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15-02 Estimating and Enhancing Public Transit Accessibility for People with Mobility Limitations

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Estimating and Enhancing Public Transit Accessibility for People with Mobility Limitations

FINAL REPORT

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This two-part study employs fine-scale performance measures and analytical techniques designed to evaluate and improve transit services for people experiencing disability. Part one puts forth a series of time-sensitive, general transit feed system (GTFS)-enhanced employment accessibility models that account for multiple transportation modes, categories of functional limitation and design characteristics of existing public transit infrastructure. Model results shed light on the degree to which a medium-size city's public transit system addresses the gap between a theoretical continuum of rider capacities and the physical demands required to achieve mobility and access to employment. Our research finds that an individual's combined physical mobility constraints (e.g., walking speed and maximum walking distance) and public transit infrastructure requirements (e.g., presence/absence of wheelchair boarding platforms and connections to pedestrian access routes) may reduce employment accessibility outcomes by as much as 86 percent.
Part two of the study utilizes performance measures developed in part one to model—via spatially explicit structural equations—the degree to which employment accessibility explains variations in public transit ridership and work commute transportation mode share. Here we find that commute share and ridership…(results). Developing a better understanding of relationships between accessibility and transit usage, we reason, will help shed light on how American Disabilities Act (ADA) compliant transit infrastructure affects mode choice decisions among people with considerable functional limitations and across the broader population.</td></tr>
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Introduction

The ease with which people are able to access opportunities greatly influences quality of life. People with inadequate transportation accessibility can be deprived of social and political activities, employment, healthcare and the ability to stay in one's current residence as long as possible (i.e., age in place). Such inabilities to participate fully in one's own community—while experienced most directly at the individual, household and familial levels—can bring about negative consequences for broader society in the form of widespread social marginalization, lost productivity and functional dependence (Brendan Gleeson 1996; Yeo and Moore 2003). The provision of efficient, inclusive and multimodal shared use mobility transportation systems, then, have the potential to improve access and some combination of physical, mental, social and economic well-being for everyone (Lee and Sener 2016).

There is growing awareness that existing transportation configurations in the United States are vastly inadequate for a growing share of the population (National Academies of Sciences 2004). Rural, older and lower-income individuals as well as people with physical, cognitive and sensory mobility limitations are increasingly likely to experience functional transportation gaps that reduce physical access to opportunities; complicating and ultimately reducing participation in the mainstream of social activities (Hine and Mitchell 2016; Sanchez 2008; Shay et al. 2016).

Such functional gaps occur when one's individual capacity fails to overcome the challenges posed by inaccessible transportation configurations. This notion of functional gap reflects the realization that disability is not an inherent attribute of select individuals but an experience that arises from interactions between a broad spectrum of individual capacities and socio-physical environments (Field and Jette 2007). Therefore, the character and intensity of such gaps evolve over time with changes in economic circumstances, physical well-being and modifications to the built environment.

Take intra-city public transit, for example. Adequate public transit services increases mobility for society generally, but is especially important for transit riders who are either unable to drive, do not have access to a private vehicle or otherwise prefer to use some form of transit to make a desired trip (Beimborn, Greenwald, and Jin 2003). For these individuals, access to transit has shown to positively influence both employment probability (Kawabata 2002) and labor force participation (Sanchez 1999).

Further, people with physical mobility limitations tend to experience far higher levels of unemployment and underemployment than those without such limitations, especially when accessible transportation services are lacking (Denny-Brown, O'Day, and McLeod 2015). In their examination of a nationwide dataset, Loprest and Maag found that lack of transportation was one of the most frequently cited reasons (29 percent) for being discouraged from looking for work among adults with disabilities (Loprest and Maag, Elaine 2001).

Advances in transportation engineering—combined with regulatory requirements for their implementation—have brought about greater adoption of assistive technologies that make interactions with the environment easier for people, thus reducing functional gaps for a growing portion of the population. Equipping busses with wheelchair lifts, providing wheelchair boarding platforms at bus stops, and creating obstruction-free pedestrian connectivity to the broader transportation network, has the potential to enhance overall network and employment accessibility for people who rely on such provisions. And while considerable progress has been made in this regard over time—in large part because of the mandatory compliance of public transit service providers with accessibility requirements stated in the Americans with Disabilities Act of 1990 (ADA)—there is still much work to be done. For instance, Lubin and Deka concluded that a large portion (47 percent) of job-seeking people *with disabilities* in New Jersey were dissatisfied with public transportation despite their frequent use of public transit services (Lubin and Deka 2012). While the study population experienced high satisfaction with vehicle equipment compliance, they were generally dissatisfied with the level of transit service (i.e., speed and frequency) and environmental barriers between origins, destinations and transit stops.

Planners, policy makers and civil society more broadly are thus challenged with continuing to identify and address functional transportation gaps to improve services for those with limited options. Such an undertaking benefits from both robust, fine-scale and time-sensitive measurements of multimodal accessibility across a continuum of individual capacities and a way to operationalize these estimates to inform decision making.

Toward this end, researchers and transportation professionals have developed increasingly sophisticated methods to measure fine-scale accessibility in order to evaluate variations and gaps in transportation system performance (Chandra Bhat et al. 2000; Zakaria 1974). These methods typically account for some combination of factors including trip mode, trip purpose, trip origins and destinations, time of day (as well as season), monetary and time costs and distance (network-based or otherwise).

However, measures of accessibility have conventionally assumed travel by private motor vehicle and largely neglected alternative modes of transportation such as public transit, say, and walking (Todd Litman 2015). Only recently—with the rapid and widespread adoption by public transit operators to publish their detailed schedule and route information via the General Transit Feed Specification (GTFS)—has it been possible for researchers to develop more nuance multimodal models of accessibility that account for temporal variants in topological public transit networks and periodicity in the patterns of transit accessibility (Kaza 2015; Andrew Owen and David Levinson 2014; J. Wong 2013). Still lacking, however, is multimodal research that applies such accessibility models toward understanding how public transit schedules and configurations accommodate work commutes for people who function across a continuum of mobility (Adie Tomer et al. 2011). This study takes steps toward filling this gap.

Research objectives

This two-part study employs fine-scale performance measures and analytical techniques designed to both evaluate and work toward improving transit services for people experiencing disability. Part one leverages spatio-analytical procedures together with open source and public transit agency-specific travel schedules and bus stop configuration survey data. These data are used as inputs to batch analytical procedures that estimate time-averaged job accessibility outcomes at the census block scale for people with different mobility profiles. The overall objective of part one is to better understand the degree to which accessibility gaps in public transit infrastructure can influence journeys to work.

Part two extends part one by incorporating multimodal accessibility estimates into an optimization model designed to prioritize investments in transit stops that most improve employment access for all, including people with limited mobility. The optimization model uses cost estimates for bus stop retrofits and multimodal accessibility estimates to develop a multi-phase implementation strategy toward ADA compliance. The optimized retrofit strategy is compared with a random or *ad hoc* strategy in order to evaluate respective gains in both employment accessibility and network connectivity.

More succinctly, this study:

1. Develops a series of models to estimate time-averaged, multimodal (i.e., public transit and walking) employment accessibility at the neighborhood scale using public datasets and open source analytical tools including OpenTripPlanner;

2. Integrates transit stop ADA compliance survey data together with customized GTFS *wheelchair_boarding* and *wheelchair_accessibility* and OpenTripPlanner *maximum walking speed* and *maximum walking distance* parameters to create more nuance estimates of accessibility that account for both detailed transit infrastructure and physical mobility limitations; and

3. Uses the above accessibility estimates and relevant bus stop-specific retrofit cost information to develop a linear program that informs a cost efficiency-based public transit infrastructure planning program that maximizes employment accessibility;

Study area

Kalamazoo County, located in southwest Michigan, serves as the research context for this study. The county spans 561 square miles and has an estimated population of 256,752 residents and 113,706 jobs (US Census Bureau 2015). The county is bordered by Calhoun County to the east, Barry and Allegan counties to the north, Van Buren County to the west and St. Joseph County to the south. The urbanized portion of Kalamazoo County contains thirteen townships and thirteen localities (i.e., villages, municipalities and census designated places) including the city of Kalamazoo, which serves as the county seat.

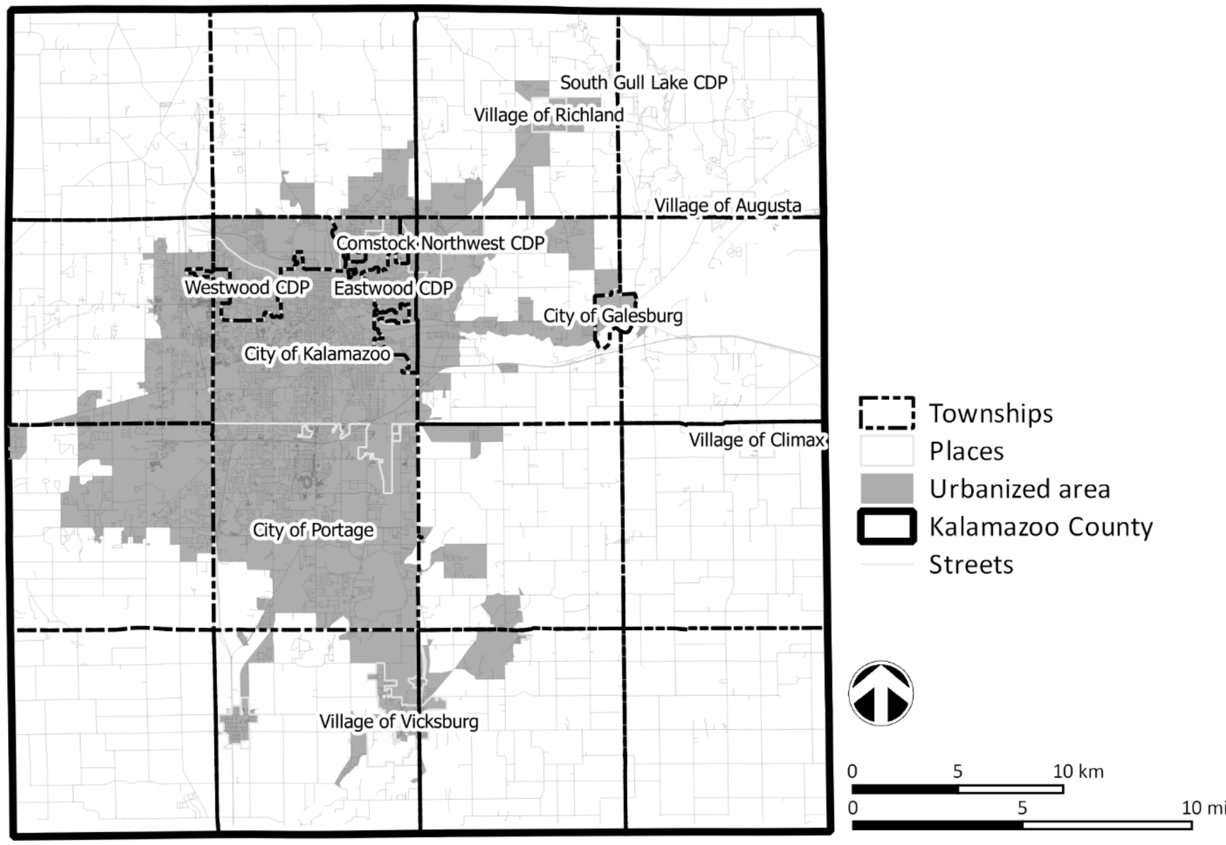


Figure 1. Kalamazoo County Study Area
Source: US Census Bureau TIGER/Line Files, 2015

The city of Kalamazoo is positioned slightly west of the geographic center of Kalamazoo County and is the county's largest city with respect to population (75,499) and jobs (34,599), comprising 29.4 percent and 28.7 percent of the county totals, respectively (US Census Bureau 2015). A historically rail city, Kalamazoo's downtown transportation center is located in a restored late nineteenth century train station through which Amtrak trains and intercity bus services operate.

The transportation center also serves as the central hub for the Kalamazoo Metro or K-Metro bus service which has 20 regularly scheduled bus routes operating on 15, 30 and 60 minute frequencies. The system has 28 buses in operation, each of which is equipped with a "kneeling" feature, wheelchair ramp and wheelchair locking features. In addition to its fixed route service, the agency coordinates a 45 vehicle Metro County Connect demand-response or paratransit program which, in accordance with federal ADA mandates, provides door-to-door transportation services throughout the service area to anyone including individuals who are unable to use regular accessible fixed-route bus service due to a physical or cognitive disability. Collectively, these two services accommodated more than 11 million passenger miles and approximately 3.1 million unlinked trips in 2014 (Kalamazoo Metro Transit, 2015).

Similar to most of Michigan, travel in Kalamazoo county is largely autocentric with more than 80 percent of the population commuting to work alone using a private car compared to approximately

1.4 percent traveling by public transportation (Figure 2). And while the city of Kalamazoo has directed commercial and residential development to its historic and walkable downtown area in recent years, such efforts have not yet translated into notable shifts in work commute mode share. This resistance may, in part, be due to the fact that average work commute times are relatively low throughout the county (approximately 21 minutes according to the ACS, 2015) due to the moderate size of the urbanized area, widespread parking availability and limited traffic congestion along area roadways (Table 1).

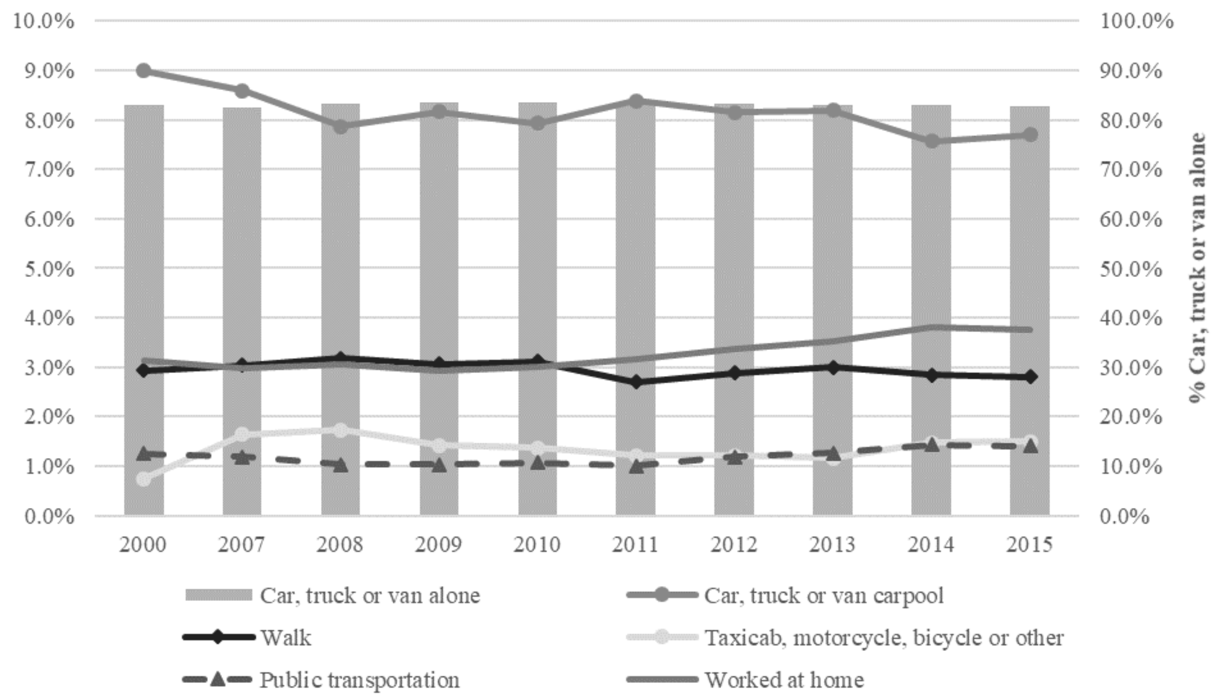


Figure 2. Means of Transportation to Work, Kalamazoo County (2000-2015)
Source: US Census Bureau American Community Survey, 2000-2015, 5-year estimates

Table 1 Means of Transportation to Work, Kalamazoo County (2000-2015

	2000	2007	2008	2009	2010	2011	2012	2013	2014	2015
Car, truck or van alone	83.0	82.6	83.1	83.4	83.5	83.6	83.2	82.9	82.9	82.7
Car, truck or van carpool	9.0	8.6	7.9	8.2	7.9	8.4	8.2	8.2	7.6	7.7
Walk	2.9	3.0	3.2	3.1	3.1	2.7	2.9	3.0	2.8	2.8
Taxi, motorcycle, bicycle or other	0.7	1.6	1.7	1.4	1.4	1.2	1.2	1.2	1.5	1.5
Public transportation	1.2	1.2	1.0	1.0	1.1	1.0	1.2	1.3	1.4	1.4
Worked at home	3.1	3.0	3.1	2.9	3.0	3.2	3.4	3.5	3.8	3.8

Source: US Census Bureau, 2000-2015

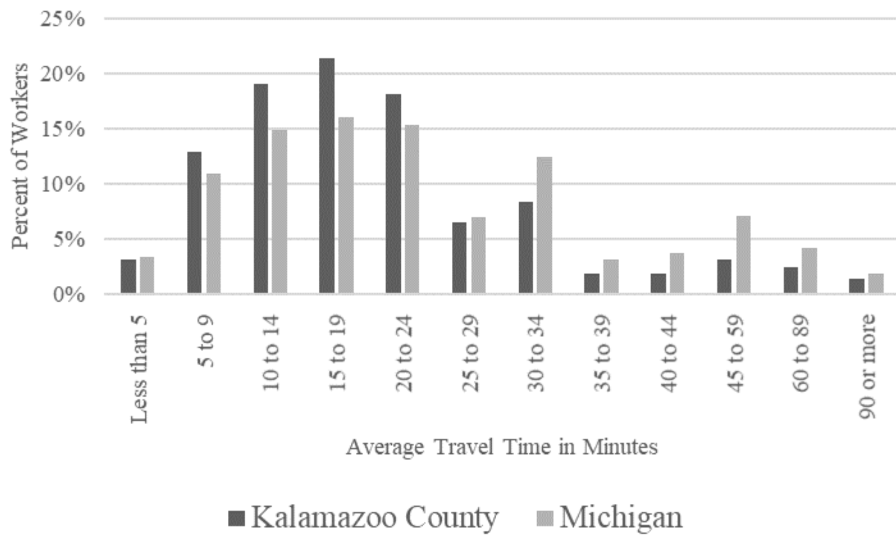
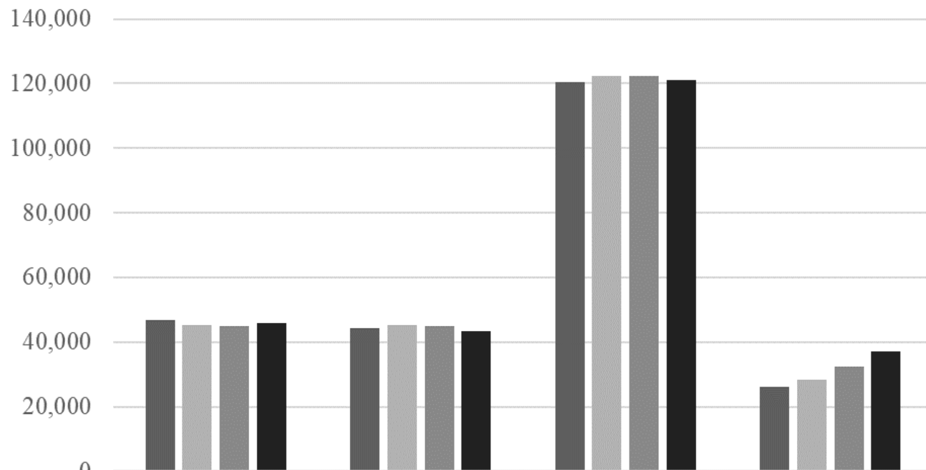


Figure 3. Average Commute Time to Work, Kalamazoo County and Michigan (2015)
Source: US Census Bureau, 2015

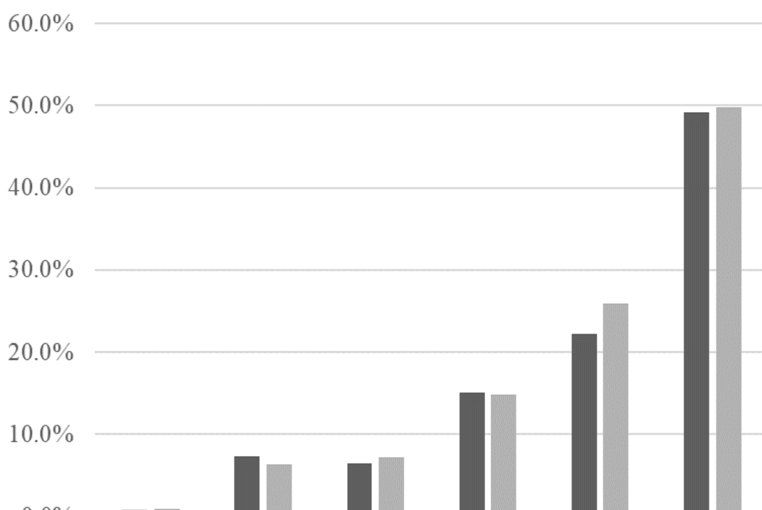
However, demographic shifts in the population are likely to complicate the area's reliance on automobiles to provide for future mobility, particularly among older age groups. The most considerable shift concerns members of the post-WWII "baby boom"—defined by the US Census as those born between 1946 and 1964—who are now beginning to turn 65 years of age. Figure 5 shows trends and projections of persons by age cohort between 2005 and 2020. In Kalamazoo county, the portion of the population over 65 years of age is projected to increase from 26,137 in 2005 to 37,202 in 2020 (Michigan Department of Information Technology). This is a 42.3 percent increase compared to a four percent increase in the overall population over the same period.

Such a growing share of older adults has important consequences for society given that people are more likely to experience disabilities as they age (Figure 6). Indeed, 32,591 or 12.8 percent of the total population in Kalamazoo county reported having some form of disability in 2015, while 49.2 percent of the 75 and older population reported having some form of disability (US Census Bureau, 2015). Further, over 25 percent of those who reported a disability, identified their limitation as an ambulatory condition such as difficulty walking or climbing stairs (Figure 5).



	14 or younger	15 to 64	25 to 64	65 and older
2005	46,981	44,188	120,598	26,137
2010	45,374	45,203	122,351	28,340
2015	44,940	44,827	122,201	32,502
2020	45,974	43,252	121,022	37,202

Figure 4. Population Trends/Projection by Age Group - Kalamazoo County 2005-2020
Source: US Census Bureau, 2005-2015



	Under 5	5 to 17	18 to 34	35 to 64	65 to 74	75 and over
Kalamazoo County	0.9%	7.3%	6.5%	15.1%	22.2%	49.2%
Michigan	0.9%	6.3%	7.2%	14.8%	25.9%	49.7%

Figure 5. Percentage of Population Reporting a Disability by Age Group - Kalamazoo County (2015)
Source: US Census Bureau, 2015

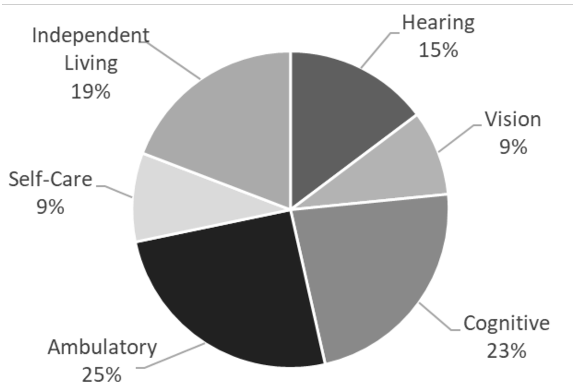
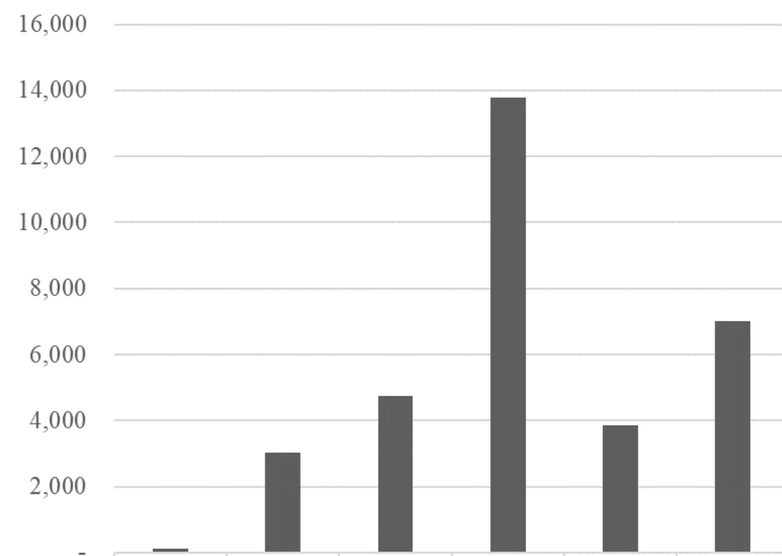


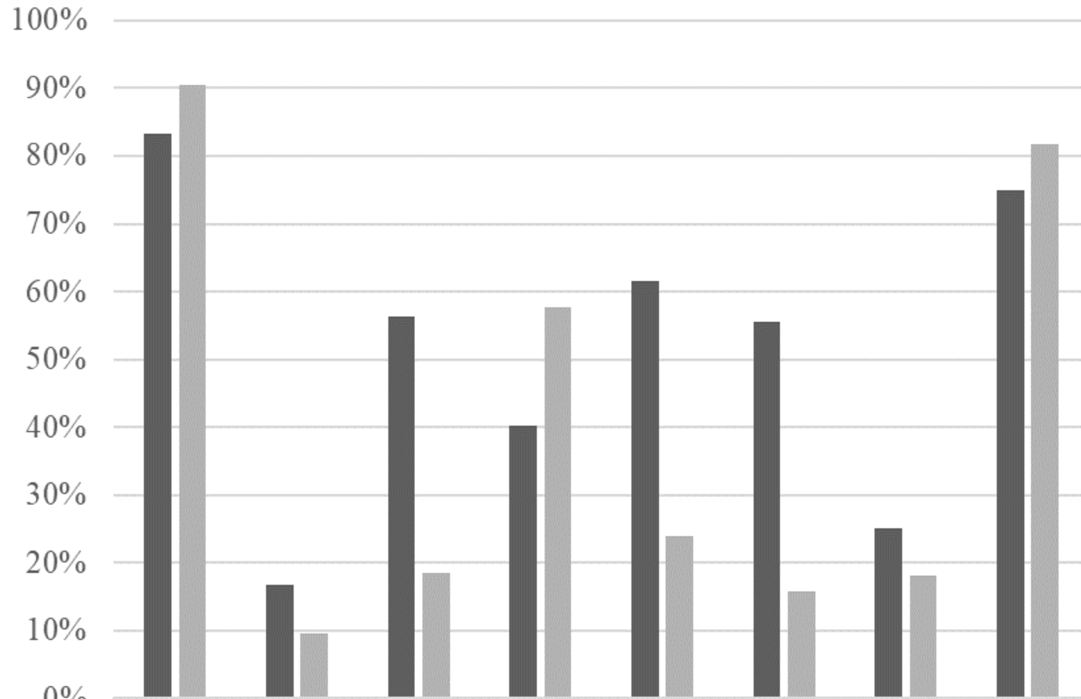
Figure 6. Disability by Type, Kalamazoo County 2015
Source: US Census Bureau American Community Survey, 5-year estimates, 2015

As stated earlier, people who are transportation disadvantaged, including those who experience disability via functional gaps in the transportation system, are more likely to rely on public transit as their primary mode of travel. Lacking mobility has the potential to severely constrain accessibility to social and economic opportunities, including employment. Figure 8 shows that conventional working age populations (i.e., people between 18 and 65 years of age) in Kalamazoo county compose a sizeable number and share of those reporting a disability; 18,531 or 56.9 percent. The degree to which transportation barriers negatively impact employment outcomes is unknown although it is clear that participation in the labor force and unemployment is considerably higher for those reporting a disability (Figure 8).



	Under 5	5 to 17	18 to 34	35 to 64	65 to 74	75 and over
■ Kalamazoo County	134	3,041	4,753	13,778	3,869	7,016

Figure 7. Total Population Reporting a Disability by Age Group - Kalamazoo County (2015)
Source: US Census Bureau American Community Survey, 5-year estimates, 2015



	Employed	Not employed	Not in labor force	Full-time	Less than full-time	Did not work	Below poverty	Above poverty
With a disability	83.2%	16.8%	56.3%	40.2%	61.7%	55.5%	25.1%	74.9%
No disability	90.4%	9.6%	18.4%	57.7%	23.8%	15.9%	18.2%	81.8%

Figure 8. Labor Force Participation and Employment Status for People with and without a Disability, Kalamazoo County (2015)

Methodology

The first part of this study employs public datasets and open source analytical tools to estimate employment accessibility at the census block level based on commute mode (i.e., private car, public transit and walking), individual physical mobility (i.e., walking speed and maximum walking distance) and transportation infrastructure need (i.e., whether or not bus stops are ADA compliant) (Figure 10). Total jobs (with and without spatial weighting), destinations, public transit boardings and walk distances were estimated for each census block based on modeled commutes between unique origin destination pairs. More thorough descriptions of the multiple datasets, tools and calculations employed in the study are provided below.

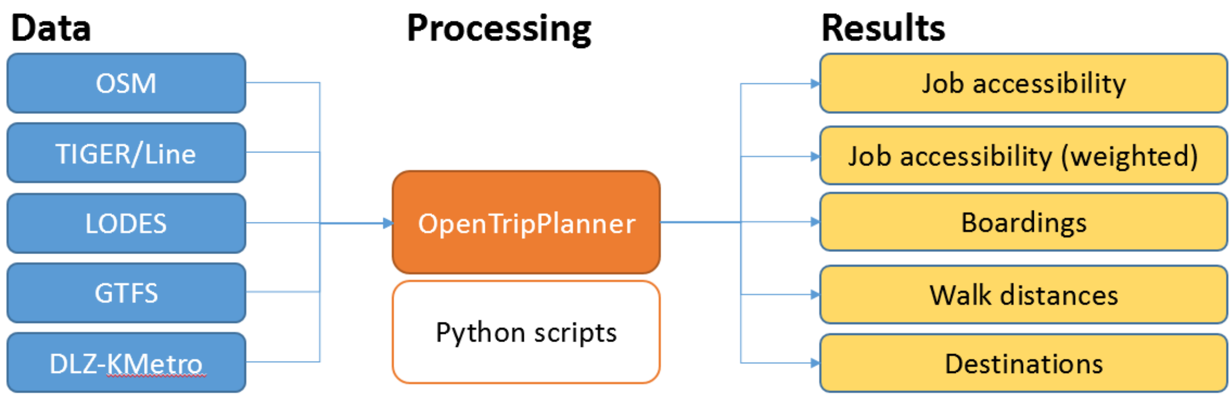


Figure 9. Data Analytical Framework

Data sources and analytical software

OpenStreetMap

OpenStreetMap (OSM) is a volunteered or crowdsourced, global geographic information database—first released in 2004—that is made freely available to everyone (Neis, Zielstra, and Zipf 2011). Because of its relative completeness and attribute accuracy—especially in urban areas—OSM is used for a variety of spatial applications and location-based services such as geocoding, 3D city modeling and route planning. For this research, we accessed the latest OSM network data for Michigan online via the download.geofabrik.de website. The statewide dataset incorporates both directionality and speed limits and served as the base street network to model both walking and automobile travel times ("OpenStreetMap" 2016).

Kalamazoo Metro (K-Metro) GTFS Data

The static General Transit Feed Specification (GTFS) is a common file format for organizing public transportation schedules and associated geographic information such as routes and bus stops. The data structure has evolved over time to include a variety of transit modes (e.g., bike share) and characteristics (including wheelchair accessibility information). At the time of this writing, over one thousand transit agencies worldwide, including over 800 transit agencies in the United States, share their GTFS data openly with the general public either directly or via data clearinghouse websites ("GTFS Overview" 2016; Antrim, Barbeau, and others 2013; J. C. Wong 2013). The data are used for a variety purposes including for estimating transit travel times and multimodal accessibility. Tomer, et al, for example, analyzed data from 371 transit providers to estimate neighborhood-level travel times across 100 of the nation's largest metropolitan areas (Adie Tomer et al, 2010).

A GTFS *feed* is a collection of a minimum of six comma-separated text files including *stops.txt*—which includes information about the location where vehicles pick up or drop off passengers—and *trip.txt*—which includes information about travel times between stops. Currently, only these two files—*stops.txt* and *trips*.txt—include information about the accessibility of public transit infrastructure. These optional GTFS attributes—*wheelchair boarding* and *wheelchair accessibility*—were of particular use for this study. The optional *wheelchair_boarding* in the stops file can take on one of three values, 0, 1 or 2. A 0 indicates that there is no accessibility information for the specific stop. A number 1 indicates that at least some vehicles at the stop can be boarded by a rider in a wheelchair. A number 2 indicates that wheelchair boarding is not possible at the stop.

The GTFS also allows for specifying whether a stop is part of a larger station complex, as indicated as a *parent_station* value in order to determine whether or not there exists some accessible path from outside the station to the specific stop or platform. These values were not used for this study given that there is only one station in the county which, by default, is assumed to have access, which it does.

The *trips* text file indicates whether the vehicle is itself wheelchair accessible. Values in the *wheelchair_accessible* field have the semantics: 0 (or empty) indicates that there is no wheelchair accessibility information for the trip. A number 1 indicates that the vehicle being used on this particular trip can accommodate at least one rider in a wheelchair, whereas a number 2 indicates that no riders in wheelchairs can be accommodated. The GTFS information retrieved from K-Metro did not initially include the optional accessibility values. Rather, the researchers used the DLZ bus stop survey described below to populate the necessary fields.

DLZ Bus Stop Survey

In 2014, Kalamazoo Metro and Disability Network Southwest Michigan organized and secured funding for a bus stop survey. The purpose of the survey was to create an inventory of the 751 bus stops throughout the Kalamazoo Metro bus system and attribute with stop-specific ADA information. Over 20 data points were collected for each bus stop, including Stop number, presence of obstructions, presence/absence of boarding platform, compliant overhead clearance, platform width, presence of protruding objects, platform depth, presence of a bench, platform running slope, space adjacent to bench if present, platform cross slope, distance from curb to sidewalk, connection to a sidewalk present, slope of area between curb and sidewalk, platform changes in elevation, existence of platform cracks or gaps and compliance of bus shelters. The survey showed that only 52 of the 751 stops were fully compliant with federal accessibility regulations. However, given the limitations of the GTFS data structure, only information relating to boarding platform compliance was used from the survey.

We synchronized the DLZ bus stops survey information with the K-Metro GTFS data by location in order to create an enhanced dataset that includes route, scheduling and ADA compliance information. Unlike the DLZ survey, the GTFS has fewer stops than the original dataset, because they did not have counterparts in the DLZ dataset, yielding a total of 707 bus stops that were used in the study; 638 of which were identified as not ADA compliant.

Longitudinal Origin Destination

In addition to the street and public transit network characteristics, job information was needed to estimate employment accessibility or job access. The US Census Bureau's Longitudinal Employer-Household Dynamics (LEHD) makes available several data products that characterize multiple dimensions of workforce dynamics across specific demographic groups. For this study, the LEHD Origin-Destination Employment Statistics (LODES) data were used to map both the location of workers by place of residence and place of work. The 2014 version 7 of LODES was enumerated using 2010 census blocks.

TIGER/Line Shapefiles

Calculations and results for this project are reported for spatial geographies defined by the US Census Bureau made available to the public via the Bureau's Topologically Integrated Geographic Encoding and Referencing (TIGER) program. Census blocks were the fundamental unit for the accessibility calculations. These geography definitions are provided by the U.S. Census Bureau's such that 5,324 blocks are located in Kalamazoo County.

OpenTripPlanner

Auto, transit and walking travel time calculations between census block origins and destinations were carried out using OpenTripPlanner (OTP). OTP is an open-source multimodal trip planning and analysis tool that calculates efficient routes through multi-modal transportation graphs using open data standards including GTFS for transit and OpenStreetMap for street networks. Several different services are built upon the OTP library, including an analyst batch processor and a scripting application programing interface (API). The analyst batch processor is a command-line tool that allows for open-ended configuration and the inclusion of population, employment and other *opportunity* data, whereas the scripting API allows the execution of routing requests from within scripts (such as Python). Python scripts were developed to leverage batch processing algorithms to carry out both isochrone- and accessibility-based analyses.

Isochrone specifications

Isochrones are connected points of equal travel time or reachable regions on a graph that are accessible within a given travel time from a specified origin (as opposed to *isodistances*, which connect points of equal travel distances). We calculated isochrones at twelve, five-minute intervals for trips originating at a single, central location at City of Kalamazoo's Transportation Center. Isochrones were developed for five mobility models with a standard departure time at 7AM. Given that the K-Metro bus system is largely designed with respect to a hub and scope pattern where most busses--indeed 16 of 20 routes, pass through this location. This origin location, then, is likely to provide superior transit mobility relative to other subareas in the county.

Five models of individual mobility by transportation mode (Table 2) were developed to account for how the study area's transportation system potentially serves people with unique commuter mobility profiles. For example, model 1 estimates isochrones for people commuting to work by private car departing directly from their respective points of origin (i.e., residences) and arriving outside their places of employment (i.e., door to door service). Model 1 assumes that travel efficiency is limited exclusively by posted speed limits. Walking speed and maximum walk distance are not considered for this model given that the minimal amount of walking required for a typical private vehicle trip and, due to data limitations, traffic congestion was not incorporated in this private vehicle-based model.

Table 2. Five Models of Commuter Mobility

Model	Transportation Mode(s) (Assumptions)
Model 1	*Private automobile* (shortest path routing on street network, speed constrained by posted limits)
Model 2	*Public transit and walking* (scheduled bus routes on street network; standard walk speed [1.3 m/s or 3 mph] and distance [1,609 m or 1 mile])
Model 3	*Public transit and walking* (scheduled bus routes on street network; limited walk speed [0.9 m/s or 2.1 mph] and distance [804.7 m or 0.5 mile])
Model 4	*Public transit and walking* (scheduled, wheelchair accessible bus route trips and stops on street network; standard walk speed [1.3 m/s or 3 mph] and distance [1,609 m or 1 mile])
Model 5	*Public transit and walking* (scheduled, wheelchair accessible bus route trips and stops on street network; limited walk speed [0.9 m/s or 2.1 mph] and distance [804.7 m or 0.5 mile])

Employment accessibility specifications

In addition to the isochrones, time-averaged employment accessibility estimates were developed at the census block level using OTP's scripting application programming interface (API). Specifically, Python scripts were developed to automate calculations of employment access (via LODES input) across five models that assume different travel modes, walking speeds and maximum walking distances. The transportation performance measures estimate cumulative opportunities for 5,324 census blocks in Kalamazoo County at five-minute intervals over a two-hour period (7am-9am) and four travel time thresholds--15, 30, 45 and 60-minutes—producing 511,104 iterations or graphs for each of the five mobility categories or models described earlier.

Specifically, the Python scripts estimate: (a) the number of destinations (i.e., census blocks with jobs) reached from each origin (Equation 1); (b) the number of transit boardings (i.e., the number of transfers plus one) needed to get from each origin to each destination (Equation 2). the sum of jobs located within reached destinations (Equation 3); and (d) the total number of jobs located within reached destinations with jobs weighted using a nonlinear, distance decay function (Equation 4).

Equation 1

$$D_i = \sum_j D_j \, f(C_{ij})$$

where i and j represent origins and destinations, respectively and D_i is the sum of total employment destinations reached from origin i within a given travel time threshold, $f(C_{ij})$. Following Owen and Levinson (2014), cumulative opportunities Equations 1-4 employ a binary weighting function, such that:

$$f(C_{ij}) = \begin{cases} 1 \;\; if \; C_{ij} \leq t \\ 0 \; if \; C_{ij} < t \end{cases}$$

t=travel time threshold

Equation 2

$$B_i = \sum_j B_{ij} f(C_{ij})$$

where B_i is the sum of total public transit boardings needed to reach destination j from origin i within a given travel time threshold.

Equation 3

$$A_i = \sum_j W_j f(C_{ij})$$

where A_i represents the total number of jobs or employment opportunities accessible from origin i to employment destinations, W_j within a given travel time threshold.

Equation 4

$$AW_i = \sum_j W_j \exp\,(C_{ij})^{-0.08} f(C_{ij})$$

where AW_i represents the total number of *weighted* jobs or employment opportunities accessible from origin i to employment destinations, W_j. Equation 4 employs the exponential distance decay function, exp $(C_{ij})^{-0.08}$ to inversely weight the value of employment opportunities with respect to travel time. While it has become conventional wisdom that distance (and/or travel time) is a major factor that influences the perceived value of opportunities (including employment), this study employs a relatively weak distance decay parameter of -0.08 to avoid overstating the effect of travel time on the desirability of employment opportunities.

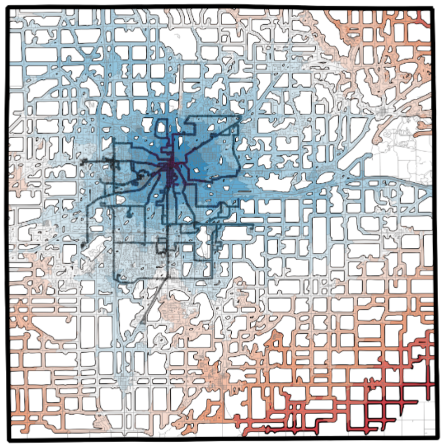
Results

Isochrone analysis

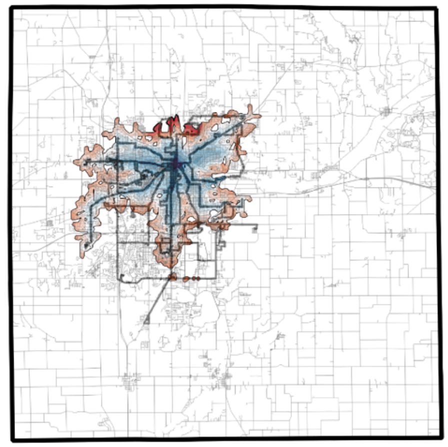
Figures 10a-e present (a), the private car show the spatial configurations of isochrones for each model type whereas Figures 11a-e present summary characteristics of the twelve, cumulative five-minute isochrones for each model in terms of their representative (a) county area percentages and shares of county (b) road network, (c) bus network, (d) bus stops and (e) jobs located within the isochrone boundaries. The maps clearly indicate that Kalamazoo county offers considerable mobility by private automobile. Within one hour, the private auto driver can access, from the sample origin location, nearly all destinations in the county. The spatial area of the 60-minute isochrone contains all county job locations, bus stops, the entire bus network and over 90 percent of the total county road network and area.

Figures 10b-e, present a clear spatial contrast to the private automobile, model 1. Model 2, with fewest mobility constraints, and thus the best-case transit scenario, is able to access less than 70 percent of all county jobs and, when work trips are limited to only accessible public transit stops requiring less than a total of a half-mile walking at a slower gait (model 5), only 30 percent of county jobs can be accessed from the origin location.

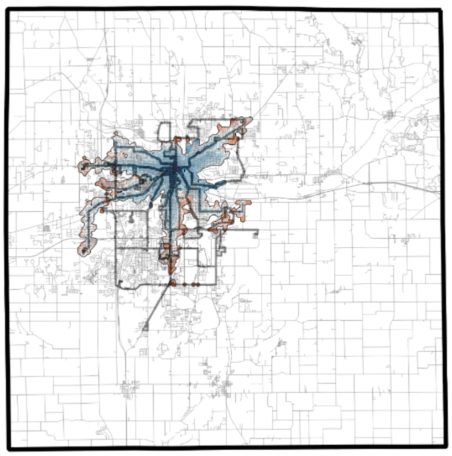
(a) Model 1: Private automobile, posted speed limits



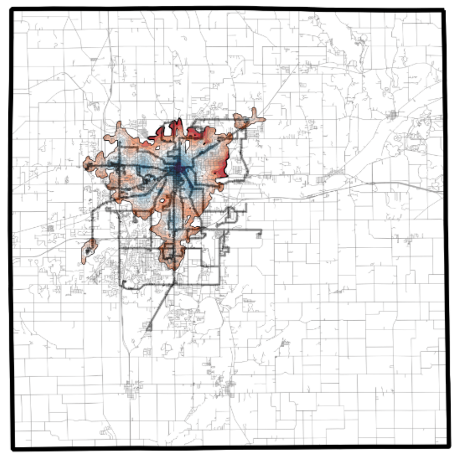
(b) Model 2: Bus, walk modes, standard walk speed (1.3 m/s or 3 mph) and distance (1,609 m or 1 mile)



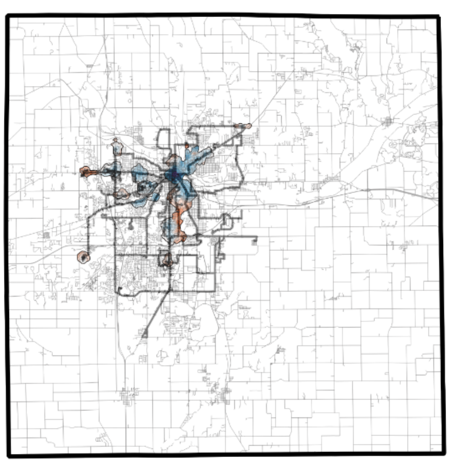
(c) Model 3: Bus, walk modes, limited walk speed (0.9 m/s or 2.1mph) and distance (804.7 m or 0.5 mi)



(d) Model 4: Bus, walk modes, (1.3 m/s or 3 mph) and distance (1,609 m or 1 mile), wheelchair accessible



(e) Model 5: Bus, walk modes, limited walk speed and distance, wheelchair accessible



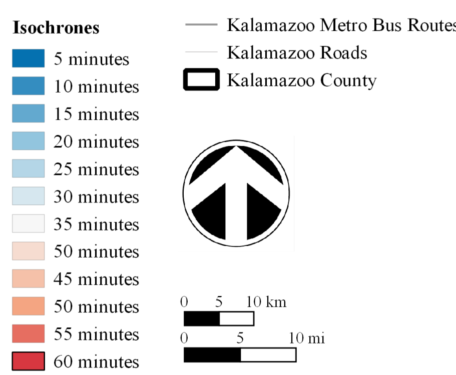


Figure 10. Isochrone Maps with Trips Originating from Kalamazoo Transportation Center by Model Type

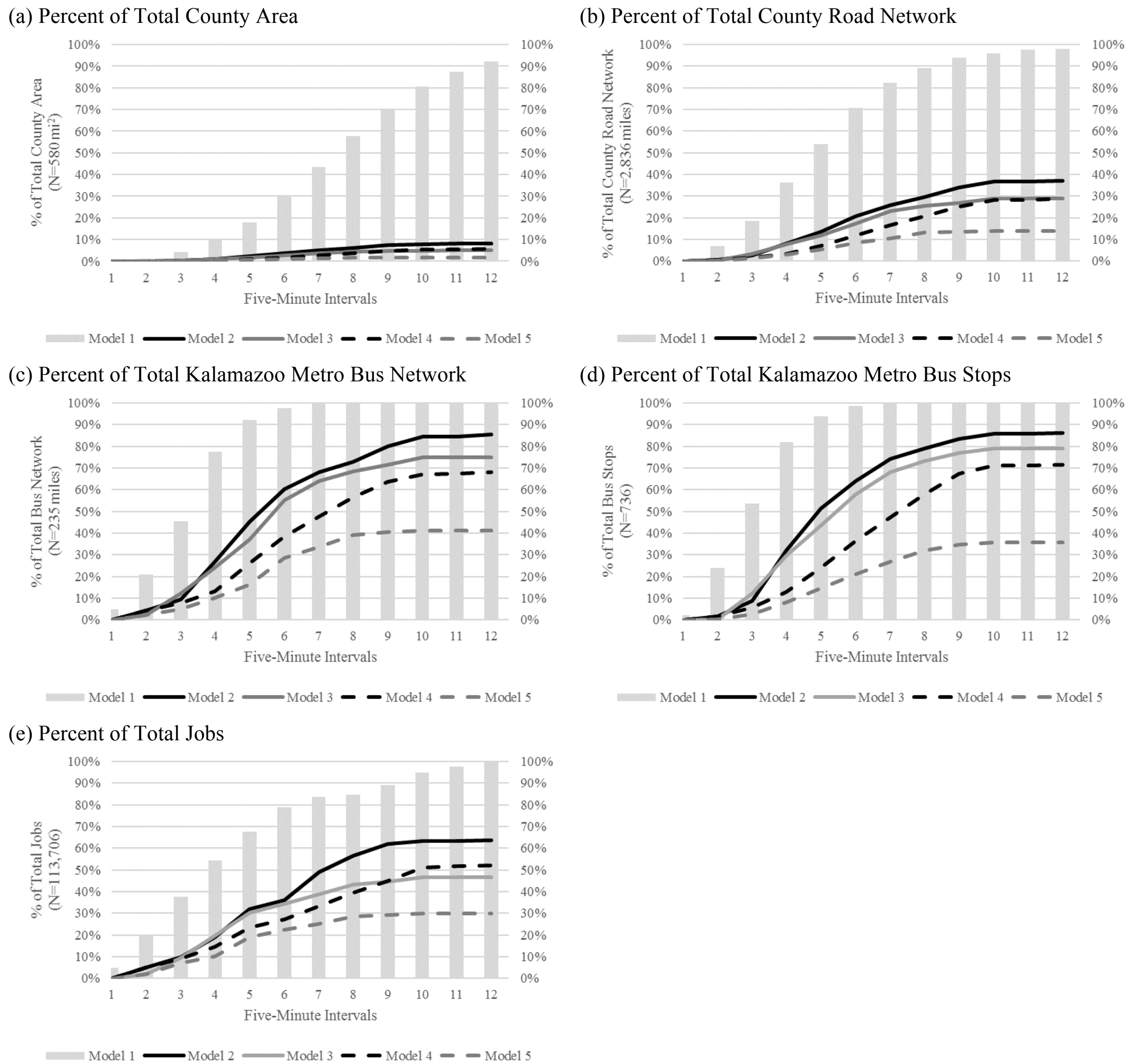


Figure 11. Characteristics of Model Isochrones Originating from Kalamazoo Transportation Center by Model Type

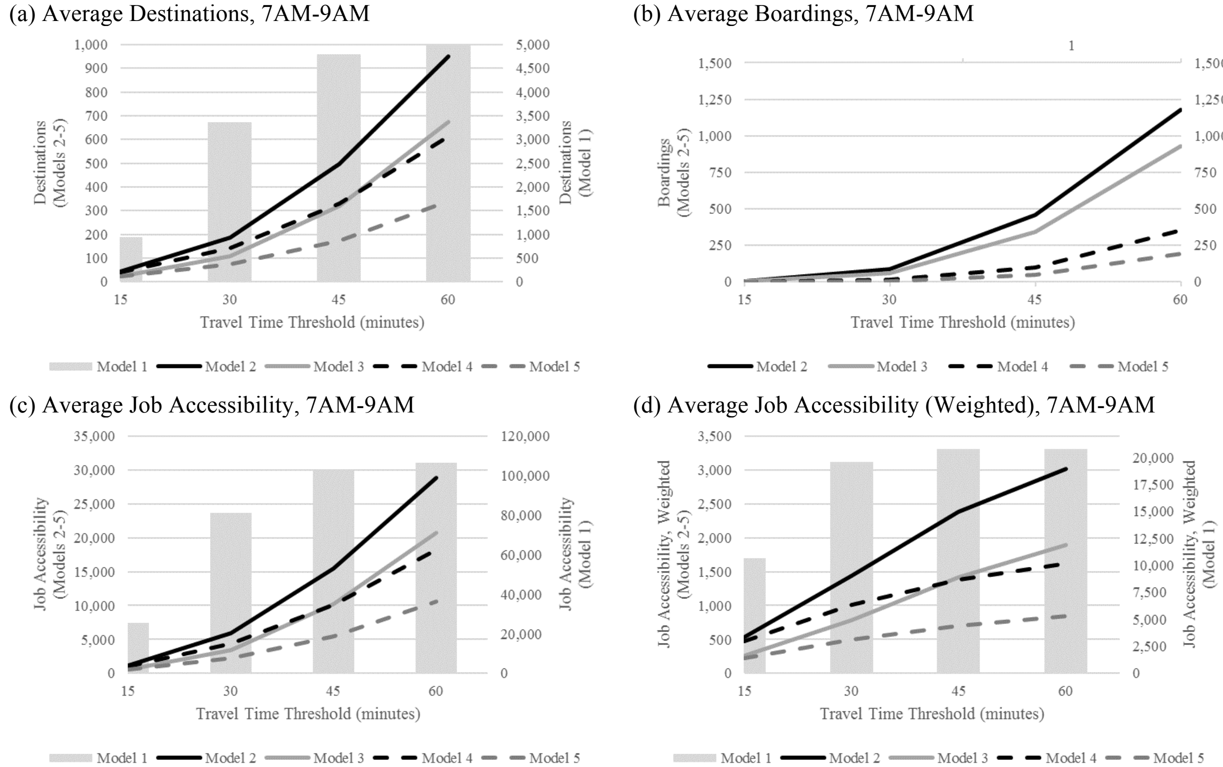


Figure 12. Cumulative Opportunities for Kalamazoo County Census Blocks by Travel Time Threshold (15, 30, 45 and 60 minutes) and Model Type

Employment accessibility

Employment accessibility estimates averaged across all 5,324 census blocks are displayed in Figures 14a-d by departure time in five-minute intervals over a two-hour AM peak travel period. The results depicted here are constrained to a one-hour maximum commute time, which is far over the countywide, sub-30 minute median work commute time reported in the census numbers. The charts show that the level of service public transit offers for the average commuter varies considerably over the two-hour period due to variations in scheduled headways and abilities to make route connections or transfers. For example, the total number of destinations (i.e., census blocks) and jobs accessed are far fewer by public transit (models 2, 3) compared to private automobile (model 1) and fewer still when only wheelchair accessible stops are utilized (models 4,5).

Perhaps most striking is the difference in estimated vehicle boardings across the four public transportation models. People requiring wheelchair accommodations (models 4,5) have, on average, 75 percent fewer boarding opportunities compared to those who do not require such facilities (models 2,3). Employment accessibility is also greatly reduced for people using public transit over private vehicle and even more so for people requiring accessible bus stops. Public transit commuters are estimated to have access to less than 25 percent of the jobs accessible by private vehicle. Worse yet, people with disabilities that require enhanced bus stop accommodations were estimated to have 37 percent fewer jobs accessible compared to fellow public transit commuters who do not have such requirements.

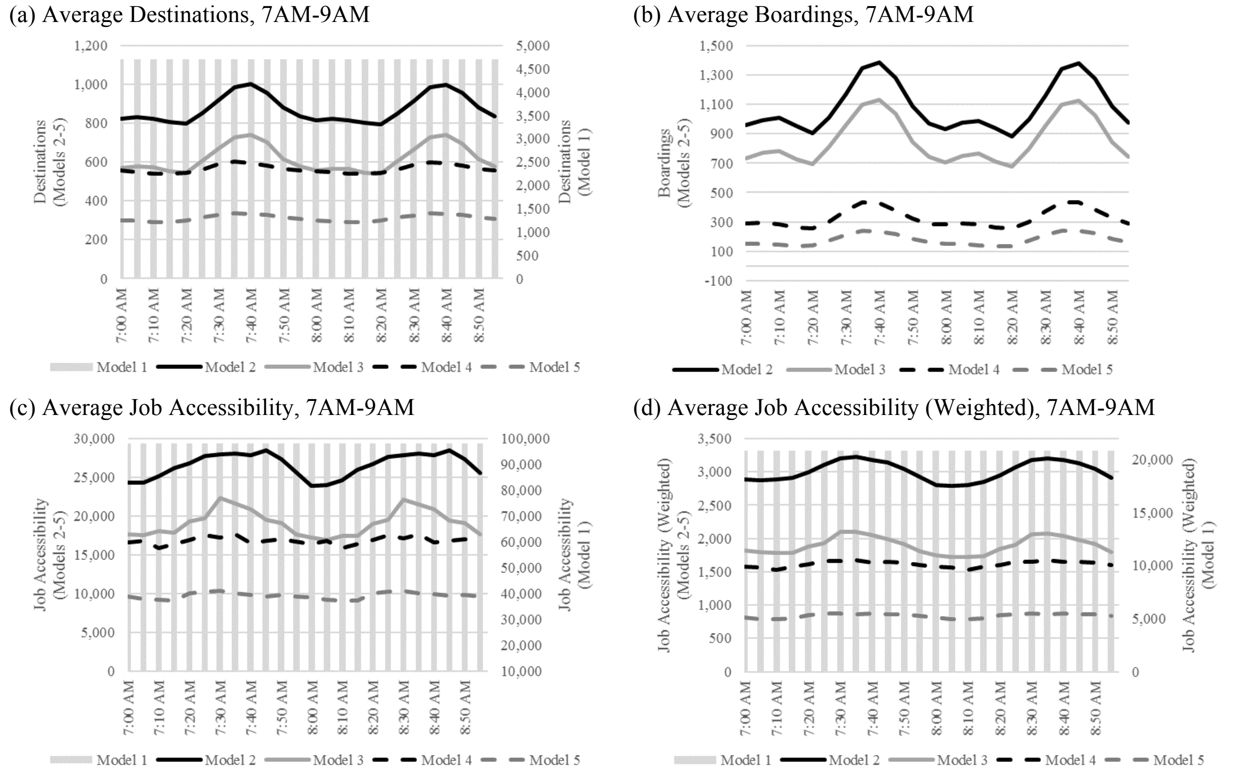


Figure 13. Average Accessibility and Public Transit Boardings by Peak AM (7-9) Departure Time

Transit stop prioritization

With this fine-scale information of public transit infrastructure quality and job accessibility outcomes, it was possible to develop a method that strategically prioritizes public transportation planning and development. In this section, we create an optimization model for prioritizing transit stop improvements directed toward improving employment accessibility for people with physical disabilities and many others who would benefit from more accessible bus stops.

This is important given that, under the ADA, transit agencies and local government public entities are required to perform self-evaluations of their current facilities, relative to the accessibility requirements of the Act. These public entities are then required to develop a transition plan, which details how accessibility issues or deficiencies within the public right of way, including public transit stops, will be corrected, scheduled, budgeted for, and monitored for progress and compliance. Adopting an optimization-based approach as opposed to an ad hoc self-evaluation and transition approach for improving accessibility can assist public entities in sorting through and prioritizing mobility issues that lead to changes that can best help people with disabilities.

Development of the linear equation

Toward this end, we develop an objective function for a linear program designed to simultaneously maximize various components of network topology, employment accessibility, destination attraction (based on jobs by place of work) and ridership demand (based on jobs by place of residence). Specifically, the above components were combined, with equal weights, into an index for each of the bus stops, represented as *catchment areas* or *buffered nodes* on the public transit network. The catchment areas (or concave hulls) were created by enclosing street edges spanning a 0.25 mile network distance from bus stop origins. Each bus stop-specific buffer was then allocated population, housing units, workers (workers by place of residence) and jobs (workers by place of work) within its boundary using block-level data from the US Census Bureau LODES and 2014 population and housing data. Allocations were weighted by the percentage of block area within the buffer, such that 50 percent of a census block's population, housing units, workers and jobs were allocated to a bus stop catchment area if only half of the block overlapped the respective catchment area.

Time averaged accessibility estimates were calculated for each bus stop using a method similar to those used in equations 1 and 2 for similar time thresholds, 900, 1800, 2700 and 3600 seconds. For simplicity, only model 2 parameters and results were used in these calculations. Together, four weighted components—(1) nodal centrality or the normalized score of each bus stop relative to its direct connectivity to other network nodes; (2) population and (3) jobs within 0.25 mile network distance of each node divided by the average population or jobs within 0.25 mile across all nodes; and (4) spatially weighted employment accessibility for each node divided by the average employment accessibility across all nodes—were maximized according to the following objective function.

Equation 4

$$maximize \sum_{i=1}^{638} x_i C_i S_i \leq B/5$$

$$x_i \subset \{0,1\}$$

where C_i represents the total cost of retrofitting non-compliant bus stop i (N=638) multiplied by a scaling factor, S_i and constrained to one-fifth of a total budget B so that design and construction are phased in over a five-year period. Since x_i is a discrete variable (1 represents positive decision to retrofit, whereas 0 indicates no intervention), a mixed integer linear program (MILP) formulation was specified. The scaling factor, S_i takes the form:

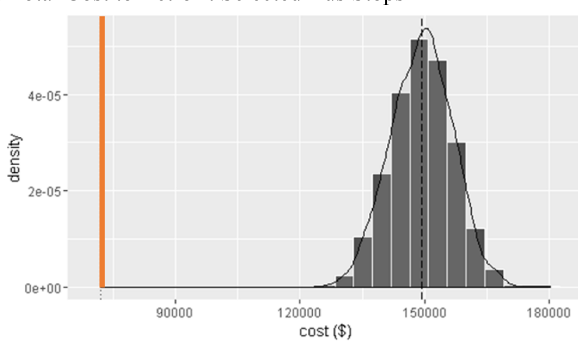
$$S_i = \sum j_i w_i p_i c_i$$

where j_i, w_i, p_i and c_i respectively represent number of jobs (i.e., workers by place of employment), workers (workers by place of residence), total residential population of census blocks located within a catchment area associated with each bus stop and nodal centrality of each stop on the network. Further, jobs, workers and population allocations of each census block were proportioned based on the percentage of block area spatially intersected by each bus stops' catchment area such that 50 percent of a census block's attributes were allocated if only half of the block overlapped (or intersected) the respective catchment area. Scaling the origin locations in this manner assigned greater weight to retrofitting bus stops that have greater network centrality and trip generation and attraction potentials.

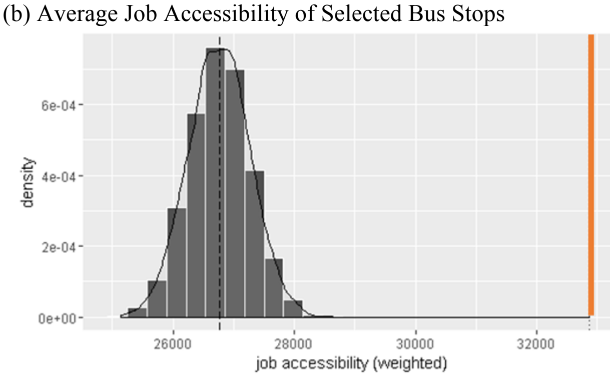
Optimization results

Figures 14a-e below present results of the linear optimization or strategic retrofitting approach compared to a series of possible ad hoc approaches with respect to five measures of effectiveness relating to total cost, improved job accessibility and total population, workers and jobs in catchment areas of selected bus stops. A total of 5,000 independent, random samples (without replacement) were selected from the set of non-compliant bus stops. Density curves were created by summing each of the five measures of effectiveness plotted alongside a single optimized approach represented as a single, solid vertical line. The optimized approach yielded a superior outcome in all five cases.

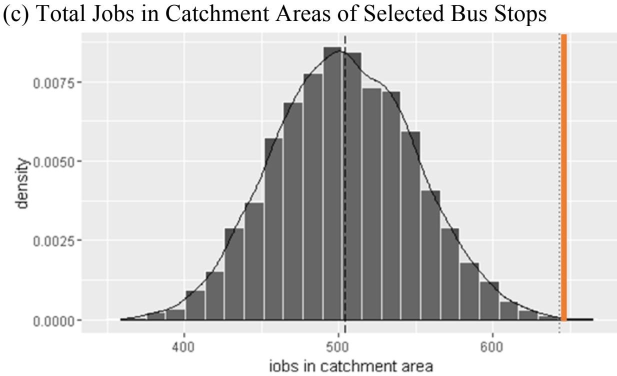
(a) Total Cost to Retrofit Selected Bus Stops



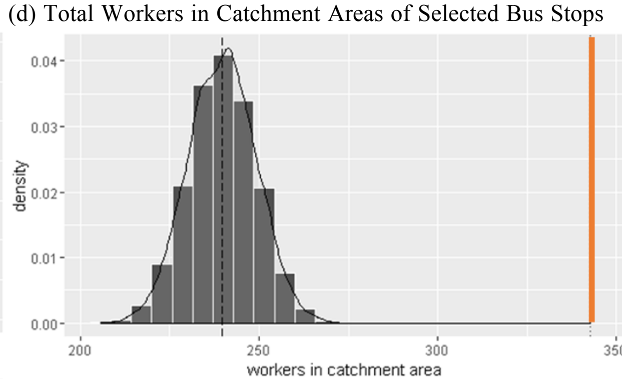
(b) Average Job Accessibility of Selected Bus Stops



(c) Total Jobs in Catchment Areas of Selected Bus Stops



(d) Total Workers in Catchment Areas of Selected Bus Stops



(e) Total Population in Catchment Areas of Selected Bus Stops

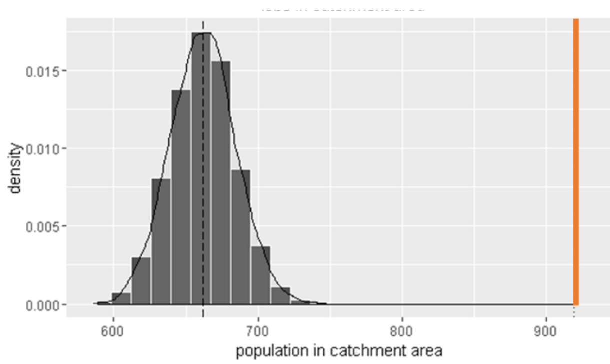


Figure 14. Comparison of Strategic vs. Ad Hoc Approach to Retrofitting Public Transit

Table 3 Standardized Costs and Impacts of Optimized Selection of Bus Stop Retrofits by Phase

	Standardized Impacts (i.e., per bus stop)					
	Job Accessibility (weighted)	**Jobs (catchment)**	**Workers (catchment)**	**Population (catchment)**	**Bus Stops**	**Cost**
Phase I	32,861.2	624.8	342.7	918.8	265	$71,989
Phase II	25,568.1	456.6	170.9	537.2	125	$71,983
Phase III	23,353.7	309.2	126.2	361.8	98	$71,985
Phase IV	20,153.5	356.8	147.8	413.9	84	$71,974
Phase V	18,415.8	591.6	245.5	634.6	66	$72,029
Random[a]	*26,764.6*	*503.8*	*239.7*	*661.8*	*265*	*$149,316*

(a) Randomized averages calculated

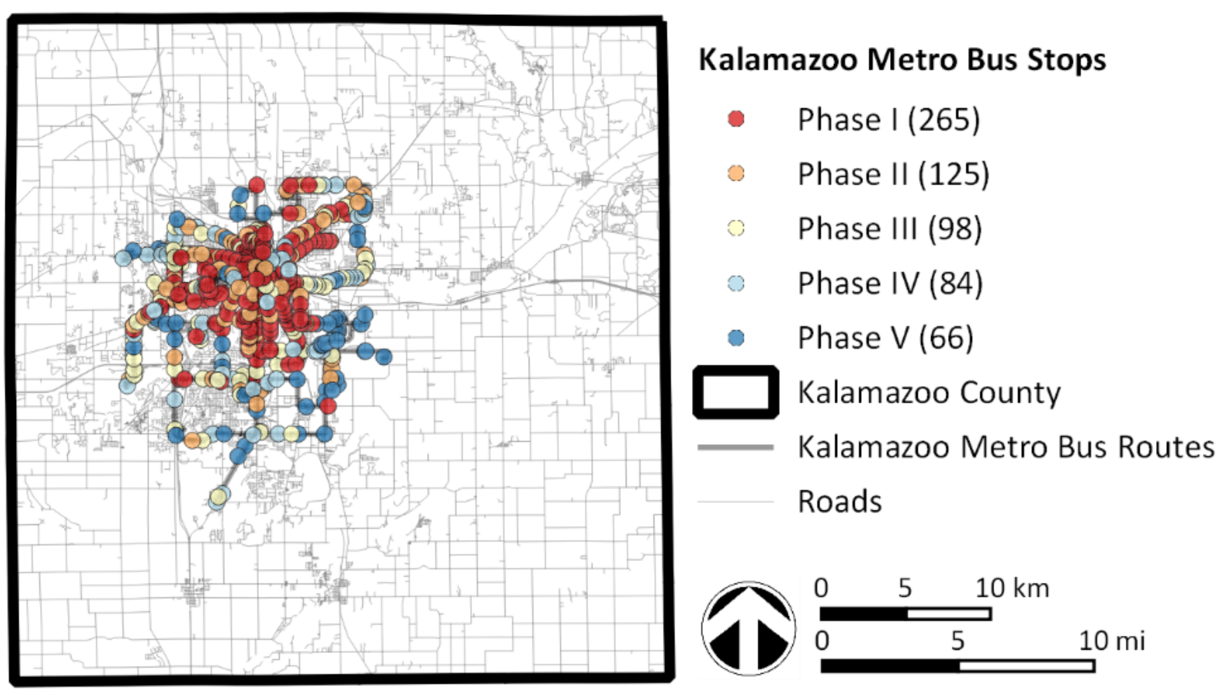


Figure 15. Map of Optimized, Phased Bus Stop Retrofits

Discussion and recommendations

This research developed procedures to calculate multimodal measures of employment accessibility using public data and open source spatial analytical tools. Critical to this analysis was the availability of GTFS data, the structured form for managing and sharing public transit stops, routes, schedules and fares. By incorporating GTFS into the employment accessibility calculations it was possible to estimate variations in job access with changes in departure time, headways and transit schedules.

The standard GTFS for a medium-size transit provider was also augmented to include information about wheelchair access along transit routes and wheelchair boarding accommodations at bus stops. The enhanced GTFS data were combined with conventional street network (for measuring walking routes and distances) and series of hypothetical individual mobility profiles to create more nuance estimates of accessibility that account for both detailed transit infrastructure and physical mobility limitations. There are several ways to improve the above methods and data to better understand and improve employment accessibility for people experiencing disability. Two general recommendations follow.

Extend the GTFS data structure to better account for and represent (in)accessible infrastructure

At the time of this writing, GTFS does not have a conventional data structure for inputing or representing detailed information about ADA infrastructure including, for example, pedestrian access routes, curb ramps and blended transitions, detectable warning surfaces, pedestrian street crossings, transit shelters, on-street parking spaces and passenger loading zones. Incorporating these elements into the standard feed structure would allow for better system evaluation and end user-based trip planning.

Incorporate job-skills correspondence in accessibility measures

The employment accessibility models detailed in this study were limited in that only total jobs were considered as inputs in the job access estimates. Future analyses could make use of the more comprehensive segmentation of LODES data to constrain possible commutes by occupation category in order to better match employment access of workers to relevant jobs.

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