Roig & Alvarez-Palau, 2020).  
103 The usage of parcel lockers in lieu of home deliveries allows delivery consolidation while  
104 decreasing vehicle miles traveled (Deutsch & Golany, 2018; Iwan et al., 2016; Verlinde et al.,  
105 2019). Parcel lockers can also benefit the supply chain by consolidating the pick-up of returned  
106 purchases. More than half of all online shoppers in most countries served by logistics company

107 UPS have returned an online purchase (Morganti, Seidel, et al., 2014), adding additional burdens  
108 and costs to supply chains. Parcel deliveries contribute to loading zone shortages in urban areas  
109 and increasing carbon emissions (Chen et al., 2017; Edwards et al., 2009; Moroz & Polkowski,  
110 2016; SCTLC, 2018), and delivery consolidation utilizing lockers may help alleviate these  
111 issues. Data from focus groups indicate that the self-service aspect of lockers not only reduces  
112 costs but may also increase value for the customers (Vakulenko et al., 2018). In addition, the use  
113 of parcel lockers may help fulfill safety recommendations regarding the COVID-19 pandemic as  
114 they are befitting of social distancing measures and contactless delivery.

115  
116 Regarding location preferences, consumers in Sweden indicated a preference for lockers near  
117 shopping areas and home. Proximity to subway or bus stops was also identified as a preference  
118 (Vikingson & Bengtsson, 2015). In Poland, consumers strongly preferred locations near their  
119 home or on the way to work, while the least attractive locations were near shopping centers and  
120 transit stops (Iwan et al., 2016; Lemke et al., 2016). In Brazil, the top three preferred locations  
121 were supermarkets, stores, and shopping malls (Oliveira et al., 2017). In Korea, Lee et al. (2019)  
122 believe placing parcel lockers along the daily life path of consumers and near public  
123 transportation will enhance their utilization. In France, Morganti et al. (2014) found that the  
124 average distance to the nearest pick-up point was only 1.6 km (1 mi.) in urban areas and 6 km  
125 (3.7 mi.) in rural areas and over 50% of the pick-up points were located within 400 m (0.25 mi)  
126 of a commuter railway station. Comparing urban, suburban, and rural regions, pick-up points  
127 were over-represented in the urban areas with respect to their share of the population. In South  
128 East Queensland (Australia), the presence of a parcel locker was associated with proximity to  
129 highways and public transport, high population density, a good balance of population and jobs,  
130 and areas with higher rates of household internet access (Lachapelle et al., 2018). Here, lower  
131 income populations might have a slight advantage when it comes to parcel locker presence.  
132 However, lower automobile ownership rates and a limited ability to travel longer distances,  
133 which are associated with lower incomes, counterbalance that benefit (Lachapelle et al., 2018).  
134 Finally, Fang et al. (2019) analyzed the distribution of Amazon Lockers in Los Angeles County  
135 and detected a positive spatial correlation of locker counts per U.S. Census tract using the Global  
136 Moran I Index. Higher education levels, internet access, and walking mode share had the highest

137 correlations with the variable locker counts. The regression analysis produced counterintuitive  
138 signs for variables such as population and internet access likely due to multicollinearity.

139

140 A recent overview of the locker location literature comes up with six factors that affect locker  
141 location: potential 24/7 service availability, accessibility by different modes, security,  
142 environmental impacts, installation costs, and regulatory constraints (Lagorio & Pinto, 2020).  
143 The e-commerce literature indicates that household income and internet usage are key variables  
144 that affect online purchases; higher-income households with more access to computers and the  
145 internet are more likely to make purchases online (Cao et al., 2012; Crocco et al., 2013; De  
146 Blasio, 2008; Farag et al., 2007). However, underserved populations appear to be less likely to  
147 participate in online shopping activities. During the COVID-19 lockdown period, significantly  
148 higher rates of home deliveries were associated with higher income and education levels, more  
149 access to electronic devices and internet, automobile ownership and usage, larger households,  
150 and white households (Figliozzi & Unnikrishnan, 2021). For consumers reliant on transit, the  
151 installation of common carrier lockers at transit stations has been proposed to improve access  
152 (Keeling et al., 2021).

153

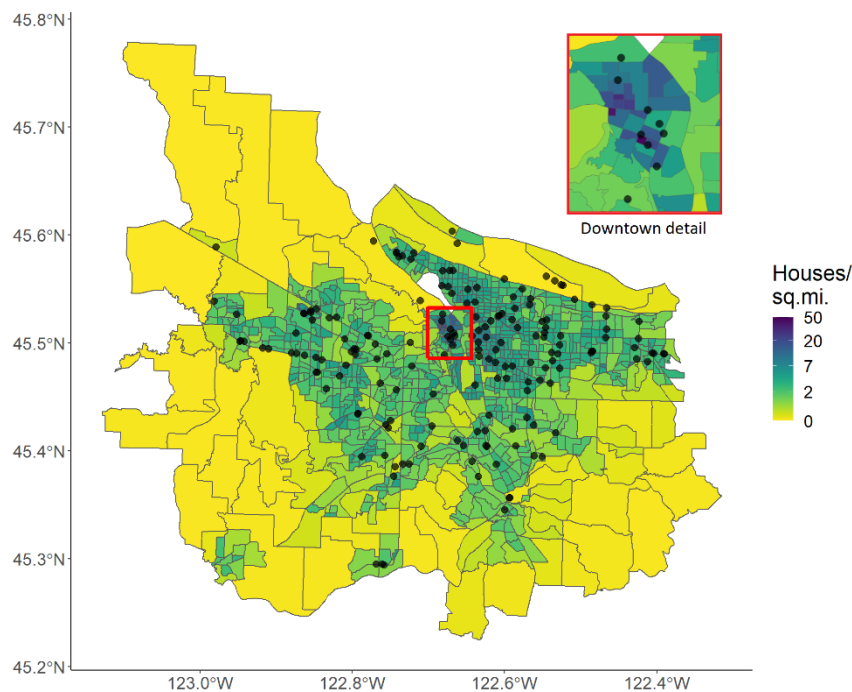
154 Although previous studies have identified parcel locker location preferences, there has not been  
155 extensive research assessing existing locations of lockers in whole metropolitan urban areas of  
156 the U.S. focusing on equity metrics and utilizing clustering methods with income, internet  
157 access, transportation, built environment, socio-demographic, and land use variables. While  
158 cluster analysis has been utilized in transportation studies to analyze freight, transit, crashes,  
159 environmental justice, and mobility (Cidell, 2010; Diaz-Varela et al., 2011; du Preez et al., 2019;  
160 Haustein & Nielsen, 2016; Schweitzer, 2006) it has not yet been applied to study locker  
161 distributions and/or equity.

### 162 **3. DATA COLLECTION**

163 The study area is defined as the Oregon portion of the Portland-Vancouver-Hillsboro  
164 metropolitan statistical area. This research does not focus on lockers that can be installed inside  
165 buildings or complexes for the exclusive benefit of its residents or employees. It focuses on  
166 lockers that are mostly installed on sidewalks and public access areas. The dataset of lockers

167 includes the name, coordinates, and host site (where available) of each locker facility. A total of  
168 176 Amazon locker facilities were identified in the study area in October 2020 and Figure 1  
169 shows housing density at U.S. Census block level overlaid by the locker locations.

170  
171 In total, 62 variables related to age, income, housing, means of transportation to work, race and  
172 origin, educational attainment, employment, and computer and internet service accessibility were  
173 collected from the U.S. Census Bureau American Community Survey (ACS). These 62 variables  
174 are listed in Table A. 1 in the appendix. The socio-demographic data are aggregated at the block  
175 group level – the smallest level of geographic detail with a wide range of publicly available  
176 variables. Census block groups are usually comprised of contiguous clusters of census blocks,  
177 containing between 600 and 3000 people (U.S. Census Bureau, 2019), and their boundaries can  
178 be viewed in Figure 1.



179  
180 **Figure 1: Study area and housing density with Amazon locker locations.**

181  
182 A GIS shapefile of the street network in the area provided by the local MPO was used to  
183 investigate locker locations in relation to transportation facilities. Another GIS shapefile  
184 containing Oregon zoning data was obtained from the Oregon Spatial Data Library to assess land  
185 use patterns associated with Amazon locker locations. Data on the business and employment  
186 patterns of the study area were downloaded from the U.S. Census Bureau's ZIP Code Business  
187 Patterns (ZBP) dataset for 2018. This data contains information about the number and type of



188 business establishments, the number of employees, and payroll figures, aggregated at the ZIP  
189 Code level. The establishment types are categorized according to the North American Industry  
190 Classification System (NAICS).

## 191 4. METHODS

192 The dataset containing information about the Amazon lockers was obtained using the Google  
193 Places API adapting a Python code from Fang et al. (2019). After locating the lockers, a kernel  
194 density estimation (KDE) was applied to each observation (point) to distribute its spatial  
195 influence based on a given bandwidth; i.e., a locker located at the border of two Census blocks  
196 services the population in both areas, but beyond a certain bandwidth, the influence tapers to  
197 almost null. The density of Amazon lockers across the study area was calculated using KDE with  
198 the function *density.ppp* from the package *spatstat* in R (Baddeley et al., 2015). A gaussian  
199 kernel function was chosen for the KDE, the standard form of which is shown in Equation 1  
200 where  $d$  represents the distance from the locker. The kernel ( $K$ ) is scaled as in Equation 2 where  
201  $h$  represents the bandwidth and  $e$  is Euler's number or constant.

$$K(d) = \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}d^2} \quad \text{Equation 1}$$

$$K_h(d) = \frac{1}{h} K\left(\frac{d}{h}\right) \quad \text{Equation 2}$$

203 For this analysis, the bandwidth was chosen to represent the maximum distance a consumer  
204 would be likely to walk to retrieve a parcel. Oliveira et al. (2019) used a 1000 m (0.6 mi.) radius  
205 (bandwidth) when calculating the kernel density of potential collection and delivery points in  
206 Brazil. In New Zealand the median tolerable walking distance to a collection point was 1.46 km  
207 (0.9 mi) (Kedia et al., 2019). In Seattle, light rail passengers most frequently chose up to a six  
208 block distance (approximately  $\frac{1}{4}$  to  $\frac{1}{2}$  mile given the average size block) when asked how far  
209 they would be willing to walk with a parcel (SCTLC, 2018). Other studies noted a consumer  
210 preference for minimizing the required travel distance to lockers for parcel retrieval (Iwan et al.,  
211 2016; Lemke et al., 2016; Vikingson & Bengtsson, 2015). A conservative bandwidth of a half  
212 mile was selected for the current KDE.

214

215 A small percentage of missing data was encountered across four of the 62 ACS variables used.  
216 The percentage of missing values within these four variables ranged from 1.1% to 9.5% over all  
217 952 block groups within the study area. Rather than exclude observations (i.e. block groups) with  
218 missing values from the analysis, the missing values were imputed using the *imputePCA* function  
219 in the R package, *missMDA* (Husson & Josse, 2020).

220  
221 The literature review indicates that income and access to computers and internet service are key  
222 variables affecting online purchases. Mode share and built environment variables are of interest  
223 from a transportation policy point of view. Also, variables such as education, race, age, home  
224 ownership, household size, and employment status are key variables from an equity perspective.  
225 Hence, four groups of ACS variables were created to represent different aspects of locker access  
226 equity: (1) income, (2) computer and internet access, (3) prevalent built environment and  
227 transportation mode, and (4) other non-income demographic factors such as age, race or origin,  
228 household occupancy, educational attainment, and work status. Income was placed in a separate  
229 group because it is key factor affecting both online purchases and equity. All variables used in  
230 the analysis and their basic descriptive statistics are provided in Table A. 1 of the appendix. For  
231 each of the four ACS variable groups, a cluster analysis was performed.

232  
233 Clustering classifies observations into groups (clusters) by computing a measure or distance of  
234 the similarity between each pair of observations. Traditional clustering methods like k-means  
235 aim to minimize total intra-cluster variation (also known as total within-cluster variation).  
236 Traditionally, the within-cluster variation ( $W$ ) is defined as the sum of squared Euclidean  
237 distances between items and a centroid:

$$W(C_k) = \sum_{x_i \in C_k} (x_i - \mu_k)^2$$

**Equation 3**

239 where:

240  $x_i$  is a data point belonging to the cluster  $C_k$

241  $\mu_k$  is the mean value of the points assigned to the cluster.

242

243 Each observation ( $x_i$ ) is assigned to a given cluster such that the sum of squares (SS) distance of  
244 the observation to their assigned cluster centers ( $\mu_k$ ) is minimized. The total within-cluster  
245 variation is defined as follows:

246

$$TWC = \sum_{k=1}^k W(C_k) = \sum_{k=1}^k \sum_{x_i \in C_k} (x_i - \mu_k)^2 \quad \text{Equation 4}$$

247

248 The total within-cluster sum of square measures the compactness (i.e., goodness) of the  
249 clustering and the goal is to make it as small as possible while keeping a reasonably low number  
250 of clusters that are easy to interpret or visualize.

251

252 The cluster analysis for each equity category was an iterative, multi-step process. The first step  
253 was to perform a hierarchical cluster analysis using Ward's method (R function *hclust* with  
254 method = "ward.D2"). This hierarchical cluster analysis produced an object describing the  
255 resulting dendrogram, which was then cut into k clusters. The centroids of these clusters were  
256 used to define the initial points for a k-means cluster analysis (R function *kmeans*). The process  
257 was iterated for multiple values of k ranging from two to six. Solutions with random centroids  
258 were also obtained to see if there was a TWC improvement. Interpretability of the results,  
259 mapping of the clusters and their spatial contiguity, plots of the total within sum of squares  
260 (TWC), and the percent deviations of the cluster averages from the median cluster averages were  
261 utilized to select an appropriate value for k.

262

263 The results of the iterative clustering process indicated the block groups would be best divided  
264 into three clusters for the income, computer and internet access, and transportation equity  
265 categories. The non-income demographic category was best represented by four clusters. For  
266 each equity category, the KDE was integrated over the cluster areas to obtain a total expected  
267 locker count per cluster. Next, the share of each cluster's population within various distances of a  
268 locker was estimated by constructing radial buffers around the lockers as a function of  
269 transportation mode. For pedestrians, conservative buffers of 0.25 miles and 0.5 miles were  
270 selected based on the range of walking distances cited in the reviewed literature. To estimate a  
271 range of reasonable biking buffers studies by Blanc & Figliozzi and Kedia et al. (2016; 2019)

272 were utilized. Median actual biking distances in the Portland area for shopping, errands, or  
273 personal business were stated as 1.3 miles to 3.1 miles. Thus, biking buffers of 1.5 miles and 3  
274 miles were determined as reasonable. Finally, driving buffers of 3 miles and 5 miles were  
275 selected based on the average car trip length of 4.4 miles in the Portland region (Small, 2016).  
276 When analyzing buffers it is important to consider that proximity is key, especially for users that  
277 walk or cycle to the locker. It should also be considered that in many cases, users pick up a  
278 package at the end of a trip chain, for example when returning home after work or after running  
279 errands.

## 280 **5. ACCESSIBILITY ANALYSIS**

281 This section discusses locker accessibility in terms of business location characteristics, land use,  
282 and proximity to transportation facilities, home, and work.

### 283 **5.1 CHARACTERISTICS OF BUSINESS LOCATIONS**

284 The majority of lockers (122 of 176 lockers, or 69.3%) are located inside or on the property of a  
285 convenience store. The next most common hosts for an Amazon locker are drugstores (22  
286 lockers, or 12.5%), department stores (9 lockers, or 5.1%) and grocery stores (8 lockers, or  
287 4.5%). The remainder of the hosts included gyms, banks, restaurants, storage facilities, a hotel, a  
288 retirement community, a go-kart center, and other retailers. This distribution is compatible with  
289 the literature, which indicated one of the best sites for parcel lockers is next to convenience  
290 stores (Iwan et al., 2016). The distribution of locker hosts observed in the Portland area also  
291 seems reasonable when considering a few of Amazon's business partnerships. For instance, early  
292 in the locker implementation, convenience store brand 7-Eleven partnered with Amazon to host  
293 locker facilities. Amazon has partnered with the drug store, Rite Aid, more recently (Cosgrove,  
294 2019). Amazon suggests that hosting a locker can increase foot traffic and drive sales of small  
295 dollar-amount purchases (Amazon, 2019). Amazon also has business partnerships with Chase  
296 Bank and Sprint, which helps to explain the few, somewhat unlikely locker hosts of a  
297 communications store and two banks. Additionally, Amazon owns grocer Whole Foods and  
298 installing lockers in those grocery stores may provide benefits for both businesses.

299 **5.2 TRANSPORTATION AND LAND USE**

300 The nearest roadway to each locker facility was identified and the distance to it was calculated to  
301 explore locker access from different types of road facilities. In addition, the distances from each  
302 locker facility to the nearest roadway of each classification (collector, arterial, highway, and  
303 freeway ramp) were calculated. While the average and median distances from lockers to freeway  
304 ramps or highways were close to one mile or more, the average and median distances from  
305 lockers to arterials and collectors were much smaller, ranging from a couple hundred feet to less  
306 than a quarter mile. It follows that most Amazon lockers were located closest to an arterial road  
307 (101 lockers, or 57.4%), followed by a collector road (52 lockers, or 29.5%), a highway (15  
308 lockers, or 8.5%), and a freeway ramp (8 lockers, or 4.5%). Arterial roads typically provide high  
309 visibility to businesses and serve higher volumes of motorized traffic compared to lower classed  
310 roads. Recalling that the majority of locker hosts were convenience stores which tend to thrive in  
311 high traffic areas, it is logical that most of the lockers were located closest to arterial roads.  
312 Transit routes are also more likely to follow arterial roads, but access by bicycle or walking may  
313 be reduced if low traffic stress bicycle and pedestrian facilities are not provided.

314  
315 The zoning shapefile was overlaid by the Amazon locker locations and the land use category  
316 corresponding to each location was extracted in R. The locker facilities were predominantly  
317 located in mixed-use commercial and residential zones (120 lockers, 68.2%), with commercial  
318 zones being the next most common (44 lockers, 25%), followed by industrial (8 lockers, 4.5%).  
319 The zoning types corresponding to areas of very low population density such as forest, farm,  
320 rural, natural areas, or parks did not contain any locker facilities.

321

322 **5.3 PROXIMITY TO HOME AND WORK**

323 One of the most often cited preferences of consumers for locker locations was near their home.  
324 Buffer ranges around the lockers were created for the walking, biking, and driving distances. A  
325 range of the number of households within the buffers was then estimated using areal  
326 proportioning for the entire study area as a metric to gauge the average locker proximity to  
327 residences. These results are displayed in Table 1 along with the range of percentages of total  
328 houses in the study area within the locker buffers. These calculations estimate that almost 85% of

329 households in the study area are within 1.5 miles of an Amazon locker and 97% of households  
330 are within five miles.

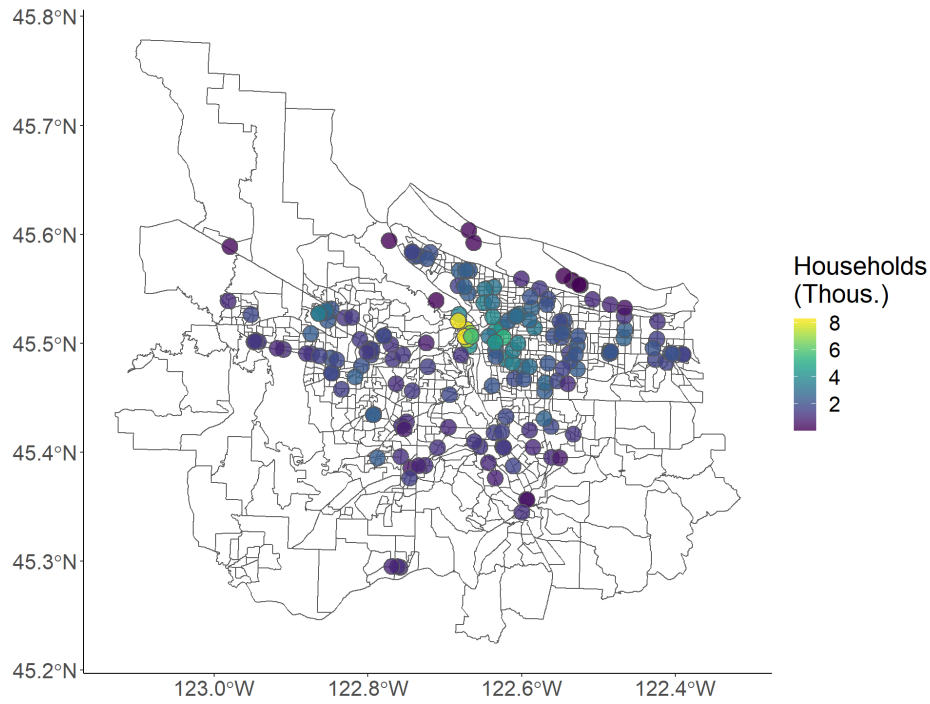
331 **Table 1: Range of estimated number of households within reach of Amazon lockers by mode.**  
332

Mode (Dist. Range)	Households		Employment	
	HH (Thous.)	% of Total HH	Emp. (Thous.)	% of Total Emp.
Walk (0.25-0.5 Mi.)	81-232	12.6-36.1	103-285	11.7-32.4
Bike (1.5-3.0 Mi.)	546-605	84.9-94.0	673-785	76.4-89.1
Drive (3.0-5.0 Mi.)	605-624	94.0-97.0	785-828	89.1-93.9

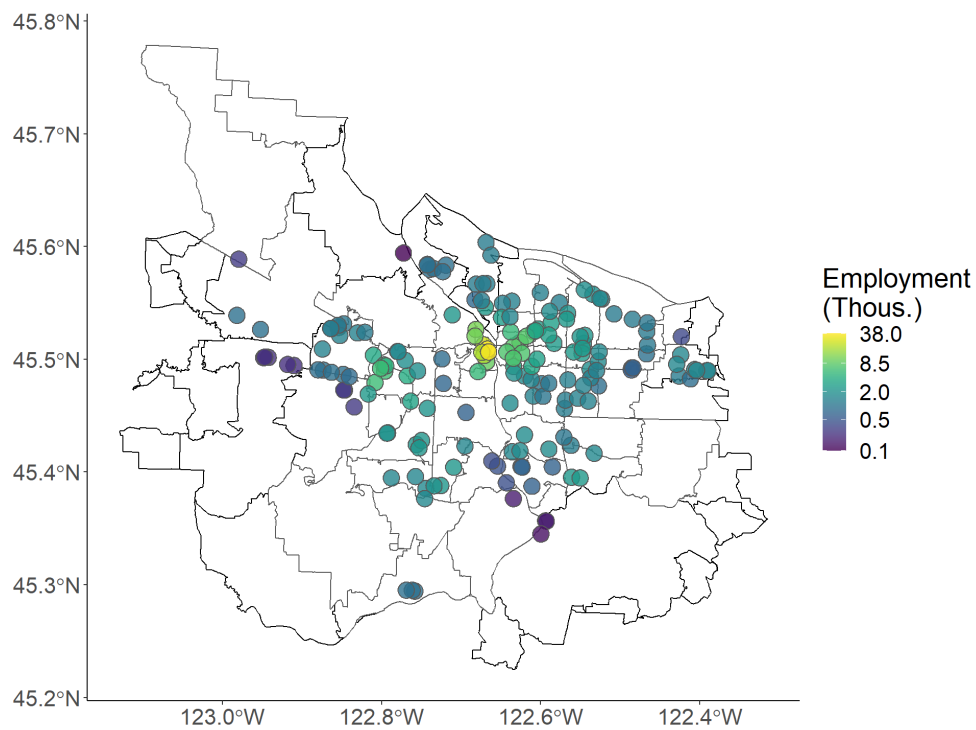
333  
334 The map in Figure 2 displays the locations of the lockers with a 0.5-mile buffer, shaded  
335 according to the estimated number of households (in thousands) within the buffer. The map  
336 shows that lockers with the greatest number of households within the buffer distance tend to be  
337 located in the city center and in the close-in neighborhoods. This observation was consistent  
338 across all buffer distances.

339  
340 Another frequently cited preference was for locker locations near the consumer's workplace.  
341 Table 1 gives the estimated ranges for the number of employees and the percentage of the study  
342 area's total employment within the range of buffer distances established for walking, biking, and  
343 driving. Approximately three-quarters of employees are within 1.5 miles of an Amazon locker.  
344 The lockers with a 0.5-mile buffer are again shown in Figure 3 but shaded according to the  
345 estimated employment within the buffer area. Note that in this figure, the scale is logarithmic.  
346 The employment density is much higher in the central city region, thus, the lockers with the  
347 greatest number of employees within 0.5 miles also tend to be located in that area.

348



349  
 350 **Figure 2: Estimated number of households within a 1/2 mile of an Amazon locker.**  
 351



352  
 353 **Figure 3: Estimated employment within a 1/2 mile of an Amazon locker.**  
 354

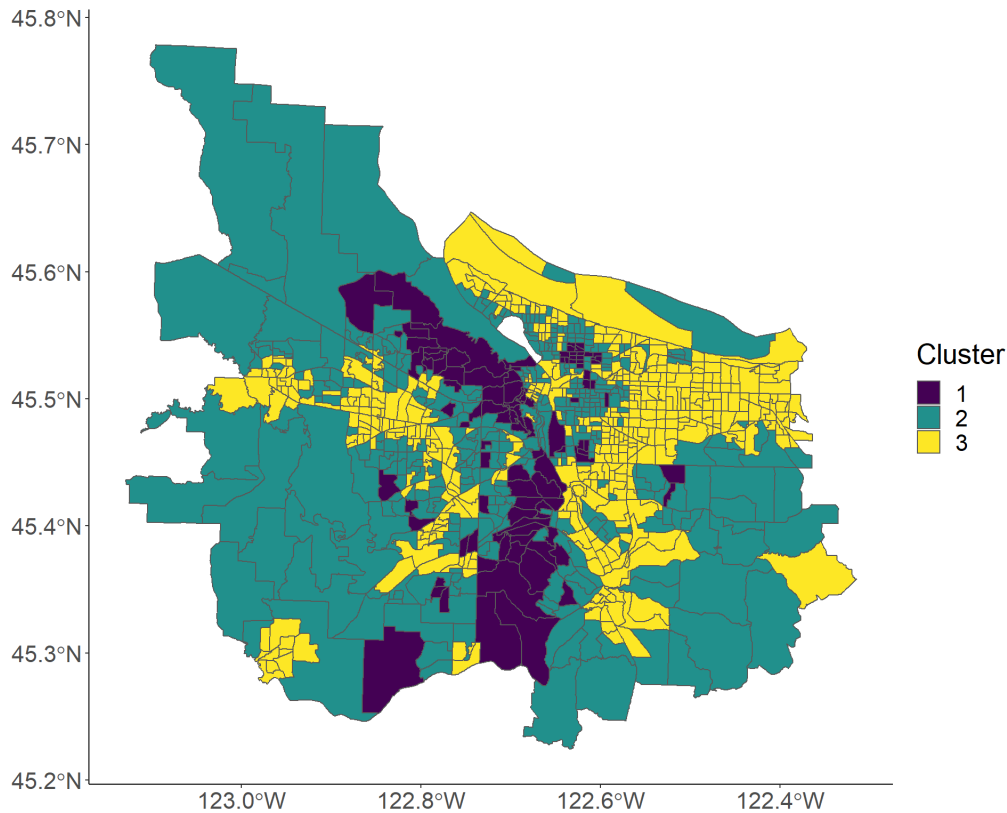
355 **6. EQUITY ANALYSIS**

356 Evaluating equity is complex and can take many forms depending on the categorization of  
357 populations, the performance measures evaluated, and what impacts are considered. Establishing  
358 parcel locker facilities in traditionally underserved communities (such as non-white, low-income,  
359 transportation disadvantaged, etc.) is important to achieve equitable access to basic services such  
360 as mail and package distribution. This section discusses the results from the cluster analyses with  
361 respect to the distribution of Amazon lockers.

362 **6.1 INCOME**

363 A map depicting the results of the cluster analysis for the income category can be seen in Figure  
364 4. It appears that block groups in Cluster 3 are more prominent in the eastern portion of the study  
365 area and block groups in Cluster 1 are generally found in the central region, relative to east-west.  
366 Block groups in Cluster 2 appear to comprise the largest portion of land area in the study region.

367



368  
369  
370

**Figure 4: Income cluster results.**



371 Table 2 provides a quantitative description of the characteristics of each income cluster. The key  
 372 variables showing the most variance among clusters are displayed. Higher income population  
 373 and households (relative to the median cluster) tend to comprise Cluster 1, and lower-income  
 374 population and households tend to be located in Cluster 3. The differences between groups are  
 375 substantial. The average densities of Amazon lockers per square mile (based on the integrated  
 376 KDE), per thousand population, and per thousand households, and the average household  
 377 incomes for the Income clusters are also provided in Table 2. The density of lockers per square  
 378 mile within Cluster 3 is three to four times greater than in Cluster 1 or Cluster 2 (0.51 versus  
 379 0.15 and 0.12, respectively). The average expected density per thousand population and per  
 380 thousand households is also greatest in Cluster 3, though the differences from the other two  
 381 clusters are less pronounced. The range of population in thousands per cluster within the  
 382 walking, biking, and driving locker buffer ranges is also shown in Table 2. The percentage of the  
 383 total cluster population within the buffers is also given. These results further suggest that Cluster  
 384 3 has greater access to the Amazon lockers overall, and particularly by pedestrian or bicycle  
 385 modes.

386 **Table 2: Income cluster characteristics**

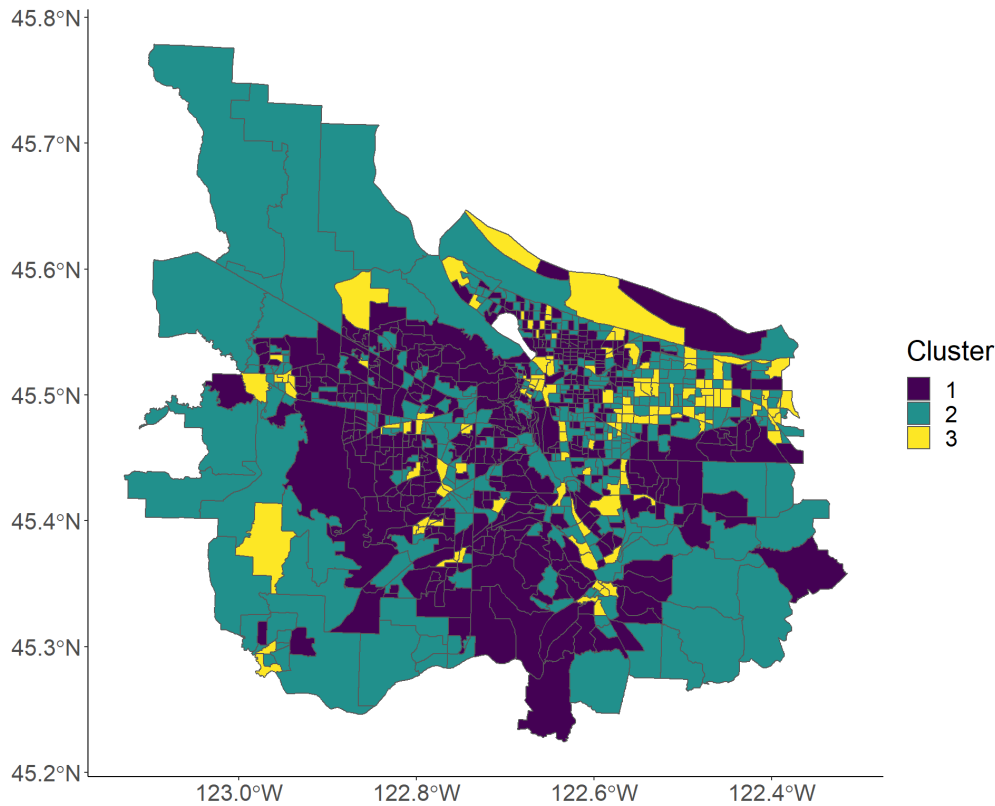
<b>Key Variables</b>	Cluster 1 “High”	Cluster 2 “Medium”	Cluster 3 “Low”
Median Housing Unit Value*	\$674,054	\$434,858	\$286,790
Average HH Income	\$186,975	\$109,166	\$65,941
Median HH Income	\$145,813	\$89,369	\$54,805
Per Capita Income	\$71,278	\$45,256	\$27,469
<b>Size or Quantity</b>			
Lockers	14.2	63.1	98.2
Population (Pop.)	156,386	681,403	806,872
Households (HH)	57,842	272,153	313,740
Area (Mi.2)	92.4	542.0	191.0
<b>Densities</b>			
Lockers per Sq.Mi.	0.15	0.12	0.51
Lockers per 1000 Pop.	0.09	0.09	0.12
Lockers per 1000 HH	0.24	0.23	0.31
<b>Access by Mode as % Pop.</b>			
Walking (0.25-0.5) Mi..	3.9-17.1	9.5-28.8	14.7-41.2
Biking (1.5-3.0 Mi.)	73.0-97.8	75.2-89.1	92.0-96.2
Driving (3.0-5.0 Mi.)	97.8-100.0	89.1-95.7	96.2-97.0

387 \*Owner-occupied

388 **6.2 COMPUTER AND INTERNET ACCESS**

389 Figure 5 shows the results of the cluster analysis for the computer and internet access category.  
390 The spatial distribution of the clusters here appears to be somewhat more dispersed than those  
391 generated by the income category, although there does appear to be some correlation between  
392 Clusters 1 and 3 in Figure 5 and Clusters 1 and 3 in Figure 4.

393



394

395 **Figure 5: Internet and computer access cluster results.**

396

397 Table 3 highlights the variables that most characterize the computer and internet access clusters  
398 and their values. Households in Cluster 1 were most likely to have access to a computer and  
399 broadband internet service. Households in Cluster 3 were least likely to have access to a  
400 computer or broadband service and were far more likely to have no access to internet at all  
401 relative to Cluster 1 or Cluster 2. Recalling the observation of the minor correlations with  
402 Clusters 1 and 3 in the Income category, these results suggest lower income populations have  
403 less access to computers and internet compared to higher income populations. Cluster 2 appeared  
404 most likely to have cell only based internet access, although the difference from Cluster 3 was  
405 very small. Considering much of the Cluster 2 area is located farther from the city center, this

406 finding may be partially explained by service area limits for broadband internet, i.e., the option  
 407 of broadband may not exist in outlying areas.

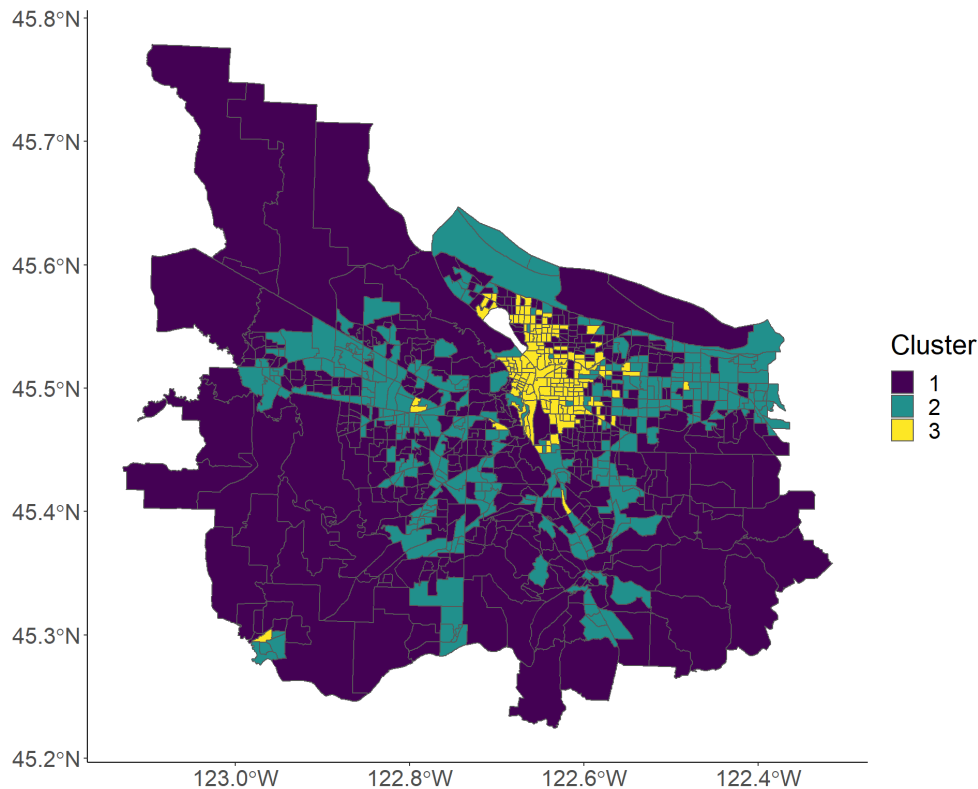
408 **Table 3: Internet access cluster characteristics**

<b>Key Variables</b>	<b>Cluster 1 “High”</b>	<b>Cluster 2 “Medium”</b>	<b>Cluster 3 “Low”</b>
% HH with Computer	97.9	93.4	82.3
% HH with Broadband	94.3	85.0	71.1
% HH with Cell Only	5.9	9.0	8.9
% HH without Internet	3.9	10.4	23.7
<b>Size or Quantity</b>			
Lockers	73.6	68.8	33.0
Population (Pop.)	834,530	594,030	216,101
Households (HH)	318,592	235,225	89,918
Area (Mi.2)	293.7	468.7	63.0
<b>Densities</b>			
Lockers per Sq.Mi.	0.25	0.15	0.52
Lockers per 1000 Pop.	0.09	0.12	0.15
Lockers per 1000 HH	0.23	0.29	0.37
<b>Access by Mode as % Pop.</b>			
Walking (0.25-0.5) Mi..	7.8-26.0	14.7-40.0	16.8-46.7
Biking (1.5-3.0 Mi.)	78.2-93.9	85.8-91.1	95.4-97.8
Driving (3.0-5.0 Mi.)	93.9-98.3	91.1-94.1	97.8-98.1

409  
 410 Computer and internet access have been linked to income, and low access households may be  
 411 considered a disadvantaged group from an equity standpoint. The percentage of households  
 412 without internet access is highest in Cluster 3, at more than twice the percentage of the next  
 413 highest cluster (23.7% vs. 10.4% for Cluster 2 and 3.9% for Cluster 1). Cluster 3 generally has  
 414 lower access to computers and internet services overall, relative to Clusters 1 and 2. However,  
 415 Cluster 3 appears to have the highest average concentration of lockers for all three measurement  
 416 units, particularly with respect to area. Cluster 3 may have greater access to the parcel lockers as  
 417 the percentage of its population within nearly all buffer distance ranges is greater than the  
 418 percentages for Cluster 1 or Cluster 2. This is a positive finding with regard to equity.

### 419 **6.3 TRANSPORTATION AND BUILT ENVIRONMENT**

420 The spatial distribution of the transportation and built environment category clusters is displayed  
 421 in Figure 6. The map shows the majority of Cluster 3 is in the center of the study area, which  
 422 generally corresponds to the downtown and inner eastside areas of Portland. Cluster 2 areas are  
 423 more dispersed around the region but seem to be located near major transportation routes.  
 424 Cluster 1 contains the most land area, consisting of most of the outlying regions and generally  
 425 surrounding the areas assigned to Clusters 2 and 3.

427  
428

**Figure 6: Transportation cluster results.**

429 Several variables related to commute mode choice, housing unit type, and population density  
 430 were selected for display in Table 4 to quantify the primary characteristics of each cluster. These  
 431 variables generally showed the most variance among clusters. Housing unit types and population  
 432 density were included in this category as a representation of the built environment, which has  
 433 been shown to influence transportation choices (Cervero, 2002). When combining transport and  
 434 housing variables it is difficult to both succinctly and accurately label the clusters, nonetheless a  
 435 non-numerical “intuitive” description is added under each cluster.

436

437 Cluster 1 is characterized by a lower likelihood of walking or taking public transit to work,  
 438 relative to the other two clusters. Single detached housing was much more likely in Cluster 1 at  
 439 almost twice the percentages of Cluster 2 or Cluster 3. Correspondingly, multi-unit housing was  
 440 least likely in Cluster 1. Furthermore, population density was lowest in Cluster 1 relative to  
 441 Clusters 2 and 3. These findings align with the spatial distribution of the clusters shown in Figure  
 442 6, whereby Cluster 1 dominates the areas furthest from the population dense city center.

443 The main characteristics of Cluster 2 are a tendency toward commuting by carpool, but not by  
 444 bicycle, relative to the other clusters. Cluster 2 also had the lowest average percentage of  
 445 workers working from home. Although the overall percentage of mobile houses is low in all  
 446 clusters, it is more than twice as high in Cluster 2 as in Cluster 1, the median cluster, and almost  
 447 ten times higher than in Cluster 3.

448  
 449

**Table 4: Transportation and BE cluster characteristics**

<b>Key Variables</b>	Cluster 1 “Drive alone – single housing”	Cluster 2 “Drive alone – multi-unit”	Cluster 3 “Transit/active – multi-unit”
% Workers Drove Alone*	72.4	68.3	45.6
% Workers Carpooled*	8.3	11.8	5.3
% Workers Public Transit*	5.4	8.8	17.3
% Workers Bicycled*	2.3	1.4	10.9
% Workers Walked*	1.9	3.4	10.7
% Workers Work from Home*	8.8	5.1	8.9
% Housing as Single Detached	86.1	39.9	44.5
% Housing as Multi-unit	8.9	47.0	50.8
% Housing as Mobile	1.9	3.9	0.4
Population Density (per mi. <sup>2</sup> )	4948	6675	11922
<b>Size or Quantity</b>			
Lockers	72.7	70.6	32.2
Population (Pop.)	794,218	623,453	226,990
Households (HH)	289,326	247,956	106,453
Area (Mi. <sup>2</sup> )	656.3	144.6	24.6
<b>Densities</b>			
Lockers per Sq.Mi.	0.11	0.49	1.31
Lockers per 1000 Pop.	0.09	0.11	0.14
Lockers per 1000 HH	0.25	0.28	0.30
<b>Access by Mode as % Pop.</b>			
Walking (0.25-0.5) Mi..	6.2-21.4	12.6-36.9	26.9-68.3
Biking (1.5-3.0 Mi.)	74.2-88.3	89.0-98.0	98.0-98.8
Driving (3.0-5.0 Mi.)	88.3-94.5	98.0-98.8	98.8-100

450 \*Aged 16 years or older

451

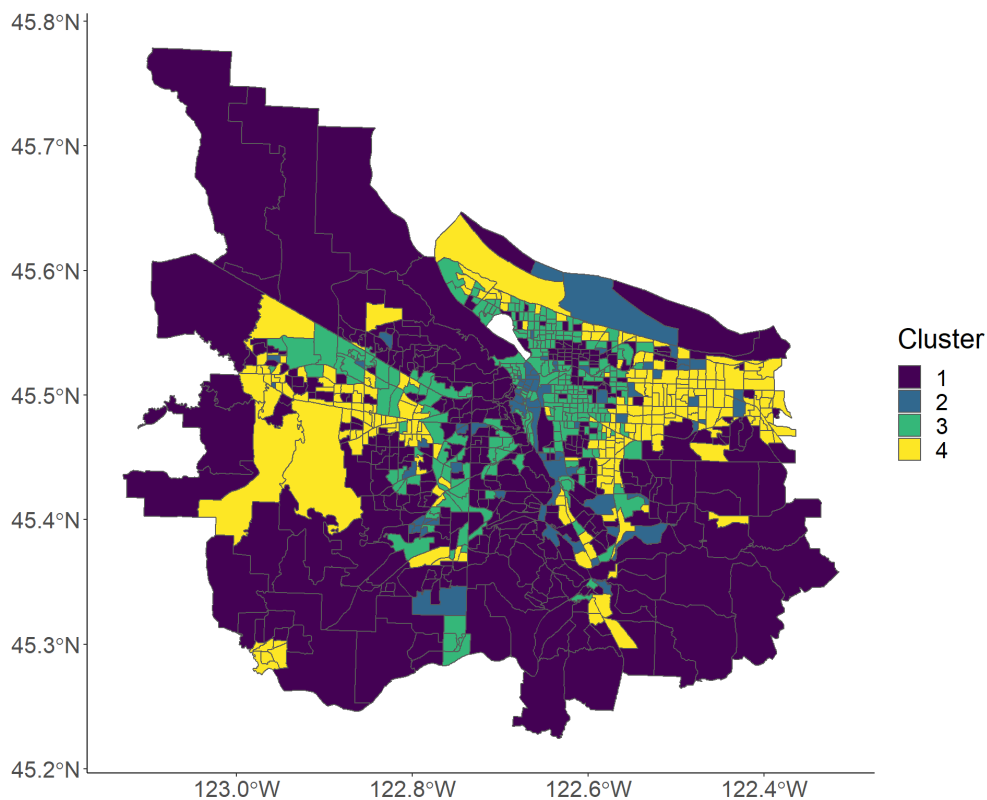
452 Cluster 3, primarily located in the central region of the city, is characterized by an appreciable  
 453 increase in population density relative the rest of the study area. Thus, it should not be surprising  
 454 that rates of public transit or active travel modes (walking or bicycling) of commuting to work  
 455 far outpaced rates elsewhere in the study area. The average expected number of lockers per  
 456 square mile is highest in Cluster 3 and lowest in Cluster 1 which tends to be more rural and has  
 457 the lowest population density. Cluster 3 also has a greater expected number of lockers per  
 458 population and per household, on average, although the differences between clusters are less  
 459 significant. The estimated percentage of the population in Cluster 3 within walking distance to an

460 Amazon locker is nearly twice that of Cluster 2 and more than three times the percentage in  
461 Cluster 1. Moreover, almost all of Cluster 3 is within 1.5 miles of an Amazon locker. As  
462 expected, the percentage of Cluster 1 within the buffer zones is lowest for all three mode choices.  
463

## 464 6.4 NON-INCOME DEMOGRAPHICS

465 Di Ciommo and Shiftan (2017) acknowledge age, educational level, and employment status are  
466 related to income and car ownership. Youth and elderly who are non-drivers are more reliant on  
467 public transportation and those with language barriers may be less likely to hold a driver's  
468 license and have trouble navigating public transit. Additionally, race or ethnicity is frequently  
469 considered in equity analyses as minorities often have lower relative incomes (Di Ciommo &  
470 Shiftan, 2017). Figure 7 displays a map of the non-income category cluster results. The map  
471 shows most of the outlying areas and a strip through the center of the study region, west of the  
472 downtown area, belong to Cluster 1.

473



474  
475  
476

**Figure 7: Non-Income Demographic cluster results.**

477 Cluster 2 is comprised of fewer block groups overall and appears to be dispersed among the  
478 central and eastern portions of the study area. Block groups immediately east of the downtown  
479 area appear to be predominantly of Cluster 3. Cluster 3 appears slightly more scattered in the  
480 western half of the study area but seems to follow primary transportation routes. Cluster 4 block  
481 groups tend to be farther from the city center than those of Cluster 3.

482  
483 This category contained the largest number of variables and only those in which higher variances  
484 were observed between clusters were selected for display in Table 5. Cluster 1 is characterized  
485 by a much higher rate of owner-occupied housing. The housing units were less likely to have  
486 only one occupant, but more likely to have four occupants compared to the other clusters.  
487 Compared to Clusters 2 and 3, Cluster 1 was generally more likely to have multiple occupants in  
488 a housing unit. The percent of the population who were age 0-9 or 10-17 was also greater in  
489 Cluster 1 than Cluster 2 or 3, but not greater than Cluster 4. In the adult age groups, Cluster 1  
490 had the largest percentage of 45–64-year-olds but the smallest percentage of 18–29-year-olds on  
491 average. This combination of age groups may indicate a high prevalence of families with  
492 children. Moving to race and origin, Cluster 1 had the lowest percentages of Black or African  
493 American and Hispanic or Latin-American in the population relative to all other clusters. The  
494 population in Cluster 1 also tended to be more educated, with the lowest rate of non-high school  
495 graduates and higher rates of bachelor's and graduate or professional degrees. However, the  
496 differences in these rates compared to Cluster 3 were small. When many variables are present it  
497 is difficult to both succinctly and accurately label the clusters, nonetheless a non-numerical  
498 “intuitive” description is added for each cluster.

499  
500 A higher percentage of housing units with only one occupant was a prominent characteristic of  
501 Cluster 2. These block groups also tended to have the lowest rates of housing with three or more  
502 occupants compared to all other block groups. Additionally, Cluster 2 had the lowest percentage  
503 of the population aged 0-9 years but the highest percentage aged 65 or older, on average. There  
504 is a noticeably lower percentage of the population in the work force, and a higher percentage was  
505 indicated to have not worked in the past 12 months. These results seem to point to the presence  
506 of a higher percentage of retired persons in these block groups.

507  
508

**Table 5: Non-Income cluster characteristics**

<b>Key Variables</b>	Cluster 1 “Educated middle-aged homeowners”	Cluster 2 “Older, less workers”	Cluster 3 “Educated, younger workers”	Cluster 4 “Young, Hispanic, Latin-American”
% Housing Occupied by Owner	82.3	40.6	45.4	51.9
% Housing with 1 Occupant	19.9	54.1	33.9	25.2
% Housing with 2 Occupants	38.7	31.2	37.2	29.8
% Housing with 3 Occupants	16.8	6.9	14.9	16.8
% Housing with 4 Occupants	17.0	5.0	9.9	13.9
% Housing with 5 Occupants	5.1	1.9	2.8	8.1
% Housing with 6 Occupants	1.6	0.4	0.9	3.9
% Housing with 7+ Occupants	0.8	0.6	0.4	2.3
% Population Age 0-9	11.5	5.2	9.4	14.3
% Population Age 10-17	10.4	4.5	5.7	10.5
% Population Age 18-29	10.6	15.3	22.5	17.4
% Population Age 30-44	19.9	19.0	30.8	24.1
% Population Age 45-54	31.3	26.3	21.9	23.0
% Population Age 65+	16.3	29.9	9.8	10.8
% Pop. Black/African Am.	1.4	4.7	4.8	4.9
% Pop. Hispanic/Latin-American	5.7	8.2	8.8	23.9
% Pop. Limited English Ability	1.3	3.8	1.7	8.6
% Pop. < High School Degree*	3.9	8.0	4.7	17.0
% Pop. Bachelor’s Degree*	31.4	24.2	32.8	16.6
% Pop. Graduate/Prof. Degree*	22.0	16.6	21.0	6.9
% Population in Labor Force**	66.8	51.3	76.8	67.6
% Population Did Not Work**	29.8	44.9	20.6	30.4
<b>Size or Quantity</b>				
Lockers	51.7	20.4	53.6	49.7
Population (Pop.)	644,447	100,009	409,093	491,112
Households (HH)	238,510	53,774	180,754	170,697
Area (Mi.2)	588.6	33.4	72.6	130.8
<b>Densities</b>				
Lockers per Sq.Mi.	0.09	0.61	0.74	0.38
Lockers per 1000 Pop.	0.08	0.20	0.13	0.10
Lockers per 1000 HH	0.22	0.38	0.30	0.29
<b>Access by Mode as % Pop.</b>				
Walking (0.25-0.5) Mi..	4.3-17.4	19.7-48.5	19.6-51.1	12.5-37.8
Biking (1.5-3.0 Mi.)	67.5-86.3	96.0-99.7	96.5-100.0	90.1-96.0
Driving (3.0-5.0 Mi.)	86.3-93.6	99.7-100.0	100.0-100.0	96.0-97.4

\*Aged 25 years or older; \*\*Aged 16 years or older



511 Cluster 3 appears to have higher percentages of 18-29-year-olds and 30-44-year-olds relative to  
512 all other clusters. The population in these block groups also tend to be more educated, with  
513 higher rates of bachelor's and graduate or professional degrees than Cluster 2 or Cluster 4. Also,  
514 on average, the percentage of the population in the workforce was highest for Cluster 3 while the  
515 percent of the population that did not work was the lowest compared to all other Clusters.  
516 Together, these characteristics may indicate a higher presence of younger working adults.

517

518 In Cluster 4, a few characteristics are quite pronounced. For example, the percentage of housing  
519 units with five, six, or seven or more occupants is much higher relative to the other clusters. In  
520 addition, the percentages of the population with Hispanic or Latin-American origins, limited  
521 English speaking abilities, or attaining less than a high school (or equivalent) degree are  
522 significantly higher compared to the other clusters. On average, the population in Cluster 4 has  
523 the lowest rates of bachelor's and graduate or professional degrees and the highest percentages of  
524 children aged 0-9 years and 10-17 years. These characteristics seem to indicate a higher  
525 prevalence of larger families and population of Hispanic or Latin-American origin.

526

527 Cluster 3 is shown having the highest average locker density with respect to area, but Cluster 2  
528 has the highest average density with respect to both population and households. The lowest  
529 average locker densities for all three measurement units exist in Cluster 1. Cluster 2 is  
530 characterized by a couple of factors that may contribute to transportation disadvantage, including  
531 greater percentages of people aged 65 or older or those who do not work as compared to the  
532 other clusters. Cluster 4 exhibits a greater number of demographic qualities that may contribute  
533 to transportation disadvantages. Cluster 4 has the highest percentage of young children (aged 0-9  
534 years), and much higher percentages of people with Hispanic or Latin-American origin or with  
535 limited English language abilities. This cluster also demonstrated the lowest education levels on  
536 average, with the highest proportion of people with less than a high school degree (and the  
537 lowest proportions of people with bachelor's or graduate degrees). For this equity category, it  
538 appears that Cluster 4 should be prioritized.

539

540 Regarding percentages of the population in each cluster within the walking, biking, and driving  
541 locker buffers, the lowest percentages are observed in Cluster 1 for all modes, followed by

542 Cluster 4. Cluster 2 and Cluster 3 demonstrate the highest population percentages within the  
543 locker buffers, reaching almost 100% within a 3-mile radius. It appears that the distribution of  
544 Amazon lockers in Cluster 4 is not on par with the distribution in Cluster 2 or Cluster 3.  
545 Additional focus should be given to Cluster 4 with when considering locations for new locker  
546 facilities if locker access equity is a policy goal.

## 547 **7. DISCUSSION**

548 Mail and package distribution are considered a basic service. Access to basic goods, services,  
549 and activities is a key component in accessibility-based transportation equity evaluations  
550 (Litman, 2002). In the postal service literature, the concept of universal service for post and  
551 packages has been frequently discussed (Cohen et al., 1993; Cremer et al., 2000; De Donder et  
552 al., 2002). Universal postal service includes accessibility for all, quality of service, and  
553 reasonableness of rates, with an overall goal of avoiding major access differences via differential  
554 pricing and product offerings that create conditions that result in a “market failure”. In the  
555 transportation literature the term market failure implies a situation when a minimum level of  
556 accessibility or mobility that should be available to all is not met (Button, 2005). The idea of  
557 avoiding market failure in transportation has many similarities with the concept of universal  
558 postal service.

559

560 Regarding locker accessibility, a market failure can be defined as situations where locker  
561 locations respond solely to customer demand and purchasing power with no coverage of  
562 populations that *need* affordable and/or convenient locker access. Amazon is a private, profit-  
563 seeking entity, and the placement of lockers responds to customer demands and the company’s  
564 overall competitive strategy, and these goals may not necessarily match the allocation of lockers  
565 based on equity or need considerations. It should be the role of policy makers and transportation  
566 agencies to analyze whether policies or the allocation of resources to improve locker  
567 accessibility based on need and/or equity considerations are justified.

568

569 Parcel policies should also take into account that there are four basic types of parcel locker  
570 systems depending on carrier and public access characteristics: a) Open or common carrier  
571 parcel locker systems which can be utilized by different logistics operators or e-commerce

572 companies and may be run by an external non-profit entity like a city or metropolitan agency.  
573 These lockers are usually located in public spaces and can be utilized by any potential customer.  
574 b) Closed locker systems which are operated and managed by one business, stakeholder, or  
575 consortium. In closed systems, only the owner or operator typically utilizes the locker (rival  
576 companies do not have access). These lockers are located on private property owned by the  
577 owner of the locker or through access granted via a contract (e.g., Amazon lockers located at  
578 convenience stores) but they can be utilized by any potential customer. The third class of locker  
579 system c) is usually located inside multi-unit residential apartment units. This third type of  
580 system is usually located indoor and run by the building or property manager and can be utilized  
581 by different carriers or logistic operators. However, they have restricted (no public) access since  
582 only residents or property owners can utilize the indoor lockers. In cases a) and b) public access  
583 is not restricted. Finally, case d) is a closed system with restricted customer access that could be  
584 utilized in some business settings. The discussion and focus of this research is on cases a) and b)  
585 where there is unrestricted public access, though at the moment only type b) is available in  
586 Portland and type a) could be promoted by policy makers where needed.

587  
588 The equity spatial analysis presented in this research has direct policy implications since it can  
589 guide the placement of incentives to locate additional (open) lockers in urban areas, for example  
590 installing *supplementary* common carrier (open) public parcel lockers in transit stations where  
591 they are needed the most to fill an equity or accessibility gap (Keeling et al., 2021). Common  
592 carrier lockers could then serve public agencies' accessibility and equity goals, facilitating  
593 deliveries for those who are transportation disadvantaged or time poor.

594  
595 Policy makers could also use the proposed methodology to monitor the ongoing installation of  
596 lockers across the urban area. In Poland, the capital Warsaw with 600 lockers (Wilczek, 2021),  
597 has a much higher density of lockers per capita than Portland, almost 4.5 times more lockers per  
598 capita. Based on Warsaw's figures, it is likely that more lockers will be installed in the future in  
599 the Portland metropolitan region. Given the dramatic growth of e-commerce the locker market is  
600 not yet mature.

601

602 **8. CONCLUSIONS**

603 E-commerce is growing rapidly, and it is critical that different populations have access to  
604 efficient and environmentally friendly last mile delivery options like automated lockers. This  
605 research presents a novel approach utilizing cluster analysis to evaluate locker distribution  
606 accessibility and equity metrics. Overall, a large percentage of the population can access  
607 Amazon lockers because they tend to be located in convenience or other small format retail  
608 stores, close to arterial roads, on land zoned for mixed-use commercial and residential, and in  
609 areas of higher population and employment density. In terms of accessibility by mode, lockers  
610 are accessible by automobile for the vast majority of the population in the Portland metropolitan  
611 region. The share of the population that can access lockers by walking is significantly smaller  
612 and this may present a challenge for non-driver populations.

613  
614 Regarding equity, clusters in the income and computer and internet access categories appear to  
615 have equitable access to parcel lockers. However, the data suggests that there is less access to  
616 parcel lockers for Hispanics, people with low education levels, or people who have limited  
617 English language abilities. Black and African Americans did not clearly fall into one cluster, but  
618 this may be due to the relatively low number of Black and African Americans in the Portland  
619 metropolitan area.

620  
621 Ancillary benefits of additional locker locations could also include a reduction in delivery  
622 vehicle miles traveled as well as reduced energy consumption and emissions. More policy  
623 implications can be found by increasing the spatial resolution, e.g., an inspection of the bottom  
624 ten block groups when ranked in order of highest to lowest number of lockers per population and  
625 per households revealed nine of them belong to the low-income cluster. Another policy  
626 implication is that equity metrics differ widely based on the units utilized, for example lockers  
627 per area, per population, or per household. Suburban low-density areas have the lowest levels of  
628 lockers per area or population, but tend to be inhabited by educated, higher income homeowners.  
629 Hispanics tend to be in more dense areas in terms of population but with lower density of lockers  
630 per population when compared to similarly dense areas. Given the larger size of Hispanic  
631 households the equity metrics are sharper when considering equity metrics per population instead  
632 of per household.

633 The equity spatial analysis presented in this research has direct policy implications since it can  
634 guide monitoring of the parcel locker system as well as the placement of resources or common  
635 carrier public parcel lockers where they are needed the most to fill an equity or accessibility gap  
636 or reduce a potential market failure. Policy makers and public agencies could use the proposed  
637 methodology to monitor locker accessibility and equity goals and recognize potential market  
638 failures. In this research parcel locker systems are classified into four basic types depending on  
639 carrier and public access characteristics. Policy makers should also monitor how locker type  
640 evolves over time, since closed or restricted locker systems do not bring the same advantages in  
641 terms of sustainability or equity respectively.

642

643 This research also introduces the concept of market failure in the parcel locker market. Lower  
644 income and underserved populations engage less in e-commerce and home deliveries, and it is  
645 possible that in addition to income barriers, there are other barriers like accessibility to  
646 affordable and conveniently located lockers that may accentuate e-commerce inequities. This is  
647 an issue that so far has not received enough attention in the parcel locker literature.

648

649 Lack of access to essential services such as food has given rise to concepts like food deserts.  
650 Similarly, lack of access to e-commerce and efficient last mile delivery systems can be studied in  
651 future research efforts as ancillary services to bridge the digital divide and barriers that impede  
652 access to new products and services. The traditional concept of accessibility can be broadened to  
653 include access to parcel lockers, i.e. adding access to lockers to expand the concept of home  
654 based accessibility for e-commerce products and services first introduced by Figliozzi and  
655 Unnikrishnan (2021). This is relevant as governments foster e-commerce access, for example to  
656 provide touchless and safe deliveries during the COVID-19 crisis and beyond, avoiding or  
657 reducing social contact in stores or with home delivery personnel.

658

659 The main ideas and methods utilized in this research are likely transferable to other urban areas  
660 but not the specific findings associated to the spatial distribution of lockers and population  
661 characteristics. Future research efforts are recommended in cities or regions with a different  
662 spatial or sociodemographic composition.

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## APPENDIX

**Table A. 1: Descriptive statistics for all ACS variables.**

<b>Income Variables:</b>	<b>Min</b>	<b>15th Perc</b>	<b>Median</b>	<b>85th Perc</b>	<b>Max</b>	<b>Mean</b>	<b>St. Dev</b>
Median Housing Unit Value (Million \$)	0.01	0.25	0.36	0.53	0.99	0.39	0.15
Average HH Income (Million \$)	0.01	0.06	0.09	0.13	0.36	0.10	0.04
Median HH Income (Million \$)	0.01	0.05	0.07	0.11	0.23	0.08	0.03
Per Capita Income (Million \$)	0.01	0.02	0.04	0.05	0.12	0.04	0.02
<b>Computer and Internet Access Variables:</b>	<b>Min</b>	<b>15th Perc</b>	<b>Median</b>	<b>85th Perc</b>	<b>Max</b>	<b>Mean</b>	<b>St. Dev</b>
% HH with Computer	0.62	0.88	0.96	1.00	1.00	0.94	0.06
% HH with Internet (All Sub. Types)	0.29	0.79	0.90	0.96	1.00	0.88	0.09
% HH with Broadband Sub.	0.29	0.79	0.90	0.96	1.00	0.88	0.09
% HH with Dial-up Only Sub.	0.00	0.00	0.00	0.01	0.10	0.00	0.01
% HH with Cell Only Sub.	0.00	0.02	0.06	0.13	0.39	0.07	0.06
% HH with Satellite Only Sub.	0.00	0.00	0.00	0.01	0.22	0.01	0.01
% HH with Other Internet Only Sub.	0.00	0.00	0.00	0.00	0.08	0.00	0.01
% HH with Internet (No Sub.)	0.00	0.00	0.02	0.06	0.44	0.03	0.04
% HH without Internet	0.00	0.02	0.07	0.17	0.56	0.09	0.08
<b>Transportation-BE Variables:</b>	<b>Min</b>	<b>15th Perc</b>	<b>Median</b>	<b>85th Perc</b>	<b>Max</b>	<b>Mean</b>	<b>St. Dev</b>
% Workers Drove Alone*	0.06	0.52	0.68	0.80	0.98	0.66	0.14
% Workers Carpooled*	0.00	0.03	0.08	0.15	0.64	0.09	0.06
% Workers Public Transit*	0.00	0.01	0.07	0.16	0.59	0.09	0.08
% Workers Bicycled*	0.00	0.00	0.01	0.09	0.32	0.04	0.05
% Workers Walked*	0.00	0.00	0.02	0.08	0.55	0.04	0.07
% Workers Work from Home*	0.00	0.02	0.07	0.13	0.35	0.08	0.05
% Workers Other Trans.*	0.00	0.00	0.00	0.02	0.21	0.01	0.02
% Workers Taxi*	0.00	0.00	0.00	0.00	0.17	0.00	0.01
% Workers Motorcycle*	0.00	0.00	0.00	0.01	0.07	0.00	0.01
% Housing as Single Detached	0.00	0.28	0.69	0.95	1.00	0.63	0.29
% Housing as Single Attached	0.00	0.00	0.03	0.11	0.45	0.05	0.07
% Housing as Multi-unit	0.00	0.00	0.23	0.61	1.00	0.29	0.28
% Housing as Mobile	0.00	0.00	0.00	0.03	0.81	0.02	0.07
Population Density (Thous. per mi.2)	0.03	2.72	6.03	10.30	59.92	6.79	5.28
<b>Non-income Demographic Variables:</b>	<b>Min</b>	<b>15th Perc</b>	<b>Median</b>	<b>85th Perc</b>	<b>Max</b>	<b>Mean</b>	<b>St. Dev</b>

% Housing Occupied	0.69	0.90	0.96	1.00	1.00	0.95	0.05
% Housing Occupied by Owner	0.00	0.33	0.65	0.88	1.00	0.61	0.25
% Housing with 1 Occupant	0.00	0.15	0.25	0.40	0.98	0.28	0.14
% Housing with 2 Occupants	0.00	0.25	0.35	0.45	0.71	0.35	0.10
% Housing with 3 Occupants	0.00	0.08	0.15	0.23	0.45	0.16	0.07
% Housing with 4 Occupants	0.00	0.05	0.13	0.21	0.61	0.13	0.08
% Housing with 5 Occupants	0.00	0.00	0.04	0.10	0.34	0.05	0.05
% Housing with 6 Occupants	0.00	0.00	0.00	0.04	0.28	0.02	0.03
% Housing with 7+ Occupants	0.00	0.00	0.00	0.03	0.22	0.01	0.02
Median Rooms Owner-Occupied	1.80	5.37	6.30	7.60	10.00	6.45	1.19
Median Rooms Renter-Occupied	1.40	3.40	4.30	5.60	10.00	4.44	1.17
% Population Age 0-9	0.00	0.06	0.11	0.16	0.31	0.11	0.05
% Population Age 10-17	0.00	0.04	0.08	0.14	0.30	0.09	0.05
% Population Age 18-29	0.00	0.08	0.15	0.24	0.88	0.16	0.09
% Population Age 30-44	0.02	0.16	0.23	0.32	0.54	0.24	0.08
% Population Age 45-54	0.03	0.19	0.26	0.34	0.61	0.26	0.08
% Population Age 65+	0.00	0.07	0.13	0.21	0.81	0.14	0.09
% Population White	0.32	0.68	0.82	0.92	1.00	0.80	0.12
% Population Black/African American	0.00	0.00	0.01	0.08	0.39	0.04	0.06
% Population Asian	0.00	0.01	0.04	0.13	0.63	0.07	0.08
% Population White Hispanic/Latino	0.00	0.01	0.05	0.13	0.64	0.07	0.09
% Population Hispanic/Latino	0.00	0.02	0.08	0.20	0.75	0.11	0.12
% Population Other Race	0.00	0.00	0.01	0.06	0.50	0.03	0.06
% Population Multi-Race	0.00	0.01	0.04	0.09	0.28	0.05	0.04
% Population Limited English Ability	0.00	0.00	0.01	0.07	0.30	0.04	0.05
% Population Less than High School Deg.*	0.00	0.01	0.05	0.16	0.46	0.08	0.08
% Population High School Deg./GED*	0.00	0.07	0.17	0.28	0.62	0.17	0.10
% Population Associate's Deg./Some College*	0.03	0.19	0.30	0.40	0.59	0.30	0.10
% Population Bachelor's Deg.*	0.00	0.15	0.27	0.39	0.58	0.27	0.11
% Population Graduate/Professional Deg.*	0.00	0.05	0.15	0.30	0.65	0.17	0.12
% Population in Labor Force**	0.20	0.59	0.69	0.79	0.96	0.69	0.10
% Population in Armed Forces**	0.00	0.00	0.00	0.00	0.05	0.00	0.00
% Population Full-time Worker**	0.08	0.35	0.45	0.53	0.79	0.44	0.09
% Population Part-time Worker**	0.06	0.21	0.27	0.34	0.69	0.27	0.07
% Population Did Not Work**	0.04	0.19	0.28	0.37	0.77	0.28	0.10

\*Aged 25 years or older; \*\*Aged 16 years or older