Multi-Activity Access: How Activity Choice Affects Opportunity

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Abstract

It is commonly seen that accessibility is measured considering only one opportunity or activity type or purpose of interest, e.g., jobs. The value of a location, and thus the overall access, however, depends on the ability to reach many different types of opportunities. This paper clarifies the concept of multi-activity accessibility, which combines multiple types of opportunities into a single aggregated access measure, and aims to find more comprehensive answers for the questions: what is being accessed, by what extent, and how it varies by employment status and by gender. The Minneapolis - St. Paul metropolitan region is selected for the measurement of multi-activity accessibility, using both primal and dual measures of cumulative access, for auto and transit. It is hypothesized that workers and non-workers, and males and females have different accessibility profiles. This research demonstrates its practicality at the scale of a metropolitan area, and highlights the differences in access for workers and non-workers, and men and women, because of differences in their activity participation.

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1 Introduction

Since the concept of accessibility was introduced in transport planning field by Hansen (1959), it has been employed in many others including urban geography, network and spatial economics, regional science, and geographical analysis over the years (Cascetta et al., 2016). Accessibility is the output of a function of mobility (speed and directness of the network) and density of destinations (quality and quantity of opportunities) (Brosnan and Levinson, 2015, Paez et al., 2010) and measures the extent to which spatial separation between people and opportunities can be overcome (Holl, 2007).

Hansen (1959) developed a very basic and widely used method to measure a given location's accessibility, as the magnitude of opportunities within some specified distance or threshold of the location (O'Kelly and Horner, 2003). The number of opportunities at each potential destination reflects its value for spatial interaction to the traveler, which is synonymous with the measure of destination attraction in spatial interaction models (Wu and Levinson, 2020).

Previous research commonly measured accessibility or destination attraction considering only one opportunity or activity type or purpose of interest. The value of a location, and thus the overall access, however, depends on many different types of opportunities, but as far as we know, only Hou et al. (2019) combined these multiple destinations into a single aggregated accessibility measure. Hence, this paper aims to fill this gap that defines a concept of multi-activity accessibility, which involves multiple types of opportunities, and asking what is being accessed, to what extent, by whom.

Additionally, growing attention has been drawn to accessibility equity analysis in recent years to investigate whether fair access to opportunities exists for individuals in different classes, e.g., income, age, or ability to travel (Geurs et al., 2016, Levinson, 2010, Thomopoulos et al., 2009) . However, few studies have compared the differences between workers and non-workers, as the conventional single-activity accessibility measure cannot impartially to do so: access to jobs is an indicator specific to workers; while other types of

opportunities are not stratified by employment status. Also, though studies on gendered mobility have been established, which analyzed travel behavior patterns concerning the effects of familial-related activities, e.g., child-care (Gordon et al., 1989, Hanson and Johnston, 1985, Mauch and Taylor, 1997, Presser, 1995, Wyly, 1998), only a few have extended this concept considering to examine how gender differentiates accessibility experiences (Kim, 2007, Kwan and Kotsev, 2015, Lecompte and Pablo, 2017).

Hence, we measure the multi-activity accessibility by employment status and by gender, for the first time, in this study, for the Minneapolis - St. Paul (Twin Cities) metropolitan area, systematically compare how accessibility varies, and identify whether there are mismatches due to the effects of employment or gender differences. We hypothesize that there are such differences.

Literature review, methodology, data collection, estimates of activity duration share, accessibility measurements, and the conclusion are discussed in Sections 2 - 7 in turn.

2 Literature Review

Accessibility evaluation generally considers one type of opportunity at a time, in which access to jobs is recognized as the major concern. Commute trips create temporal and geographical concentrations that lead to the greatest potential of accessibility loss (Cao et al., 2008, Li et al., 2004), and reaching jobs bears more strict time constraints so commute time, then accessibility in a certain amount of time, matters. The "Access Across America" project, conducted by Owen and Murphy (2018*a*), performs national accessibility evaluation and ranks job accessibility by traffic mode for 50 metros in the US, the results of which are further adopted for a global comparison (Wu et al., 2020).

Job accessibility has been applied in various disciplines, and a primary one is to evaluate transport or land-use projects, as a support for decision-making or for financing and investments (Anderson et al., 2013, Black and Conroy, 1977, Bocarejo S and Oviedo H,

2012, Geurs and Van Wee, 2004, Koenig, 1980, Wu and Levinson, 2020). Cui et al. (2017) selected six real-world planning projects in the US to examine how the changes in land use planning or transit or highway networks can affect job accessibility, which provides insight on how job accessibility can be employed in planning practices. Additional applications also make efforts to understand spatial mismatches (Grengs, 2010, Shen, 1998), to explain travel behavior patterns (Levinson, 1998), to estimate real-estate values (Ibeas et al., 2012, Srour et al., 2002), and to model economic productivity (Melo et al., 2017).

Studies on other types of opportunities can be found. For instance, access to population, seen as a critical factor for location analysis (Harris, 1954), were measured to picture the population redistribution or growth considering transport network changes (Kotavaara et al., 2011, O'Kelly and Horner, 2003). It has also been used to understand transport evolution and network expansion (Levinson et al., 2016). Access to healthcare services, especially in the equity considerations, have received attention, to explore the uneven spatial distributions of health facilities and populations as well as the transport links in between (Brondeel et al., 2014, Knox, 1978, Mao and Nekorchuk, 2013). There are some localized level of accessibility analyses as well, looking at the access to neighboring retail and services (Handy and Clifton, 2001, Krizek, 2003, Krizek et al., 2012) or local food (Forsyth et al., 2010).

Though some studies stratified multiple opportunity types separately (Cervero et al., 1999, Van Wee et al., 2001), few have built an integrated indicator to involve them all in accessibility analysis (Levinson and Wu, 2020). We address that gap here.

Geurs and Van Wee (2004) conducted a careful review on accessibility measures and classified them as infrastructure-based, location-based, person-based, and utility-based measures, in which location-based measures analyze accessibility on a macro-level, represent the value of a location, and so are relevant with our topic. We select the ones derived from the cumulative opportunity measure (Ingram, 1971, Vickerman, 1974, Wachs and Kumagai, 1973), which is more transparent and explainable in terms of multi-activity ac-

cessibility. Discussion can be found in Section 3.1 in detail.

3 Methodology

Figure 1 shows the framework adopted in this study that summarizes required inputs, applied methods, as well as desired outcomes.

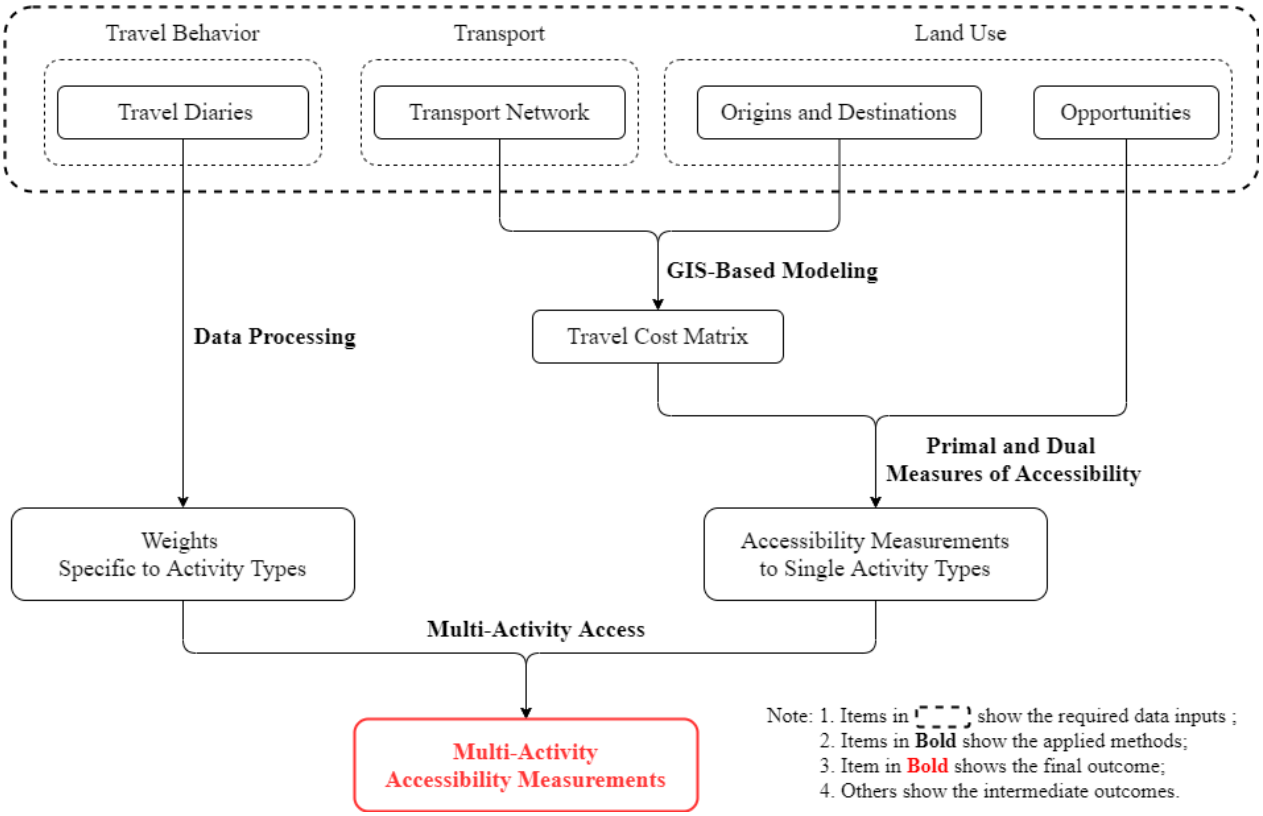

Figure 1: Methodology Framework: Multi-Activity Accessibility

Many Geographic Information System (GIS) software provide support for GIS-based modeling. To generate travel cost matrix, it needs to join all pairs of origin and destination with transport network and then calculate the travel cost for each of those trips using the network. In this study, Network Analyst tool in ArcGIS is used following the rules that points are assigned to the nearest links and the travel costs are accumulated along with the shortest path, e.g., travel time on the shortest travel time path, using the Dijkstra's algorithm (Dijkstra et al., 1959, Esri, 2019).

Other applied methods are explained in the following subsections.

3.1 Primal and Dual Access

Cui and Levinson (2019) defined the *primal measure* of cumulative opportunities accessibility as a generalization of the first accessibility formulation by Hansen (1959), which counts how many opportunities can be reached in a given travel cost.

$$A_{i,z,\tau} = \sum_{j=1}^{J} O_{j,z} f(C_{ij}, \tau) \tag{1}$$

$$f(C_{ij,\tau}) = \begin{cases} 1 & \text{if } C_{ij} < \tau \\ 0 & \text{if } C_{ij} \geq \tau \end{cases} \tag{2}$$

Where:

$A_{i,z,\tau}$: primal accessibility of origin i to opportunity z with cost threshold τ;

$O_{j,z}$: number of opportunities z in destination j;

$f(C_{ij,\tau})$: function of costs with respect to cost threshold τ, in which C_{ij} is the impedance factor representing the travel cost between i and j;

J: total number of destinations.

The *dual measure* of cumulative opportunities accessibility, which also considers the interrelationship between reachable opportunities and travel cost, in contrast, is the reciprocal of the primal access that solves for the travel cost required to reach a fixed number of opportunities. It is exactly the inverse matrix of the primal, in theory, when the spatial resolution is high and temporal threshold for access measurements is sufficiently fine (Cui and Levinson, 2019).

The dual access ($A_i^{'}$), is formulated as:

$$A_i^{'} = \widehat{Q_{ij}} C_{ij} \tag{3}$$

where $\widehat{Q_{ij}}$ results from:

$$\widehat{Q_{ij}} = \underset{Q_{ij}}{\operatorname{argmin}} \sum_{j=1}^{J} O_j Q_{ij} C_{ij} \tag{4}$$

subject to:

$$\sum_{j=1}^{J} O_j Q_{ij} \geq \Omega \tag{5}$$

$$Q_{ij} \in \{0, 1\} \tag{6}$$

Where:

$A_i^{'}$: dual accessibility of origin i;

Ω: opportunity threshold;

Q_{ij}: cells in incidence matrix Q; '1' if destination j is included in the set of destinations, '0' otherwise.

The primal access has been widely applied in previous studies when measuring access to opportunities where quantity of opportunities is critical, e.g., counting how many reachable jobs (Cui and Levinson, 2018*a*,*b*, Deboosere et al., 2018, El-Geneidy and Levinson, 2006, Gutierrez and Gomez, 1999, Hess, 2005, Srour et al., 2002), restaurants (Krizek et al., 2009), retail (Apparicio et al., 2007, Guy, 1983, Krizek et al., 2009, Srour et al., 2002), green space (Ekkel and de Vries, 2017, Reyes et al., 2014), or recreation facilities (Kim and Fesenmaier, 1990). A recent innovation also uses it when the time budget constraint is critical, minutes available for participating in an activity (Niedzielski and Kucharski, 2019, Widener et al., 2015, 2013). Comparatively, the dual measure is not normally seen in urban planning applications, but is suitable for cases where time to a service is critical, e.g., measuring the travel time needed to reach (be reached by) fire stations or hospital emergency departments, or for any distribution of public services, e.g., walking time to schools, parks, or libraries is under some thresholds.

As multi-activity access cares many different types of opportunities, we apply both primal and dual measures here to explore the patterns when multiple opportunity types are embedded in one accessibility matrix.

3.2 Multi-Activity Access

A single aggregated access measure involving multiple types of opportunity can be built if we sum over different types of opportunities using appropriate weights (Hou et al., 2019, Levinson and Wu, 2020). This is equivalent to summing over accessibility matrices with regard to different types of opportunities for cumulative access measures, which is operationally simpler to implement and so selected in this study. However, setting a fixed number of threshold, time threshold (τ, e.g., 30 minutes, for the primal) or opportunity threshold (Ω, e.g., 100,000 opportunities, for the dual), is not acceptable when we weight and combine those accessibility matrices, as the number of opportunities varies significantly by type. Those with fewer points of interests would be,

- mainly ignored in the primal access, which counts the number of reachable opportunities;

  e.g., the number of jobs (1,707,388 in total) in the Twin Cities is about 10,000 times greater than the number of colleges and universities (177 in total), so the primal access to tertiary education would barely affect the multi-activity results, unless its weight is nearly 1.

- mostly overthought in the dual access, which measures the travel cost needed to reach opportunities.

  e.g., it would take forever to reach 100,000 colleges or universities in the Twin Cities, regardless of those out of the study area, so the dual access to tertiary education as well as the multi-activity dual access would be infinite in this case, unless the weight for college is 0.

Hence, for the primal access, instead of counting the absolute number of reachable opportunities, we standardize this value and measure the percentage of reachable opportunities given a cost threshold,

$$A^{\oslash}_{i,z,\tau} = \frac{A_{i,z,\tau}}{\sum\limits_{j=1}^{J} O_{j,z}} \tag{7}$$

Where:

$\sum\limits_{j=1}^{J} O_{j,z}$: total number of opportunities among all destinations for activity type z.

In this case, the multi-activity primal access gives the weighted average percentage of reachable opportunities,

$$A^{\oslash}_{i,.,\tau} = \sum_{z=1}^{Z} W_z A^{\oslash}_{i,z,\tau} \tag{8}$$

Where:

W_z: weights of activity type z.

We normalize activities so that,

$$\sum_{z=1}^{Z} W_z = 1 \tag{9}$$

The value of this multi-activity primal access can be further averaged across all origins, weighted by population, that represents the value of accessibility experienced by an average person considering multiple activity types (Owen and Murphy, 2018*b*),

$$A^{\oslash}_{.,\tau} = \frac{\sum\limits_{i} A^{\oslash}_{i,.,\tau} \times P_i}{\sum\limits_{i} P_i} \tag{10}$$

Where:

P_i: population in origin i.

For the dual access, we apply the relative opportunity thresholds ($\Omega^{\oslash}_{z}$), n% of total

opportunities, and calculate the travel cost required to reach a percentage of opportunities weighted over different types of opportunities.

$$A'_{i,.,\Omega^{\varnothing}_{.}} = \sum_{z=1}^{Z} W_z A'_{i,z,\Omega^{\varnothing}_{z}} \tag{11}$$

In this study, we choose W_z to be the average share of time per day spent at each activity. Details are discussed in Section 3.3.

The downside of normalizing opportunities (i.e. at using relative accessibility) is that it reduces comparability over time or between places, compared with absolute accessibility. The relative accessibility for a small place will tend to be better than for a large place – a traveler may be able to reach 100% of opportunities in a small town in 30 minutes, but only 20% of opportunities in New York, that doesn't mean they have better accessibility. However for the purposes of this study, comparing within a metropolitan area, between groups, rather than between cities or over time, that trade-off is appropriate.

3.3 Travel Diary Data Processing

Activity duration refers to the time spent at an activity and describes "how the 1440 minutes in a day are allocated to different activities for different groups of people" (Levinson and Wu, 2005). The way to calculate activity duration can be data specific. In this study, we acquired travel diary data collected by the Metropolitan Council for the Travel Behavior Inventory (TBI) (Metropolitan Council, 2019), which record trips of individual travelers for a selected day or days, including information like origin, departure time, destination, arrival time, and activity type.

It is unavoidable that some errors are included as the TBI Home Interview Survey is self-reported. With reference to the data filter rules proposed by Brosnan and Levinson (2015), we apply the following processes:

- Trips were excluded if:

  - trip duration was greater than 120 minutes;
  - the calculated travel distance was greater than 200 km;
  - the calculated average speed was greater than 150km/h.

- Individuals were excluded if:
  - any of the trips were excluded;
  - the origin of the first trip or the destination of the last trip was not **Home**;
  - personal information, e.g., work status or gender, were missing;
  - non-workers reported work activities.

For each individual, the activity duration is calculated by subtracting the arrival time of the former trip from the departure time of the next trip. The remaining time, the time from midnight to the departure of the first trip plus the time from the arrival of the last trip to midnight, is attributed to time at home, due to the filter rule that all selected individuals had begun and ended their travel day at home. This remaining time can be cross-checked by subtracting the calculated activity durations and the travel times for each trip from 1,440 minutes. More detailed illustration can be found from Brosnan and Levinson (2015).

The average share of activity duration by activity type is then aggregated using as the weights (W_z) in multi-activity access calculation.

4 Data

Several data sources have been employed in accessibility calculations for the case of the Twin Cities.

4.1 Transport Network

We collected the TomTom road network from the Metropolitan Council, which is formatted as a GIS shapefile that contains geospatial information of roads in the Twin Cities. The

travel time en route is measured for all pairs of origins and destinations using it as the base map.

TomTom speed data report different percentiles of speed values, aggregated from millions of GPS records, on a link basis. In this study, we select the 50th percentile (median) speed at the morning peak hours (7am - 9am), joining with the TomTom road network to calculate auto travel time. Note that this auto travel time only counts the in-vehicle time, disregarding the parts of walking to and from parking due to the lack of accurate data, though for the vast majority of automobile travelers in this region, these times are small.

The General Transit Feed Specification (GTFS) data is a collection of tables, mainly including files of transit routes, stops, trips, frequencies, and fares, describing the scheduled operations of a transit system (Wikipedia, 2019). The data for the Twin Cities are collected from the Metropolitan Council (Metropolitan Council, 2018), which can be added to the network dataset created on the TomTom road network and used for transit travel time calculations. Note that this transit travel time counts walking time from and to the transit stops, waiting time at the origin transit stop, on-vehicle time, and transfer time if needed. Note also that, for an origin-destination (OD) pair, if walking needs less time than taking transit, the walking time would be used to replace the transit travel time for accessibility calculations.

4.2 Origins and Destinations

The 2010 TIGER/Line shapefile defines the boundaries of census blocks (US Census Bureau, 2010). The features in the Twin Cities were selected from the Minnesota dataset, for which the centroid of each block was extracted as the origin and destination for accessibility measurements.

4.3 Opportunities

Job opportunities data were collected from the Workplace Area Characteristic (WAC) table of the LEHD Origin-Destination Employment Statistics (LODES), where LEHD refers to Longitudinal Employment Household Dynamics (US Census Bureau, 2013). The WAC table details the total number of jobs located in each census block, as well as the number of jobs for male workers and female workers, specifically. As it shares the same Geo ID with the TIGER/Line census block shapefile, it can be joined to visualize how job opportunities are distributed over the Twin Cities.

The number of male workers and female workers living in each census block is also counted and reported in the Residence Area Characteristic (RAC) table of LODES dataset, using which we can sum over the accessibility values and measure the gender-specific population-weighted average.

For other types of opportunities, we used the Dun and Bradstreet data for Minnesota, which provide business information reports for 220,839 companies, categorized by the Standard Industrial Classification (SIC) (Dun & Bradstreet, 2019). The coordinates of the companies were extracted using Nominatim, an API that allows to return the coordinates by searching OpenStreetMap based on names and addresses. We treated these companies as the Points of Interests (PoIs). In total, there are 178,042 valid PoIs identified and located in the Twin Cities and further clustered into 7 categories: stores, restaurants, schools, colleges, recreation facilities, religious sites, and other opportunities, to match with the travel diary records. The number of opportunities are then aggregated by census block.

Table 1 shows the total number of PoIs for each classification. Figure 2 displays the spatial distributions of stores and job opportunities. It is quite clear that stores are more evenly distributed over the Twin Cities but many of the jobs are grouped along major highways spreading out from downtown Minneapolis. Other types of opportunities have similar patterns as stores, though with relative lower values of density, except colleges, which cluster near the University of Minnesota, highlighted in Figure 2b.

Figures/StoreDen_2.jpg

(a) Store Density

Figures/JobDen_College.jpg

(b) Job Density with Colleges Highlighted

Figure 2: Store and Job Density in the Twin Cities Metro Region with Locations of Colleges Highlighted

5 Average Share of Activity Duration

The filtered travel diary dataset includes 61,613 trips generated from 14,442 individuals, based on which Table 2 gives the average daily activity duration and total travel time by employment status by gender in minutes. As expected, except for at-home activities, for workers, working time dominates the daily time, and on average, male workers spend more time at work and less time at home, compared to female workers, due to gender differences in parenting and domestic responsibilities (Ferree, 1991, Jolly et al., 2014, Presser, 1994). While non-workers engage in more out-of-home activities at schools, recreation, and other opportunities, e.g., personal business, social events, accompany another person.

Table 1: Opportunities by Type in the Twin Cites

Type	Total
Jobs	1,707,388
Jobs held by Male Workers	848,388
Jobs held by Female Workers	859,000
Stores	16,470
Restaurants	5,165
Schools	1,982
Colleges and Universities	177
Recreation Facilities	3,045
Religious Sites	2,625
Other Opportunities	148,578

6 Accessibility Measurements

The impedance factor in the cumulative access (C_{ij}) could be time, distance, monetary cost, or other travel related expenses (Cui and Levinson, 2018*c*, El-Geneidy et al., 2016). As travel time is more widely used and the same time cost is experienced relatively equally by different demographic groups (Levinson and Wu, 2020), so, to perform accessibility measurements, travel time is used as a measure of travel cost.

To report the accessibility measurements, we initially focus on the dual access by auto, as

- Cui and Levinson (2019) stated that multi-activity dual access, weighted average travel time to reach n% of opportunities in a city, has more meaning than the multi-activity primal access, weighted-average number or percentage of reachable opportunities. One might argue that the primal access is easier to understand or thought more meaningful or intuitive than the dual, so we do compare the multi-activity primal and dual access later in Section 6.2;

- Access by transit has the same spatial distribution patterns and the same trends of

Table 2: Average Daily Activity Duration and Total Travel Time by Employment Status by Gender (Minutes)

	Male			Female			Total Workers	Total Non-Workers
	Worker	Non-Worker	Total	Worker	Non-Worker	Total		
Jobs	404	0	269	347	0	208	375	0
Stores	8	19	12	15	29	20	12	25
Restaurants	10	16	12	11	17	13	11	17
Schools	6	70	27	9	48	25	8	57
Colleges	3	8	5	3	5	4	3	6
Recreation Facilities	19	34	24	18	29	23	19	31
Religious Sites	5	10	6	5	15	9	5	13
Other Opportunities	27	59	38	37	65	48	32	62
Home	876	1,158	970	918	1,163	1,016	897	1,161
Travel Time	82	67	77	77	69	74	80	68
Total	1,440	1,440	1,440	1,440	1,440	1,440	1,440	1,440

population-weighted average values varying with different threshold settings as the access by auto, for both single- and multi-activity access using both primal and dual measures. The results for transit are all attached in the appendix, and not discussed in further detail here.

6.1 Accessibility to Different Types of Opportunities

Figure 3 summarizes the population-weighted dual access by auto to different types of opportunities, where total population is adopted regardless of employment status or gender. It shows the average travel time needed to reach a specific percentage of opportunities, so a higher value in the graph refers to a lower level of accessibility. Opportunity threshold negatively affects the dual access, for any opportunity types, that more time is needed to reach a higher percentage of opportunities.

The trendlines visualizing the dual access vs. opportunity threshold relationship can be well explained by cubic functions ($R^2s > 0.95$), see details in Figure 3, which, however,

except for colleges, do not have notable differences among activities. Reaching a higher percentage ($> 30\%$) of jobs is easier than the other types of opportunities but only to a small extent (1 to 3 minutes less). For opportunity threshold less than 30%, their dual access are almost the same (absolute differences are in 1 minute). Colleges, unlike other opportunities, are clustered in central Minneapolis, near the University of Minnesota, see Figure 2b. So travelers need time to reach the cluster first, which is around 20 minutes on average, and then can reach all the college opportunities in this cluster only with a little incrementally higher travel time.

Figure 4 visualizes the 5% dual accessibility matrices specific to different activity types, where the red colors represent a higher level of accessibility. Consistent with Figure 3, those accessibility matrices have similar spatial distribution patterns. Downtown areas, especially downtown Minneapolis, but also St. Paul, where more opportunities are centered, have the highest accessibility, and accessibility declines with distance from downtown. Figure 4e shows apparent differences from other maps due to the highly clustered college opportunities.

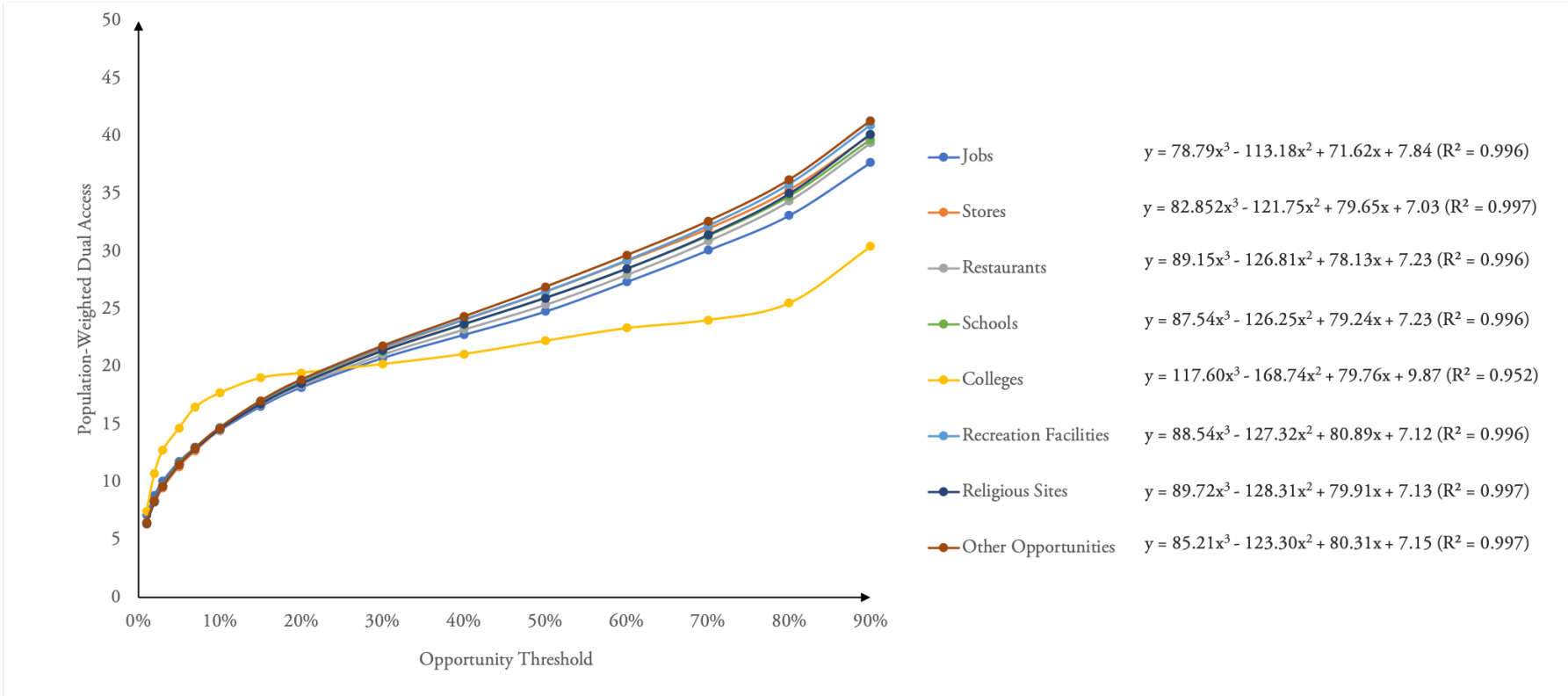

Figure 3: Population-Weighted Dual Accessibility to Different Types of Opportunities in Different Opportunity Thresholds in the Twin Cities by Auto (Lower is better) (Population in each census block, regardless of gender or employment status, is used as the weight here)

Figures/wac_5th_2.jpg

(a) Jobs

Figures/shopping_5th_2.jpg

(b) Stores

Figures/restaurants_5th_2.jpg

(c) Restaurants

Figures/school_5th.jpg

(d) Schools

Figures/college_5th_2.jpg

(e) Colleges

Figures/recreation_5th_2.jpg

(f) Recreation Facilities

Figures/religious_5th_2.jpg

(g) Religious Sites

Figures/others_5th_2.jpg

(h) Other Opportunities

Figure 4: 5% Dual Accessibility to Different Types of Opportunities in the Twin Cities by Auto

6.2 Multi-Activity Accessibility: Primal vs. Dual Measures

Figure 5 shows the multi-activity dual accessibility, using male workers as a representative, where only job opportunities held by male workers are considered, with different opportunity thresholds, by auto.

The general patterns are the same as the access to a single type of opportunity that blocks centered on the downtown area experience higher accessibility, as well as the ones close to primary highways. Opportunity threshold also has significant negative effects on the multi-activity dual access, as the shrinkage of the red color area happens with the increase of opportunity threshold from 1% (Figure 5a) to 50% (Figure 5f).

No evident conflicts are found between the primal and dual measures when they are used for multi-activity accessibility measurements, see Figure 6, that their spatial distributions share the same patterns. The arguments here are still that one measure might be easier or harder to understand and that one measure might be more or less suitable for specific project evaluations, as for the single-activity accessibility (Cui and Levinson, 2019).

Figures/male_worker_1th_2.jpg

(a) 1%

Figures/male_worker_5th_2.jpg

(b) 5%

Figures/male_worker_10th.jpg

(c) 10%

Figures/male_worker_20th_2.jpg

(d) 20%

Figures/male_worker_30th_2.jpg

(e) 30%

Figures/male_worker_50th_2.jpg

(f) 50%

Figure 5: Multi-Activity Dual Accessibility for Male Workers in Different Opportunity Thresholds for the Twin Cities by Auto

Figures/male_worker_5min_2.jpg

(a) 5 minutes

Figures/male_worker_10min_2.jpg

(b) 10 minutes

Figures/male_worker_15min.jpg

(c) 15 minutes

Figures/male_worker_20min_2.jpg

(d) 20 minutes

Figures/male_worker_30min_2.jpg

(e) 30 minutes

Figures/male_worker_50min_2.jpg

(f) 50 minutes

Figure 6: Multi-Activity Primal Accessibility for Male Workers in Different Time Thresholds for the Twin Cities by Auto

For a further comparison, Figure 7 plots the correlations between the primal and dual multi-activity accessibility, applying the value of each block as an observation, for each of the time and opportunity thresholds.

The correlation curves possess the same trends as the ones with respect to job opportunities only, presented in Cui and Levinson (2019). The coefficients are all negative as expected, since the primal and dual measures are reciprocal so a higher numerical value represents a higher level of accessibility for the primal but a lower level for the dual. The curves roughly give an inverted U-Shape that, for a certain dual accessibility matrix, its absolute correlation values rise first and then decline with the time threshold associated with the primal. The 30 and 40 minutes primal access are strongly correlated with the dual, no matter how we set the opportunity threshold.

The primal vs. dual correlations for male non-workers and female workers and non-workers have the same patterns.

6.3 Accessibility by Employment Status and by Gender

Multi-activity dual access, as shown in Figure 8, varies by employment status and by gender.

Figure 8a and Figure 8b compare the 5% multi-activity dual access of workers and non-workers, for males and females, respectively. For both, the brown colors, which represent the blocks with a relative higher access for workers, are spread out roughly as a radial pattern centered on downtown Minneapolis and downtown St. Paul, via some highways towards four directions: northeast (I-35W), northwest (I-94), southeast (MN-55), and southwest (MN-7). Blocks along part of I-494, parallel to the corridor connecting the two downtowns, also show advantages for workers.

These differences are mainly caused by job opportunities, which are offered to workers in particular. Around 80% of time among out-of-home activities (83.75% for males, 77.95% for females) are spent on working, so access to jobs dominates the final results, which,

however, are not the destinations non-workers count on. Hence, the clustering of the brown colored area can be easily explained by the fact that more job opportunities are located there, see Figure 2.

Comparatively, female workers join more non-work activities, so their worker vs. non-worker differences are not quite as severe as males; lighter colors are drawn in Figure 8b.

Figure 8c and Figure 8d compares males and females, where the brown colors identify the blocks with a relative higher access for males. Apparently, gendered variations, in terms of multi-activity accessibility, are less severe than worker vs. non-worker differences, as the colors turn lighter.

For workers, similar radial patterns can be found in Figure 8c but with more vague boundaries, which is mainly caused by the gender-specific job distributions, see Figure 9. Several clusters of dark blue areas, tagged out by the dotted circles in the figure, referring to a notable higher number of jobs for male workers, lead to the directions of the radial patterns; while dark red ones are more randomly located. But no evident clues show advantages of jobs for male workers in count over female workers, or the other way around. A paired T-test tells that the two samples have no significant differences (p-value=0.476), which explains why the boundaries cannot be clearly specified.

Gender-specific average share of activity duration can affect the male vs. female differences as well yet insignificantly. Although female workers do spend less time on working but more on other activities, comparing with male workers, the differences are minor, see Table 2. Also, dual access has no significant variations by activity type, except for attending colleges, which, however, is not gender-specific [1].

In addition, downtown areas do not show evident gender-specific advantages in terms of accessibility, such that only slight differences appear, in [-0.3, 0.3] minutes. It implies that workers, both males and females, who live in downtown areas, where many opportunities surround, experience high value of multi-activity accessibility.

[1] Accessibility to jobs are gender-specific, while accessibility to other opportunities are not.

For non-workers, the male vs. female differences of accessibility are quite moderate, as the only influence factor here is the gender-specific average share of activity duration, which, as explained, have less extent of effects.

Paired T-tests results, using each block as an observation, show that the worker vs. non-worker differences (for males, females, and all in total) and the male vs. females differences (for workers, non-workers, and all in total) of multi-activity dual access are all statistically significant at a 99% confidence level. This further demonstrates the imbalance of accessibility distributions considering the needs of attending multiple activities among different groups of travelers.

Table 3 summarizes the population-weighted average by employment status and by gender in different opportunity thresholds, where the corresponding population are applied as the weight. The number of workers, both males and females, are reported in the RAC table of LODES dataset, see details in Section 4.3. The number of non-workers are adjusted by census track level of unemployment rate measured by 2017 American Community Survey (ACS) 5-year estimates by sex by age by employment status for the population 16 years and over (The unemployment rate of a census track was applied for all contained census blocks).

Comparing the last two columns, non-workers have a higher dual access (a lower numerical value of required travel time), compared to workers, when opportunity threshold is lower than 15%, which is expected as access to neighboring opportunities, e.g., retail stores and food, contributes more for non-workers; while jobs that only contributes for workers are normally separated from residential areas. Workers do need less time to reach a higher percentage (>=15%) of opportunities, as jobs are more clustered, so it brings the lead to workers. Such patterns remain for gender-specific worker vs. non-worker comparisons.

For any given thresholds, females show advantages on reaching activities over males for workers, while opposite pattern occurs for non-workers. This indicates that, for fe-

male workers, their job opportunities are more friendly located. Females have a higher dual accessibility overall even when we consider workers and non-workers together. It is not surprising because working dominates the out-of-home activities, and other types of opportunities are not gender-specific so gendered variations for non-workers are minor.

Table 3: Population-Weighted Multi-Activity Dual Accessibility (minutes) in Different Opportunity Thresholds by Employment Status by Gender in the Twin Cities by Auto (Lower is better)

Threshold	Male			Female			Total Workers	Total Non-Workers
	Worker	Non-Worker	Total	Worker	Non-Worker	Total		
1%	7.10	6.35	6.95	6.83	6.50	6.82	7.04	6.37
2%	8.88	8.31	8.75	8.57	8.45	8.63	8.82	8.31
3%	10.11	9.61	9.99	9.80	9.76	9.89	10.07	9.60
5%	11.81	11.45	11.72	11.51	11.64	11.66	11.79	11.45
7%	13.06	12.84	12.99	12.78	13.06	12.97	13.05	12.85
10%	14.58	14.52	14.55	14.30	14.78	14.55	14.59	14.54
15%	16.69	16.71	16.67	16.36	17.03	16.66	16.69	16.74
20%	18.42	18.43	18.39	18.00	18.79	18.33	18.38	18.47
30%	21.04	21.18	21.03	20.53	21.60	20.95	20.97	21.24
40%	23.15	23.52	23.19	22.57	23.98	23.08	23.05	23.60
50%	25.30	25.89	25.38	24.64	26.36	25.20	25.14	25.98
60%	27.91	28.46	27.99	27.21	28.98	27.77	27.72	28.57
70%	30.67	31.27	30.76	29.96	31.84	30.55	30.48	31.41
80%	33.77	34.71	33.93	33.08	35.32	33.77	33.60	34.88
90%	38.42	39.70	38.63	37.76	40.34	38.54	38.27	39.88

7 Discussion and Conclusion

Instead of targeting at one opportunity or activity type or purpose of interest as many previous studies did for accessibility analysis, the concept of multi-activity accessibility is clarified in this paper, which combines multiple types of opportunities into a single aggregated access measure using appropriate weights, e.g., share of time spent at each activity.

The primal and dual measures of relative cumulative access were applied that calculated the percentage of opportunities that can be reached in a given cost threshold (the primal) or the travel cost required to reach a percentage of opportunities (the dual), considering the two measures are logically more suitable for different types of opportunities. We select the Minneapolis - St. Paul metropolitan region as the study area to implement the multi-activity accessibility evaluations and aim to solve how activity choice can affect opportunity, specifically for travelers in different groups by employment status by gender.

Multi-activity accessibility, for either primal or dual measure, has similar patterns as accessibility to any single type of opportunities, that blocks with relative higher accessibility are centered on downtown Minneapolis and downtown St. Paul, where more opportunities are located, or along with primary highways, for auto, or high frequent transit routes, for transit. Threshold significantly affects the multi-activity accessibility, which follows the rules of cumulative access that more opportunities are reachable with higher travel cost.

Multi-activity accessibility varies by employment status mainly due to the effects of access to jobs, which weights around 80% for workers but 0% for non-workers. Blocks showing advantages for workers are roughly distributed as a radial centered on the downtown area moving along highways, for both males and females, where more job opportunities are located. It somehow provides the evidence for the spatial separation of other types of opportunities from jobs, which is not surprising as occupational clustering have been confirmed (Benson, 2011) and are more likely to be away from residential areas (favoring decentralization) (Li et al., 2020); localized services, however, tend to be near home places more.

The gendered variations are less severe, which also have this radial pattern for workers, yet with vague boundaries, indicating that those are also the blocks with a relative higher access for male. Gender-specific distributions of job opportunities can explain the differences, but no clues show that male workers have advantages over female workers

considering the number of jobs in count, or the other way around. Moderate gendered differences can be found for non-workers, comparatively. The population-weighted average, however, tells that females experience a relative higher multi-activity accessibility, considering workers and non-workers in all.

Paired T-tests further demonstrate the significant differences between workers and non-workers, and males and females statistically. This implies the imbalance of accessibility distributions considering the needs of attending multiple activities among different groups of travelers. It can be further extended to employment status or gender inequity analysis to explore whether there are spatial barriers from origins to the desired destinations and to what extent from the perspective of accessibility to opportunities, the results of which can support policy-makers for relevant decision-makings.

Multi-activity accessibility is recommended for transport or land use project appraisals as a more comprehensive measure, except for cases having specific priority on one type of destinations, e.g., modeling unemployment rate. It has the potential to reorder the rankings of proposed investments as one might benefit partially on, say, access to jobs but cost more from others' aspects; the widely applied measures of just access to jobs would bias toward that one and might cause the wrong pick.

Multi-activity accessibility can be applied to model travel behavior, real estate prices, and economic productivity as well, with reference to those applications of single-activity accessibility. Many different types of opportunities are embedded so it might explain the travel behavior or the value of locations better than concerning one opportunity only, commonly seen as access to jobs or access to retail.

This analysis does not deal with the demand or the supply of opportunities regarding competition among travelers for opportunities, or differentiate within opportunity classes, e.g., high-educational workers vs. low-educational workers. If such data are available future studies should expand the multi-activity accessibility measure to consider competitive accessibility measures (Allen and Farber, 2020, Cheng and Bertolini,

2013, Merlin and Hu, 2017, Van Wee et al., 2001).

Note also that multi-activity accessibility should be sensitive to the weighting method used to sum over accessibility matrices regarding to different types of opportunities. Duration share of daily out-of-home time, which we choose in this study, is the most straightforward way to do so. Levinson and Wu (2020) also introduced some other methods, e.g., using the subjective priority assigned to each place to build the weighting schema and calculate the weighted average (Antunes et al., 2003), or using the Cobb-Douglas function, a multi-factor production function, rather than a simple weighted average, to combine opportunities. Future studies should test other weighting methods and compare the outputs systematically.

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Figures/primal-vs-dual-auto.png

Figure 7: Correlation between Primal (Percentage of Activities) and Dual (Travel Time in Minutes) Multi-Activity Access by Auto Specifically for Male Workers in the Twin Cities

Figures/dif_multi_male_w_nw_5th_2.jpg

(a) Male: Worker - Non-Worker

Figures/dif_multi_female_w_nw_5th.jpg

(b) Female: Worker - Non-Worker

Figures/dif_multi_male_female_w_nw_5th_1.jpg

(c) Worker: Male - Female

Figures/dif_multi_male_female_nw_5th_2.jpg

(d) Non-Worker: Male - Female

Figure 8: 5% Multi-Activity Dual Accessibility Changes by Employment Status by Gender for the Twin Cities by Auto

Figures/job-den-dif-male-female-highlight.jpg

Figure 9: Gender-Specific Distribution of Job Opportunities: Differences in Job Density (Male - Female)

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Appendix

Figure 10 - Figure 13 and Table 4 show the accessibility measurements by transit.

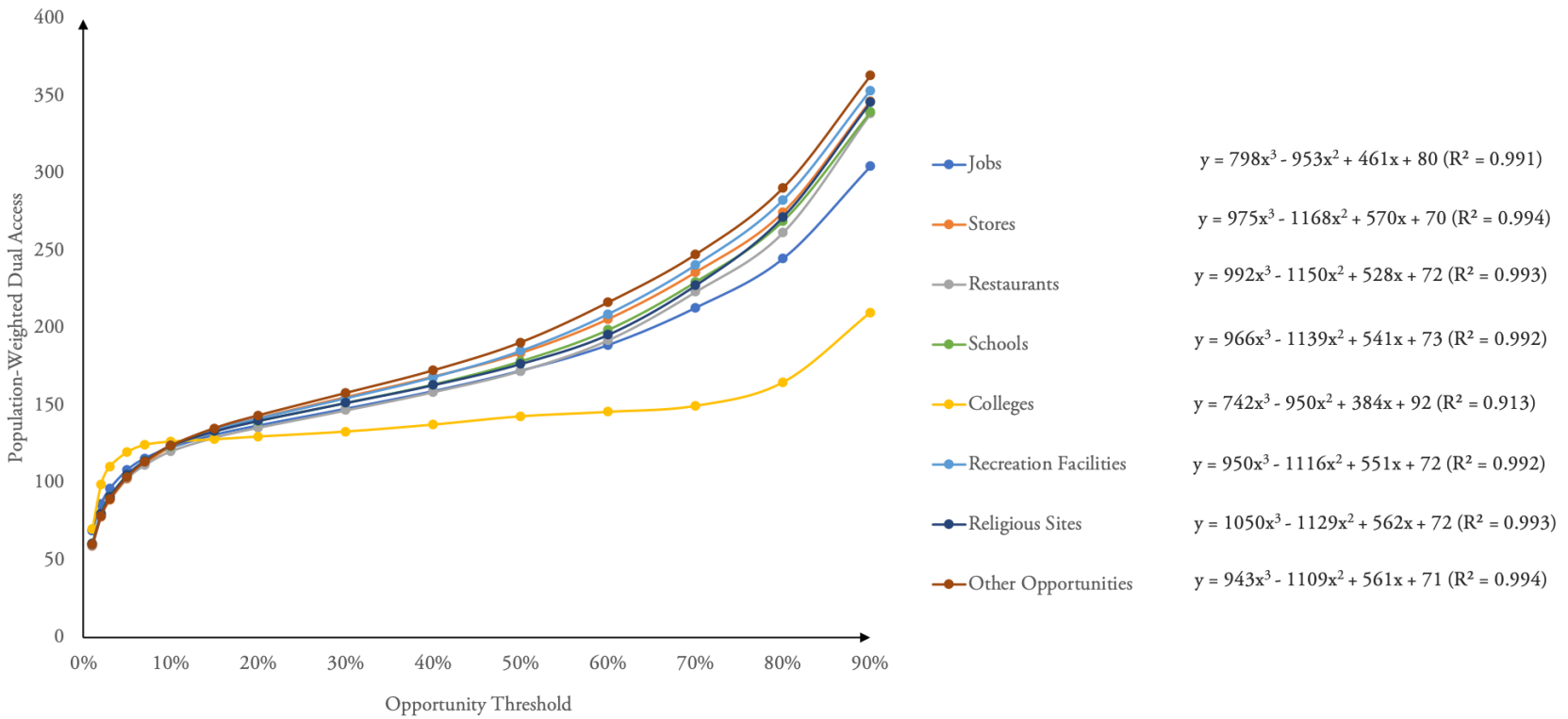

Figure 10: Population-Weighted Dual Accessibility to Different Types of Opportunities in Different Opportunity Thresholds in the Twin Cities by Transit

Table 4: Population-Weighted Multi-Activity Dual Accessibility (minutes) in Different Opportunity Thresholds by Employment Status by Gender in the Twin Cities by Transit (Lower is better)

Threshold	Male			Female			Total Workers	Total Non-Workers
	Worker	Non-Worker	Total	Worker	Non-Worker	Total		
1%	68.98	58.32	66.71	64.00	61.04	64.67	67.91	58.52
2%	86.46	77.32	84.29	80.48	80.31	82.07	85.43	77.21
3%	96.53	87.98	94.44	90.17	91.43	92.37	95.60	87.86
5%	108.90	100.97	106.94	101.93	105.33	105.03	108.09	100.98
7%	116.77	109.56	114.99	109.10	114.57	113.00	115.93	109.67
10%	124.57	118.77	123.21	116.17	124.71	121.00	123.56	119.04
15%	133.33	128.15	132.17	124.47	134.77	129.81	132.17	128.61
20%	139.79	135.22	138.73	130.55	142.07	136.20	138.43	135.80
30%	151.54	147.75	150.61	141.40	154.83	147.49	149.69	148.51
40%	163.85	160.58	163.06	152.72	167.81	159.17	161.42	161.44
50%	177.97	176.36	177.51	166.31	183.68	173.26	175.18	177.31
60%	195.80	198.40	196.13	183.99	205.87	191.99	192.91	199.58
70%	221.21	228.94	222.45	209.13	236.28	218.25	218.17	230.26
80%	254.10	269.39	256.73	243.72	276.83	254.11	251.66	270.98
90%	316.15	340.79	320.48	306.30	348.37	318.45	313.57	342.76

Figures/transit-multi-access-m-w-1th_2.jpg Figures/transit-multi-access-m-w-5th_2.jpg Figures/transit-multi-access-m-w-10th.jpg

(a) 1% (b) 5% (c) 10%

Figures/transit-multi-access-m-w-20th_2.jpg Figures/transit-multi-access-m-w-30th_2.jpg Figures/transit-multi-access-m-w-50th_2.jpg

(d) 20% (e) 30% (f) 50%

Figure 11: Multi-Activity Dual Accessibility for Male Workers in Different Opportunity Thresholds for the Twin Cities by Transit

Figures/transit-multi-dif-m-w-nw-5th_2.jpg

(a) Male: Worker - Non-Worker

Figures/transit-multi-dif-f-w-nw-5th.jpg

(b) Female: Worker - Non-Worker

Figures/transit-multi-dif-m-f-w-5th_2.jpg

(c) Worker: Male - Female

Figures/transit-multi-dif-m-f-nw-5th_2.jpg

(d) Non-Worker: Male - Female

Figure 12: Multi-Activity Dual Accessibility Changes by Employment Status by Gender for the Twin Cities by Transit

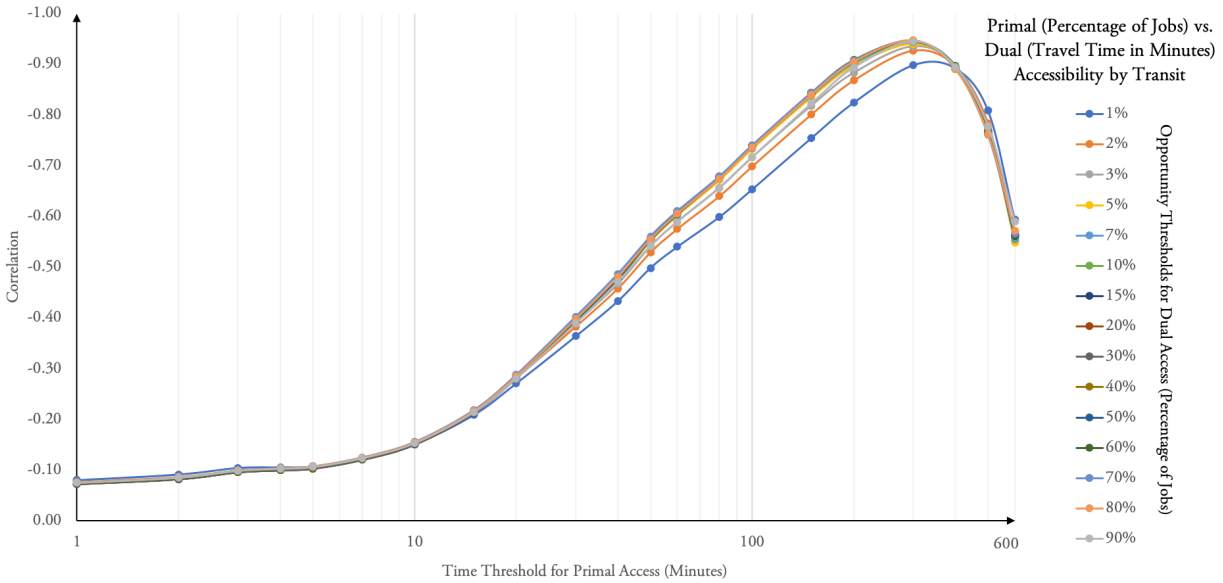

Figure 13: Correlation between Primal (Percentage of Jobs) and Dual (Travel Time in Minutes) Access by Transit Specifically for Male Workers in the Twin Cities