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Measuring full cost accessibility by auto

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Abstract: Traditionally accessibility has been analyzed from the perspective of the mean or expected travel time, which fails to capture the full cost, especially the external cost, of travel. The full cost accessibility (FCA) framework, proposed by Cui and Levinson (2018b), provides a theoretical basis to fill the gap, that combines temporal, monetary, and non-monetary internal and external travel costs into accessibility evaluations, considering the time cost, crash cost, emission cost, and monetary cost. This paper extends the FCA framework and measures the full cost accessibility by auto for the Minneapolis - St. Paul Metropolitan area, demonstrating the practicality of the FCA framework on real networks.

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1 Introduction

Accessibility measures the ability to reach valued destinations. It is widely accepted that accessibility is a reliable tool to evaluate the performance of transport systems, and that a higher accessibility indicates a more effective interaction between the transport network and land-use (Cervero *et al.* 1997; Cheng and Bertolini 2013a; El-Geneidy and Levinson 2006; Geurs and Van Wee 2004; Hansen 1959; Levine *et al.* 2017; Levinson 1998; Martellato and Nijkamp 1998; Owen and Levinson 2012; Páez *et al.* 2012). Traditional accessibility measures use travel time to represent the cost of travel. While time is a determinant cost for travelers' choice of mode, route, or departure time, it neglects other internal cost factors, as well as the external costs of travel. Few applications include monetary costs, such as transit fares or tolls (El-Geneidy *et al.* 2016). Utility-based accessibility, typically derived from travel demand choice models, may include such internal costs, but cannot be directly measured, and does not include external costs that lie outside an individual's utility function.

Cui and Levinson (2018b) developed a full cost accessibility (FCA) framework, which incorporates both internal and external costs of time, safety, emission, and money, into accessibility analysis. It can be used to evaluate transport and land use more comprehensively, as the full cost accessibility has the potential to change the rankings of transport investments and land developments, compared to the time-based (or time-and-money-based) accessibility evaluations, by incorporating additional cost factors, especially the cost of externalities. Many projects may be beneficial for individual travelers but present society with the expense of greater externalities. FCA can be applied to monitor the changes on transport services or land-use from the aspect of a specific cost component or the combined internal and full costs of travel.

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The FCA framework was implemented in a toy network as a proof-of-concept (Cui and Levinson 2018b), which illustrates its applications based on basic cost functions and plausible assumptions. However, a real-world implementation of the FCA framework remains to be done. This paper, focusing on auto travel, extends and applies the FCA framework to the Minneapolis - St. Paul (Twin Cities) metropolitan area with more sophisticated cost estimates, which aims to, first, further demonstrate the practicality of the FCA framework for real-world applications, and, second, identify the differences and correlations between the time-based, internal cost, and full cost accessibilities. Job accessibility is measured in this study.

The review of the FCA framework, data collection, FCA measurements, and the conclusion are in Section 2 - 7 in turn.

2 FCA Framework

The FCA framework comprises three stages: analyzing the travel cost, evaluating new path types, and performing FCA measurements, shown in Figure 1.

The cost analysis, at first, aims to estimate the internal and external costs for each cost component, and combines them into total internal, external, and full cost of travel. Cui and Levinson (2018b) defined the costs for each single cost component, summarized in the blue dashed box in Figure 1, based on which Cui and Levinson (2019) proposed the rules of adding all the single cost components, to avoid the double counting problem, for measuring the internal and full costs of travel. The expected output of this travel cost analysis is to have a comprehensive full cost estimate for each link segment on the road network, accounting for link properties, such as geometry and traffic.

One specific path type was proposed for each single cost component and their composite. It finds the optimal route with the minimum cumulative cost from the perspective of the corresponding travel cost. For instance, the lowest internal cost path refers to the route with the minimum internal cost on-road; while the lowest full cost path has the lowest full cost of travel. The cumulative travel costs along these path types provide the inputs for accessibility calculations.

Many combinations of paths and considered costs are possible, as shown in Table 1. Full cost accessibility, as the main output of this study, focuses on the full cost along with the lowest full cost path (⋆) (Section 5). For accessibility difference assessment, in addition, we focus on the first row (•) to explore the accessibility loss if travelers ignore other internal cost factors as well as the external cost, likely in the absence of pricing (Section 6.2), and the diagonal (∘) to measure the extent, to which we overestimate the job accessibility without knowing those costs (Section 6.1). If the analyst were only interested in traditional accessibility but pricing was in place to internalize full costs, then the last row makes sense. The implicit behavioral assumption is that travelers consider the same costs as the analysts, which identifies the destinations travelers can reach, rather than the ones they actually reach, with the restriction of a specific cost category.

Table 1: Path and Travel Cost Consideration for Accessibility Calculations

		Analyst Interest		
		Time	Internal Cost	Full Cost
Traveler Behavior	Shortest Travel Time Path	∘ •	•	•
	Internal Cost Minimizing		∘	
	Full Cost Minimizing			⋆ ∘

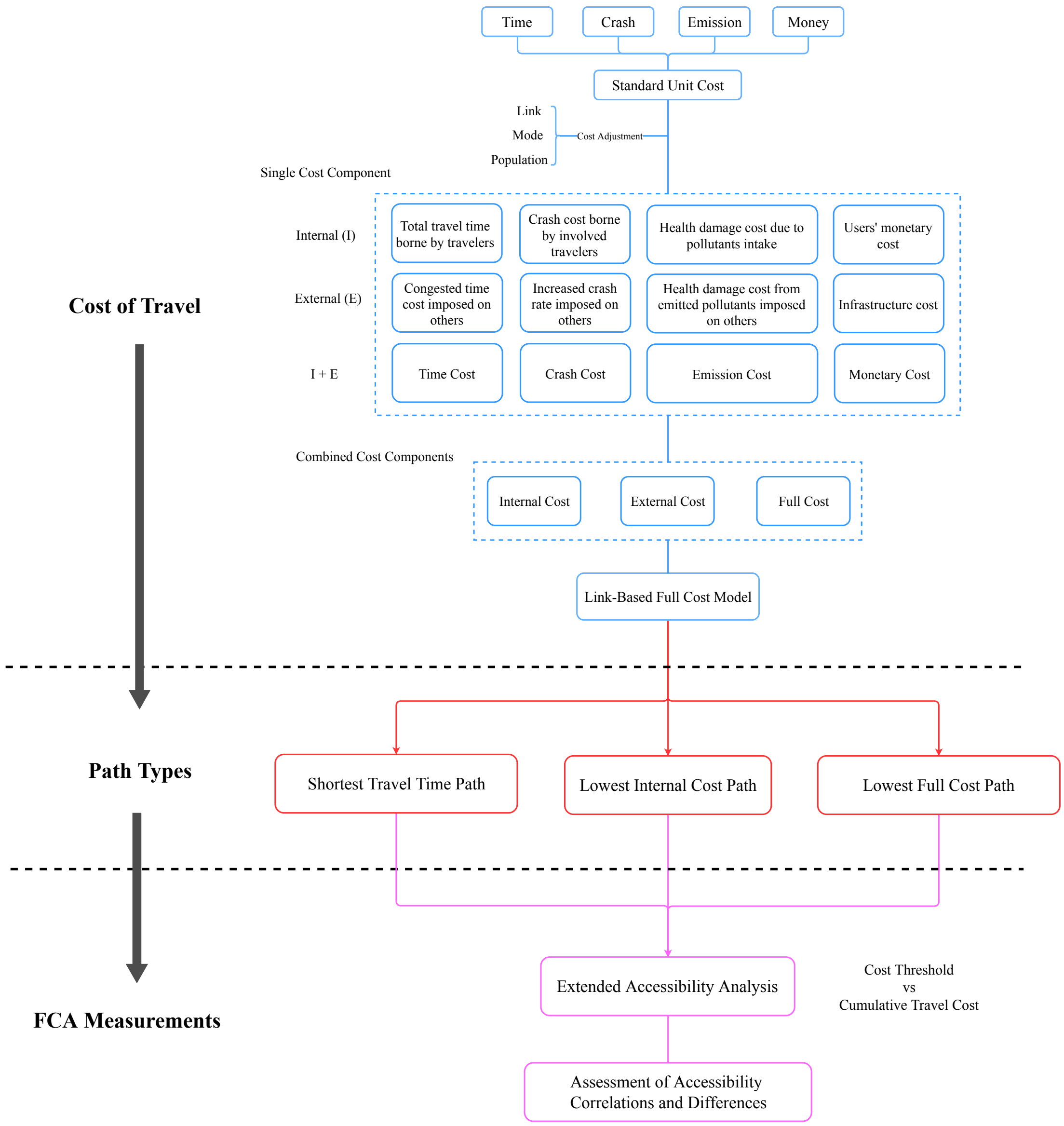


Figure 1: Full Cost Accessibility (FCA) Framework that Incorporates Both Internal and External Costs of Time, Safety, Emission, and Money into Accessibility Analysis

A cumulative opportunity measure for accessibility calculations in FCA analysis is employed here, which counts the number of reachable opportunities within a given cost threshold (Vickerman 1974; Wachs and Kumagai 1973). For auto travel, it is written as,

$$A_{i,c,T_c} = \sum_j O_j f(C_{ij,c,P_c}) \tag{1}$$

$$f(C_{ij,c,P_c}) = \begin{cases} 1 & \text{if } C_{ij,c,P_c} \leq T_c \\ 0 & \text{if } C_{ij,c,P_c} > T_c \end{cases} \tag{2}$$

Where:

A_{i,c,T_c}: the accessibility of origin i for cost category c by auto with the corresponding cost threshold T_c;

O_j: the number of opportunities at destination j, for job accessibility, it refers to the number of jobs;

C_{ij,c,P_c}: the cost between origin i and destination j for cost category c , which is accumulated along the path P_c, the optimal path from the aspect of cost category c.

Cost-weighted accessibility, with reference to the time-weighted measure, proposed by Anderson *et al.* (2013), combines different cost thresholds into a complete measure. It applies a decay factor showing that accessibility decreases with a higher cost from the origin (Hansen 1959), which mitigates the artificial distinctions caused by the binary cost function of the cumulative opportunity measure.

$$A_{i,w_{\tau_c}} = \sum_{\tau_c \in T_c} (A_{i,\tau_{c,n}} - A_{i,\tau_{c,n-1}}) f(\tau_{c,n}) \quad (3)$$

subject to:

τ_c is in ascending order.

Where:

$A_{i,w_{\tau_c}}$: cost-weighted accessibility of origin i;

$\tau_{c,n}$: the nth cost threshold in the set T_c;

$f(\tau_{c,n})$: travel cost decay function.

3 Data Collection

The Twin Cities metropolitan region, named after the two largest cities in Minnesota, Minneapolis and St. Paul, shown in Figure 2, is selected as the study area. The whole region has a total area of 7,704 km^2, including 631 km^2 of water (source: Tiger/Line Census Geography, US Census Bureau), and a population of 3,075,563 (source: 2017 Population Estimates, Census Data, Metropolitan Council).

For FCA measurements, several data sources are applied in this study, which are described as follows,

- **TomTom Road Network**
  TomTom road network was acquired from the Metropolitan Council of the Twin Cities, which has licensed the data (TomTom International BV 2013). The network covers 48,000 links in the Twin Cities metro area and is formatted as a GIS shapefile containing the geographical information of the roadways. It can be joined with the travel cost data, which allows us to search for the optimal paths for each cost category and to measure the accumulated travel cost along the paths, using the ArcGIS network analyst tool.
- **Transportation Analysis Zone**
  Accessibility is measured at the Transportation Analysis Zone (TAZ) level, using a system developed by the Metropolitan Council. TAZs are contained in a polygon shapefile showing the zone boundaries, aggregations, and household and employment information for each zone. In the Twin Cities metro area, there are 2,485 TAZs. For accessibility calculations, the centroids of each TAZ were extracted as origins and destinations to calculate the travel cost matrices.
- **LEHD Data**
  The LEHD Origin-Destination Employment Statistics (LODES), in which LEHD stands for Longitudinal Employment Household Dynamics, was obtained from the US Census Bureau (2013). The Origin-Destination (OD) table tracks the number of home-to-work trips at the census block level, which is used for the calibration of the cost decay functions, explained later in Section 5. The employment data (total number of jobs) were used to represent the job opportunities, and assigned to each TAZ centroid. Figure 2 visualizes the spatial distribution of the job density in the Twin Cities.

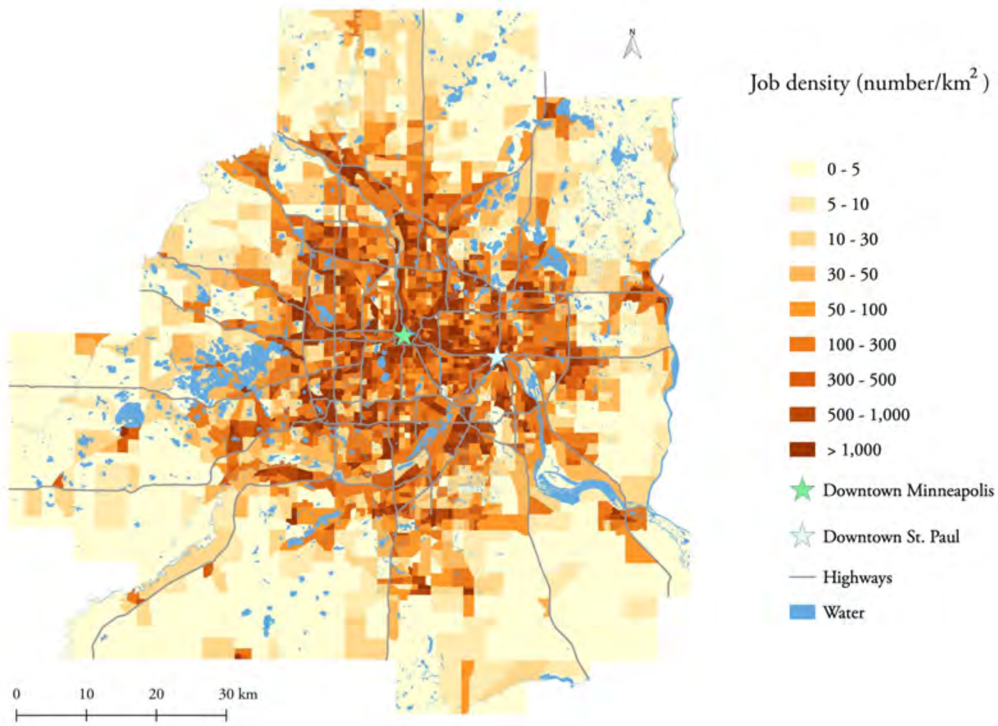


Figure 2: Job Density in the Minneapolis - St. Paul Metropolitan Area (number/km^2)

4 Travel Cost Estimates

Link-based cost estimates for each cost component as well as the combined internal and full costs were conducted by us in a separate analysis for the Twin Cities metro area (Cui and Levinson 2019), which we briefly summarize.

TomTom provides speed profiles for each link segment on the Twin Cities road network, using calculated on-road travel time. Negative Binomial Models were applied to estimate the expected crash frequency considering all types of crashes, with variables of AADT, segment length, speed, speed variance, and road classifications, based on the crash records from 2003 to 2014, collected from the Minnesota Department of Transportation (MnDOT). An ordered-probit model was then used to identify the crash severity giving the probability of each type of crashes. For modeling the emission cost, we conducted project-level of MOVES (Motor Vehicle Emission Simulator) simulations to estimate the quantity of localized air pollutants of each link (US Environmental Protection Agency 2016), requiring the inputs of link properties (e.g., length, flow, speed, road grade), link source type (composition of link traffic flow by vehicle type), meteorology, and fuel type. RLINE model, which is a dispersion modeling tool developed for concentration simulations for line type emission sources specifically (Snyder *et al.* 2013), was then used to estimate the on-road and off-road vehicle emission concentrations using the output of the MOVES simulations, as well as other parameters like wind speed and wind direction. The user monetary cost covers many factors. Some of them are distance-based cost, e.g., fuel cost (also determined by driving speed), vehicle maintenance and repair cost, allowing to be assigned on each link, while some are time-based cost, e.g., time-based vehicle depreciation cost, insurance. Infrastructure cost was estimated based on models of total infrastructure expenditures on price inputs (labors and materials), travel-related inputs, and network variables specific to road classifications (Levinson and Gillen 1998). The unit costs we used to monetize the travel time, expected crash rate, emissions, as well as the unit user monetary costs are described in Table 2 (Cui 2018).

Table 2: Unit Cost Used for Travel Cost Estimates

Cost Components	Classifications		Unit Cost
Time Cost (Minnesota Department of Transportation 2015)	Travel Time	-	\$18.30/hour
Crash Cost (Blincoe *et al.* 2015)	Fatal Crashes	Cost per Injuried Person	\$9,134,786
		Cost per Crashing Vehicle	\$10,712
	Incapacitating Injury	Cost per Injuried Person	\$997,688
		Cost per Crashing Vehicle	\$3,518
	Non-incapacitating Injury	Cost per Injuried Person	\$273,544
		Cost per Crashing Vehicle	\$2,465
	Complaint of Pain	Cost per Injuried Person	\$125,360
		Cost per Crashing Vehicle	\$2,407
	Property-damage Only	Cost per Injuried Person	\$40,673
		Cost per Crashing Vehicle	\$1,624
Emission Cost (McGarity 2012)	PM	Intake Emission Cost	\$30,650/g
	SO2	Intake Emission Cost	\$3,960/g
	Nox	Intake Emission Cost	\$670/g
	CO2	Greenhouse Gas Emission Cost	\$22/ton
Monetary Cost (American Automobile Association 2015; Barnes and Langworthy 2004; IHS Automotive 2014; US Department of Labor, Bureau of Labor Statistics 2015; US Energy Information Administration 2018)	Fuel Cost	Midgrade Fuel Cost in 2014	\$0.888/liter
	Maintenance and Repair Costs	City Driving Cost	3.11/veh-km
		Highway Driving Cost	2.74/veh-km
	Distance-based Depreciation Cost	City Driving Cost	4.83/veh-km
		Highway Driving Cost	4.11/veh-km
	Vehicle Finance Charges	-	\$204/veh-year
	Vehicle Insurance	-	\$1,162/veh-year
	Time-based Depreciation Cost	-	\$2,481/veh-year
	Vehicle Registration Fee	-	\$46.50/veh-year

Table 3: The Mean and Standard Deviation of Link-based Cost Estimates Among All the Links on the Twin Cities Road Network for Each Cost Component ($/veh-km)

	Single Cost Components								Combined Cost		Full Cost	
	Time		Safety		Emission		Money					
	Avg	S.D.	Avg	S.D.	Avg	S.D.	Avg	S.D.	Avg	S.D.	Avg	S.D.
Internal	0.382	0.289	0.040	0.063	0.001	0.001	0.219	0.063	0.642	0.365	0.678	0.360
External	-	-	0.023	0.022	0.019	0.035	0.036	0.023	-	-		

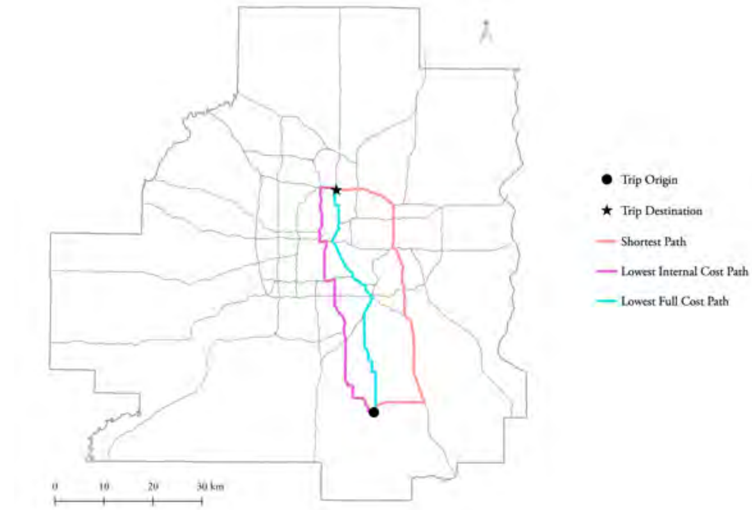
Table 3 summarizes the cost estimates and shows the mean and standard deviation among all the links. These estimates are consistent with our expectation. Time is the dominant cost component, which accounts for more than 50% of the total for both combined internal and full costs. User monetary cost shares a large percentage as well, around 30%. While, comparatively, other cost factors, safety, emission, and external monetary costs, are much lower than the time and user monetary costs. It is also shown that the average combined internal cost of travel is $0.642/veh-km, while the average full cost is approximately $0.678/veh-km, which implies a $0.036/veh-km non-internalized external cost. This value is small, and depends on conditions, definitions, and assumptions, but implies the fact that failing to count it could result in biased investment that overestimates the received benefit.

The data are displayed in a shapefile on the basis of the TomTom road network, showing the travel costs when road users drive on different links. Figure 3 gives an example visualizing the shortest travel time path, lowest internal cost path, and lowest full cost path of three actual OD (home-to-work) pairs in the Twin Cities, with respect to three different scenarios, based on the link-based travel cost estimates. We say three routes are different if any of the two routes use distinct links for 90% or more of the total trip length, see Figure 3(a), which counts 114 (out of 1,180,600) OD pairs in the Twin Cities. 622,612 (out of 1,180,600) OD pairs have three overlapping routes, see Figure 3(c), for which any of the two routes share the same links for 90% or more of the total trip length. The rest of them (557,844 out of 1,180,600) partially overlap, as Figure 3(b) shows.

Note, based on the rigorous framework to avoid double-counting, costs that might in some analyses be considered as external costs, like congestion, are considered internal here, as the total time of travel is considered in the internal cost of each traveler, even though it is imposed by others. This analysis is concerned with who bears the cost, rather than who imposes it. More than half of crash costs are borne by the vehicles involved in crashes (without attributing blame for between vehicle crashes), so the external cost is associated with collisions that injure or kill non-motorists. Monetary costs include the cost of fuel as well as fuel taxes. While it is well known that fuel taxes do not cover the full cost of infrastructure, they could, and if they did would only cause monetary costs to rise slightly. Environmental costs are thus the primary externality, as only a small share are borne by travelers directly. The theory of marginal cost road pricing argues external costs such as delay should be monetized and imposed on those causing the delay (Hau 2005), and a similar logic applies to pollution and other externalities.

5 Full Cost Accessibility Measurement

Figures 4(b) - 4(g) show the full cost accessibility basd on the lowest full cost path at thresholds from $3.05 to $18.30, which is equivalent to a 10 minutes to 60 minutes time cost (at $18.30 per hour value



(a) Three Routes Differ (represents 114 out of 1,180,600 OD pairs)

(b) Three Routes Partially Overlap (represents 557,844 out of 1,180,600 OD pairs)

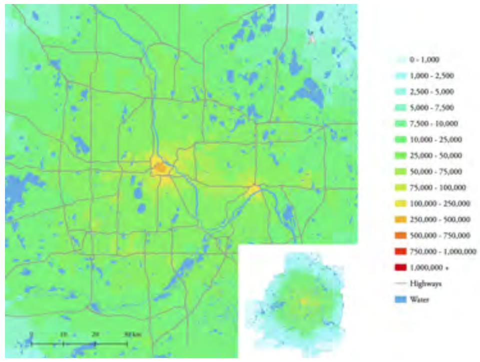
(c) Three Routes Overlap (represents 622,612 out of 1,180,600 OD pairs)

Figure 3: Illustration of the Shortest Travel Time Path, Lowest Internal Cost Path, and Lowest Full Cost Path Based on the Link-Based Travel Cost Estimates for Accessibility Calculations

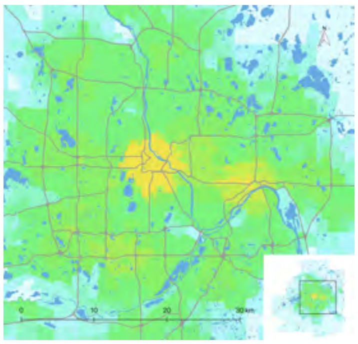
of time [1]). Its basic spatial distribution patterns are expected, and similar to the traditional time-based ones (Cui and Levinson 2018a).

For a specific cost threshold, say a \$9.15 full cost threshold (Figure 4(d)), the zones with higher job accessibility are centered on downtown Minneapolis, which is visualized with the red color. With the increase of distance to the downtown area, the colors change gradually from red to light blue, which illustrates the decline of job accessibility. Exurban zones have the lowest job accessibility. This condition comports with our understanding of the region, since the number of jobs accessible in and around the downtown area are relatively higher than in the far reaches.

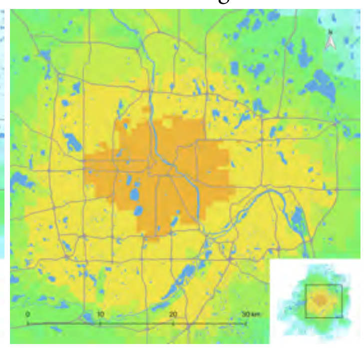
[1] The value is adapted from US Department of Transportation's estimates on valuation of travel time in economic analysis with Minnesota earnings rates (Minnesota Department of Transportation 2015). The mean hourly wage in Minnesota for all occupations is \$25.35 in 2017 (Source: Occupational Employment Statistics data, US Bureau of Labor Statistics)



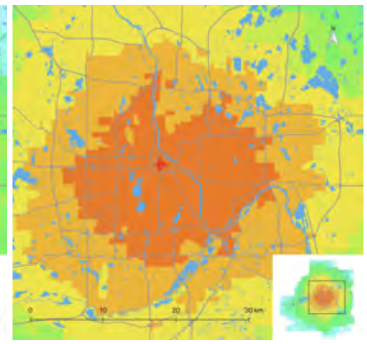
(a) Cost-Weighted



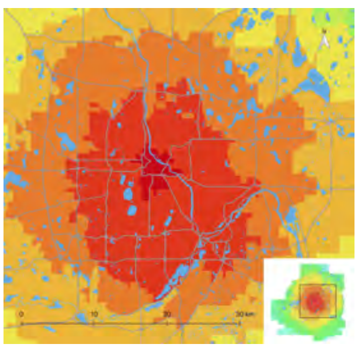
(b) $3.05



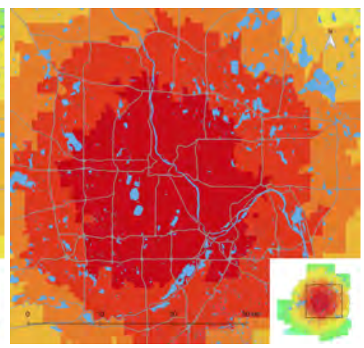
(c) $6.10



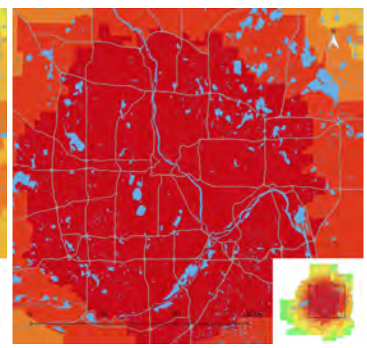
(d) $9.15



(e) $12.20



(f) $15.25



(g) $18.30

Figure 4: Full Cost Accessibility: Cost-Weighed Job Accessibility and Job Accessibility with Different Full Cost Thresholds [$3.05 to $18.30], Based on the Lowest Full Cost Path by Auto

With different cost thresholds, the results of job accessibility change significantly. We see that an expansion of the red area, which stands for the higher accessibility, centering on the downtown, occurs with the increase of time threshold. It is obvious that most of the Twin Cities region can reach most jobs when the full time threshold was set as $18.30.

Figure 5 summarizes the correlations among the time-based, internal cost, and full cost accessibilities at alternative cost thresholds. It is obvious that the internal and full cost accessibilities are highly correlated, more than 0.95, for all cost thresholds. It is understandable as the internal cost is fully covered by the full cost and the non-internalized external cost is only $0.04/veh-km, which does not affect the difference between the lowest internal cost path and the lowest full cost path in most cases.

In contrast, the time-based vs. internal cost accessibility show a lower correlation, which is expected since, even though time is the dominant cost, it does neglect the other 40% of the internal cost. The correlation between the time-based vs. full cost accessibility is even lower because of the additional $0.04/veh-km of external cost. More importantly, correlations of time-based vs. internal cost accessibility and time-based vs. full cost accessibility are sensitive to the cost thresholds, which

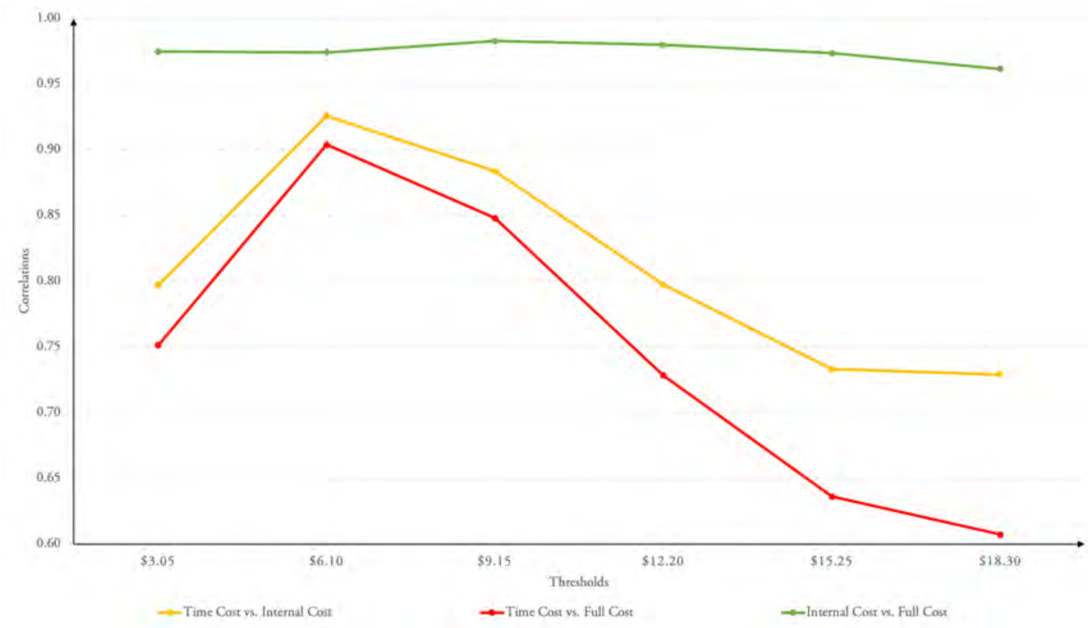


Figure 5: Correlations among Time-based, Internal Cost, and Full Cost Accessibilities with the Corresponding Cost Threshold [$3.05 to $18.30]

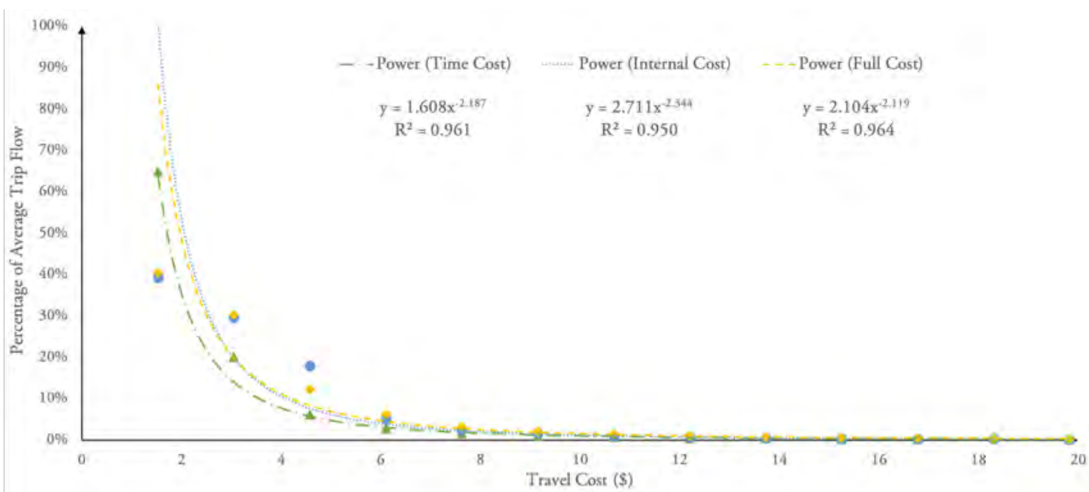


Figure 6: Cost Decay Function Calibrations for Time Cost, Internal Cost, and Full Cost of Travel

reach a maximum with a $6.10 (or 20 minutes) threshold and a minimum with a $18.30 (60 minutes) threshold. It demonstrates that the full cost accessibility has the potential to change the rankings of transport investments and land developments, as a higher time-based accessibility is not necessarily associated with a correspondingly higher full cost accessibility.

To measure the cost-weighted job accessibility, we count the percentage of average trip flow in each cost category, e.g., $0 - $1 or $1 - $2, where trip flow refers to the number of trips divided by the number of opportunities for an origin in a cost category, using the LEHD OD table. On that basis, we fit the time cost, internal cost, and full cost decay functions for auto travel to work, see Figure 6 (exponential, power, and natural log formats of functions are tested, but we show the ones with the best fit).

Applying the corresponding decay function, Figure 4(a) displays the cost-weighted full cost accessibility, which implies the same spatial distribution patterns as the accessibility with specific cost thresholds.

6 Accessibility Difference Assessment

6.1 Path and Travel Cost Consideration on the Diagonal

This section compares the accessibility with the combinations of path and considered cost on the diagonal of Table 1 and measures the extent that we overestimate the job accessibility without knowing the full cost of travel.

Figure 7 visualizes the time-based vs. full cost accessibility differences (time - full) showing the spatial distributions. It is clear that more severe differences happen around downtown Minneapolis for the cost-weighted result, see Figure 7(a), or when a lower cost threshold is selected, see Figure 7(b). At \$18.30, a hole with a lighter color, which represents a smaller change, appears in Figure 7(g). Those places can reach most of the job opportunities in the Twin Cities area in \$18.30 no matter which cost is considered.

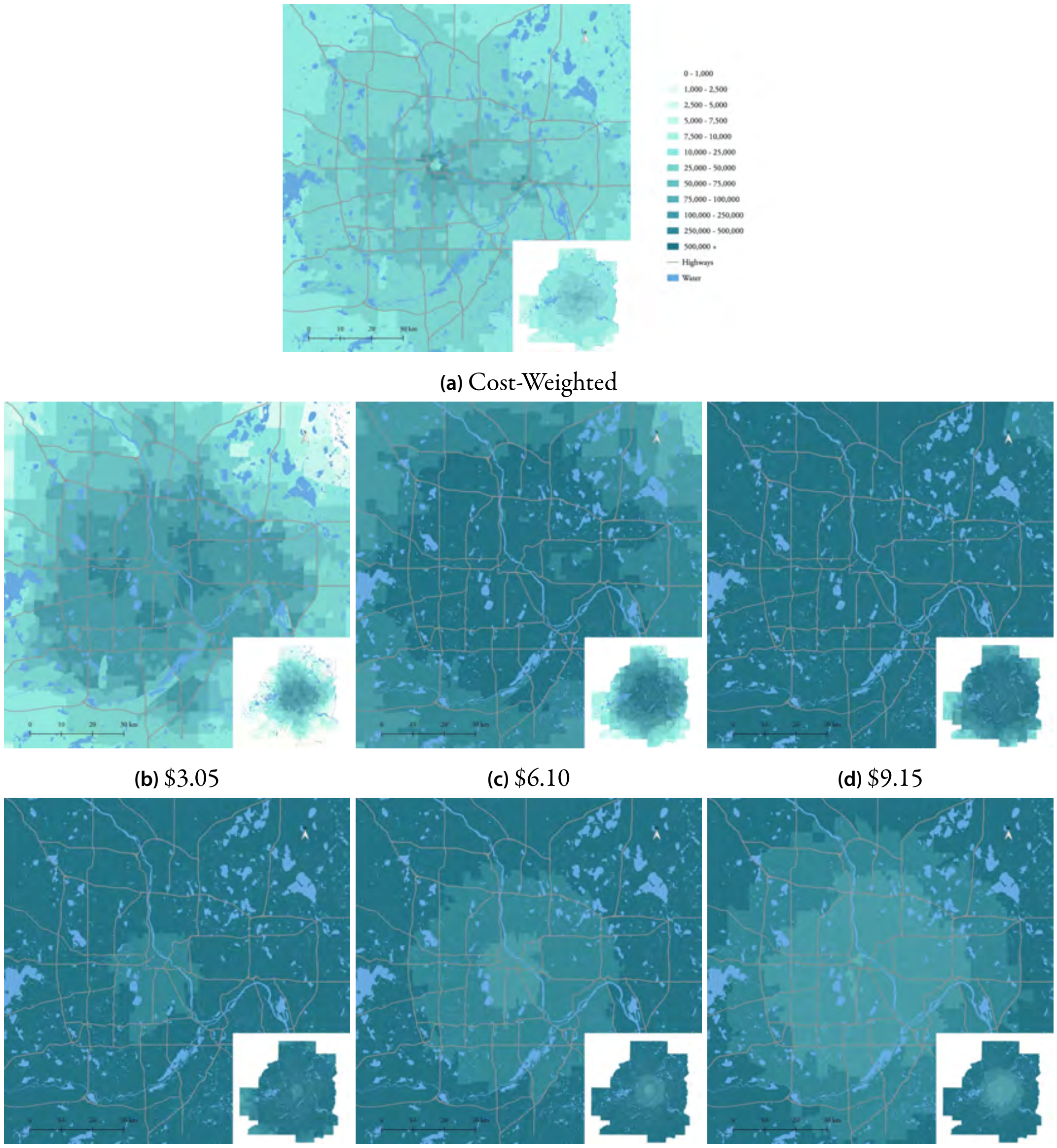
To explain the patterns better, Table 4 shows the regression results of the differences on the Euclidean distance to downtown Minneapolis (D_{MN}) and downtown St. Paul (D_{SP}), in which the quadratic terms (D^2_{MN} and D^2_{SP}) are also included (the Euclidean distance to the nearest highway and the number of low-income, mid-income, and high-income workers are tested as well, but do not have significant effects.). It illustrates that the Euclidean distances to downtown areas explain the differences very well that the adjusted R^2s are around 0.8 or more varying by cost threshold, while the adjusted R^2 for the cost-weighted accessibility differences is slightly lower. The variables are mostly statistically significant, except for D_{SP}, when it describes the \$9.15 accessibility differences.

For downtown Minneapolis, the coefficient of D_{MN} is negative and that of D^2_{MN} is positive when the cost threshold is no larger than \$6.10. It implies that the Euclidean distance to downtown Minneapolis has a varying effect on the accessibility differences, which decreases before the turning point and then increases. The turning points are 43km and 135km, respectively, for \$3.05 and \$6.10 cost thresholds. In the Twin Cities, the maximum distance among all TAZs to downtown Minneapolis is 64km, 94% of TAZs are nearer than 43km to downtown. It seems reasonable that we regard the effect as negative for the time-based vs. full cost accessibility differences with a lower cost threshold. The cost-weighted accessibility differences show the same patterns and have a turning point at 44km.

While the signs of D_{MN} and D^2_{MN} flip the other way around when a higher threshold is set, which indicates that the differences increase before the turning points and then decrease. The turning points are 17 km, 31 km, 55 km for \$9.15, \$12.20, and \$15.25 cost thresholds, correspondingly. In \$18.30, a longer distance to downtown Minneapolis would have a more severe difference, as the signs of both D_{MN} and D^2_{MN} are positive. Similar results exist for D_{SP} and D^2_{SP}.

The regression results, similar to Figure 7, illustrate that the greatest differences occur in the downtown areas first and expand with the increase of the ring's radius towards the suburban and exurban areas.

Comparatively, time-based accessibility exceeds full cost accessibility since the full cost covers the time cost, as Figure 7 shows that all the changes are positive. The differences here imply the magnitude of bias of accessibility provided when non-time travel costs are excluded from project evaluations. This has important consequences when ranking transport or land use projects that require public investment.



(a) Cost-Weighted

(b) \$3.05 **(c)** \$6.10 **(d)** \$9.15

(e) \$12.20 **(f)** \$15.25 **(g)** \$18.30

Figure 7: Differences between the Time-Based and Full Cost Accessibilities based on the Cost-Weighted Results and with the Corresponding Cost Thresholds [\$3.05 to \$18.30] (Time-based Accessibility - Full Cost Accessibility)

Table 4: Regression of the Time-Based vs. Full Cost Accessibility Differences on the Euclidean Distance to Downtown Minneapolis and Downtown St. Paul

	\$3.05		\$6.10		\$9.15		\$12.20		\$15.25		\$18.30		Cost-Weighted	
	Est	Signif.	Est	Signif.	Est	Signif.	Est	Signif.	Est	Signif.	Est	Signif.	Est	Signif.
Intercept	2.86E+05	***	8.77E+05	***	6.59E+05	***	8.70E+04	***	-1.78E+05	***	-1.69E+05	***	9.25E+04	***
D_{MN}	-1.15E+01	***	-1.96E+01	***	1.96E+01	***	4.86E+01	***	4.07E+01	***	2.02E+01	***	-3.09E+00	***
D_{MN}^2	1.32E-04	***	7.23E-05	***	-5.83E-04	***	-7.89E-04	***	-3.68E-04	***	1.11E-04	***	3.48E-05	***
D_{SP}	-1.97E+00	***	-6.20E+00	***	-5.87E-01		1.08E+01	***	1.49E+01	***	1.12E+01	***	-5.59E-01	***
D_{SP}^2	2.09E-05	***	7.18E-05	***	-2.19E-05	*	-1.90E-04	***	-2.24E-04	***	-1.43E-04	***	4.69E-06	***
Adj R^2	0.800		0.878		0.796		0.829		0.900		0.930		0.756	

*** p-value<0.001, ** p-value<0.01, * p-value<0.05, . p-value <0.1

6.2 Path and Travel Cost Consideration on the Row of the Shortest Travel Time Path

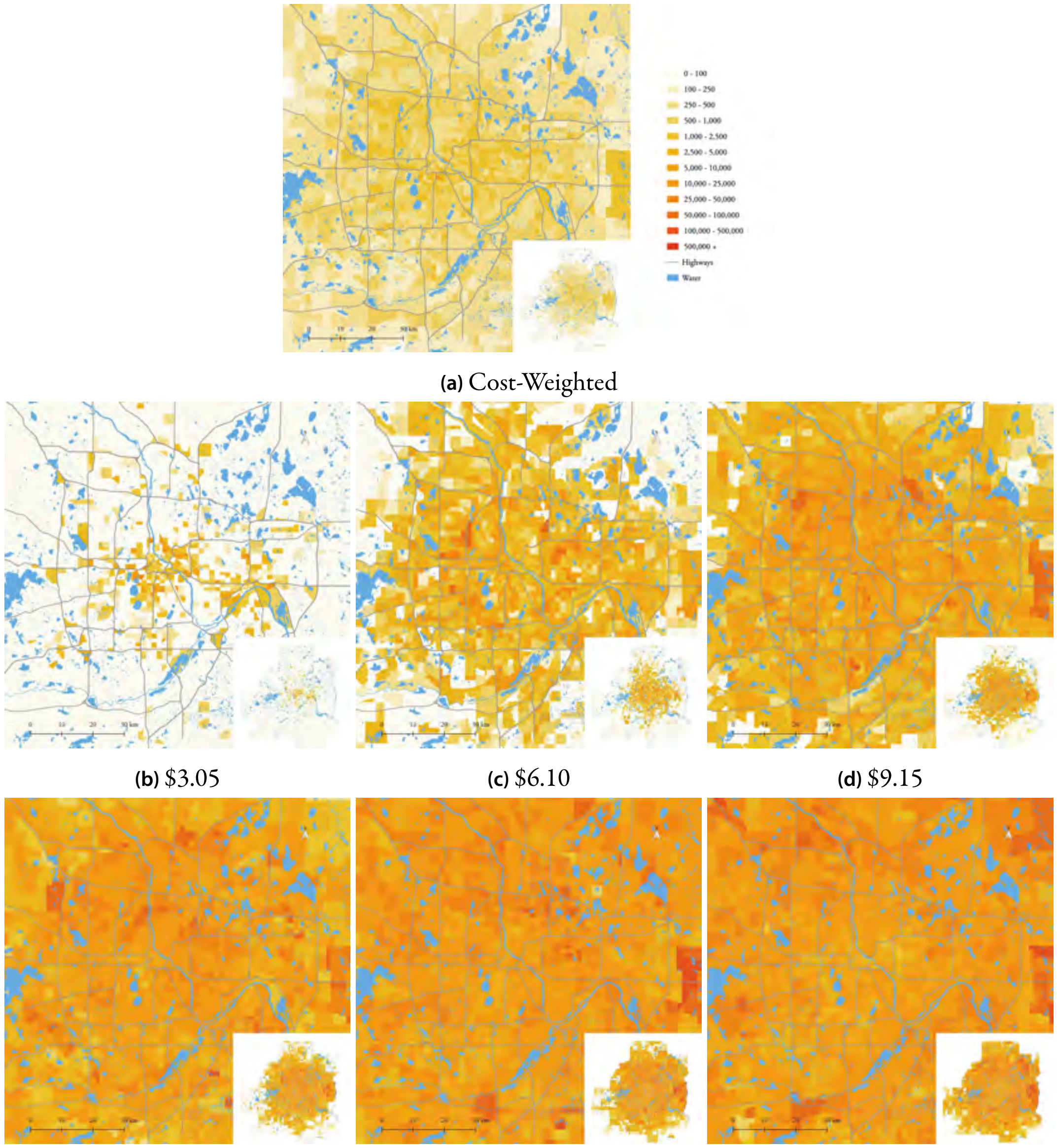
This section focuses on the combinations of path and considered cost on the row of the shortest travel time path in Table 1 and explores the accessibility loss if travelers optimize the travel time and ignore other internal and external cost factors.

Figure 8 shows the full cost accessibility differences when travelers use the shortest travel time path compared to travelers using the lowest full cost path (lowest full cost path - shortest travel time path). The changes indicate the accessibility reductions of pursuing the travel time optimization to the exclusion of other costs, which generates a higher full travel cost. In general, using the shortest travel time path, more trips would route on highways where travel speeds are higher. Using the lowest full cost path however, many trips will reassign from major interstate highways to state or local routes where the infrastructure costs are lower, despite the highway network still serving more trips (Cui 2018) (We recognize that many of the fixed costs of infrastructure are already 'sunk', and so independent of use today, the costs for maintaining a functioning interstate system over the long run requires collecting funds today for future rebuilding.).

From the figures, the changes first appear in the center area with a lower full cost threshold. In Figure 8(b), darker rings are formed in both downtown Minneapolis and downtown St. Paul, which indicate a higher accessibility reduction. Though the ring is getting blurry on the maps with an increased full cost threshold, we still see the radius of the ring increasing. In \$18.30, the ring moves to the exurban area, while the downtown area is less affected. The cost-weighted full accessibility loss is more randomly distributed but can still see changes across the urban area.

Table 5 summarizes the regression results of this accessibility loss on the Euclidean distance to downtown Minneapolis (D_{MN}) and downtown St. Paul (D_{SP}), as well as their quadratic terms (D_{MN}^2 and D_{SP}^2). The selected independent variables have similar signs as Table 4. The linear terms are negative first and change to be positive with an increased cost threshold; while the quadratic terms vary in the opposite way, which implies the same ring shape changes as described above. But as the ring shapes are not clustered as clearly as Figure 7, the Euclidean distance to the downtown areas cannot explain the accessibility loss that well. The maximum adjusted R^2 is 0.364 for the cost-weighted full accessibility loss, while D_{SP}^2 is not statistically significant.

These accessibility differences imply the importance of ensuring travelers recognize other travel cost factors, which could be achieved with road pricing, and translating fixed costs like insurance into a variable cost.



(a) Cost-Weighted

(b) $3.05 **(c)** $6.10 **(d)** $9.15

(e) $12.20 **(f)** $15.25 **(g)** $18.30

Figure 8: Full Cost Accessibility Loss Using the Shortest Travel Time Path Compared with the Lowest Full Cost Path, Based on the Cost-Weighted Results and with the Full Cost Threshold [$3.05 to $18.30] (Lowest Full Cost Path - Shortest Travel Time Path)

Table 5: Regression of Full Cost Accessibility Loss Using the Shortest Travel Time Path on the Euclidean Distance to Downtown Minneapolis and Downtown St. Paul

	$3.05		$6.10		$9.15		$12.20		$15.25		$18.30		Cost-Weighted	
	Est	Signif.	Est	Signif.	Est	Signif.	Est	Signif.	Est	Signif.	Est	Signif.	Est	Signif.
Intercept	1.83E+03	***	1.08E+04	***	2.07E+04	***	2.31E+04	***	1.68E+04	***	3.21E+03	**	1.29E+03	***
D_{MN}	-1.06E-01	***	-4.16E-01	***	-5.31E-01	***	-3.02E-01	***	6.69E-01	***	1.48E+00	***	-4.05E-02	***
D^2_{MN}	1.61E-06	***	4.77E-06	***	5.00E-06	***	–	–	-1.50E-05	***	-2.46E-05	***	4.82E-07	***
D_{SP}	-7.79E-03	*	-9.53E-02	**	-2.11E-01	***	-1.58E-01	***	-2.24E-01	***	–	–	-1.08E-02	***
D^2_{SP}	–	–	9.91E-07	.	1.34E-06		–	–	–	–	-3.21E-06	***	5.67E-08	
Adj R^2	0.095		0.166		0.235		0.223		0.134		0.126		0.364	

1. *** p-value<0.001, ** p-value<0.01, * p-value<0.05, . p-value <0.1;
2. – Excluded independent variable, adding which would decrease the Adj R^2.

7 Conclusion

This paper measures the full cost accessibility by auto for the Twin Cities metropolitan area following the steps of the full cost accessibility (FCA) framework proposed by Cui and Levinson (2018b). On the basis of previous research, this study further demonstrates the practicality of the FCA framework on real networks, and clarifies the data used for real-world FCA measurements.

For the Twin Cities, the full cost accessibility, referring to the accessibility based on the lowest full cost path, shows the same spatial distribution patterns as the traditional time-based accessibility. Areas with a higher job accessibility are centered on downtown Minneapolis, which decreases along with the increase of the distance to the downtown area. A higher threshold gives a higher accessibility overall. Most of the jobs could be reached from people living in most parts of the Twin Cities when the cost threshold is $18.30, which is equivalent to a 60 minute time cost at an average value of time.

The internal cost and full cost accessibility matrices have a correlation higher than 0.95 for any given cost thresholds. The correlations between the time-based vs. full cost accessibility and the time-based vs. internal cost accessibility are lower and vary significantly with the threshold changes. The accessibility matrices demonstrate that the time-based accessibility exceeds the full cost accessibility with the same thresholds. Their differences show the magnitude of bias of time-based accessibility for social evaluation purposes (e.g., highway investment prioritization), when not fully considering other internal and external cost factors.

Accessibility losses were measured as the changes of accessibility for travelers using the shortest travel time path and failing to know other internal cost factors, as well as the external costs, due to the absence of pricing. The more severe changes occur in a ring shape around downtown Minneapolis and downtown St. Paul, the radius of which increases with the threshold.

By considering the sensitivity of cumulative opportunity measures to the changes on transport network and land-use, FCA presents advantages over traditional cost-benefit analysis. Specifically, it allows discovery of where the benefit is received and where the cost is borne, and to what extent. It can be used to evaluate projects, especially those prioritizing social benefit, such as infrastructure investments for electric vehicles, or the location of land developments, that might change the rankings of the proposed investments, compared to the traditional time-based accessibility.

Future studies should extend the framework to modes such as transit, walking, and bicycle, to illustrate the mode-combined accessibility measurements on real networks, which should be critical for intermodal investment applications. Considering just time by each mode will tend to show the automobile as producing the highest accessibility, however considering the full cost reduces (person-weighted) access to jobs by auto from over 1,000,000 to 300,000 at a $9.15 (equivalent to thirty minute) threshold compared with considering travel time only. It is expected that the accessibility for some other modes will not drop as much, as a greater share of the costs are already borne by the traveler in the form of travel time. For instance, walking and biking impose essentially zero external emission cost, compared to $0.0192/veh-km by auto. The increasing recognition of financial, safety, and sustainability issues requires considering monetary, crash, and environmental costs so that investment in bike and walk infrastructure are treated fairly in evaluation. In this case, we believe FCA will become a valuable tool for investment appraisals.

In addition, the cumulative opportunity measure does not consider the constraints on both travelers and destinations, associated with the demand and supply of the opportunities as well as the relevant facilities , e.g., parking near the points of interests is always assumed available (Bunel and Tovar 2014; Cheng and Bertolini 2013b; Merlin and Hu 2017; Van Wee *et al.* 2001), and ignores other factors besides the travel costs that can influence travelers' behavior, e.g., habits, preferences, or familiarity, which affect accessibility (Chorus and De Jong 2011; Van Wee *et al.* 2013). Future research should address this problem as well.

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A Appendix

Population-weighted accessibility is calculated as follows:

$$A_{w_p,c,T_c} = \frac{\sum_{i\in I} A_{i,c,T_c} \times N_i}{\sum_{i\in I} N_i} \tag{4}$$

Where:

A_{w_p,c,T_c} stands for the population-weighted accessibility for cost category c by auto with the corresponding cost threshold T_c;

N_i stands for the population in origin i;

I stands for the set of origins.

Figure 9 gives the population-weighted accessibility by auto based on the time-based, internal cost and full cost accessibilities.

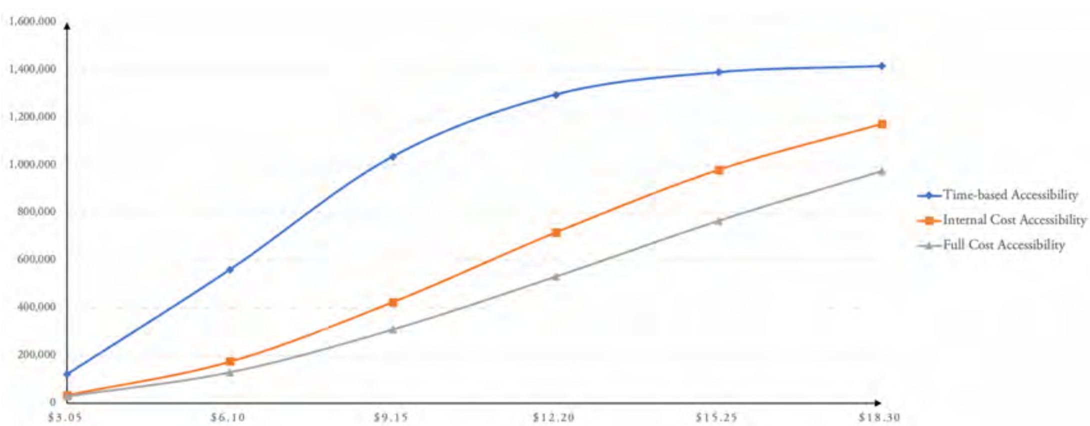
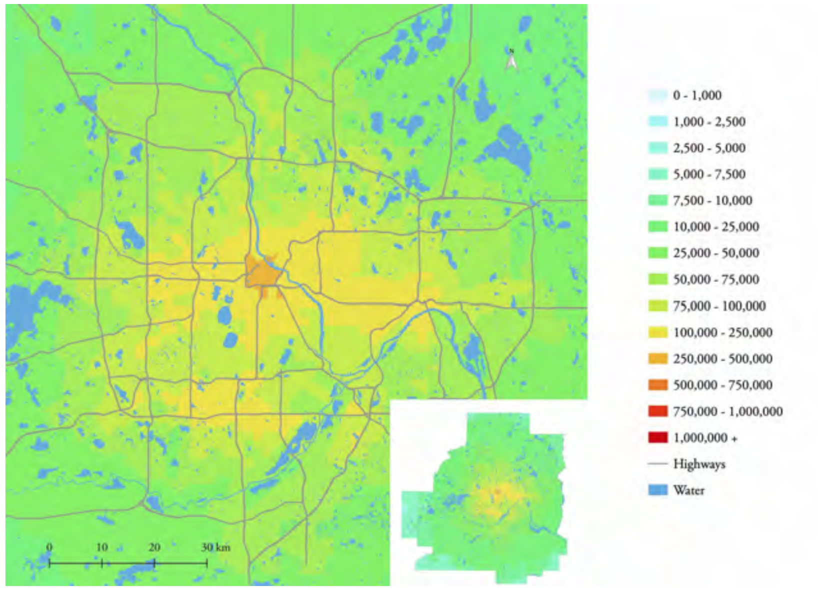
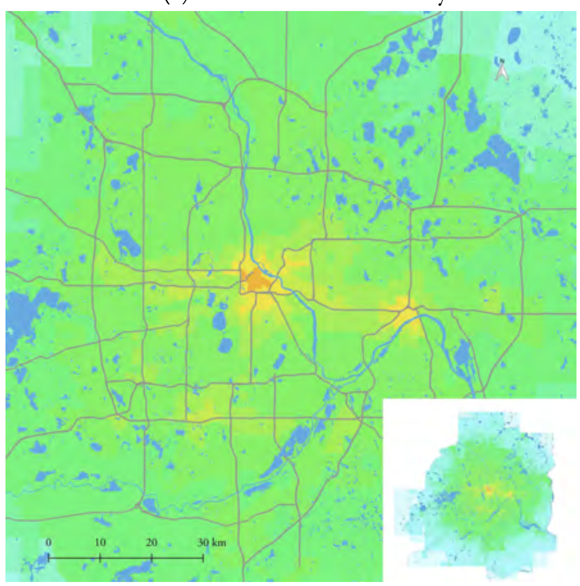


Figure 9: Population-Weighted Average Accessibility by Auto Based on Time-based, Internal Cost, and Full Cost Accessibilities with the Corresponding Cost Threshold [$3.05 to $18.30]

Figure 10 gives the cost-weighted time-based and internal cost accessibility by auto.



(a) Time-Based Accessibility

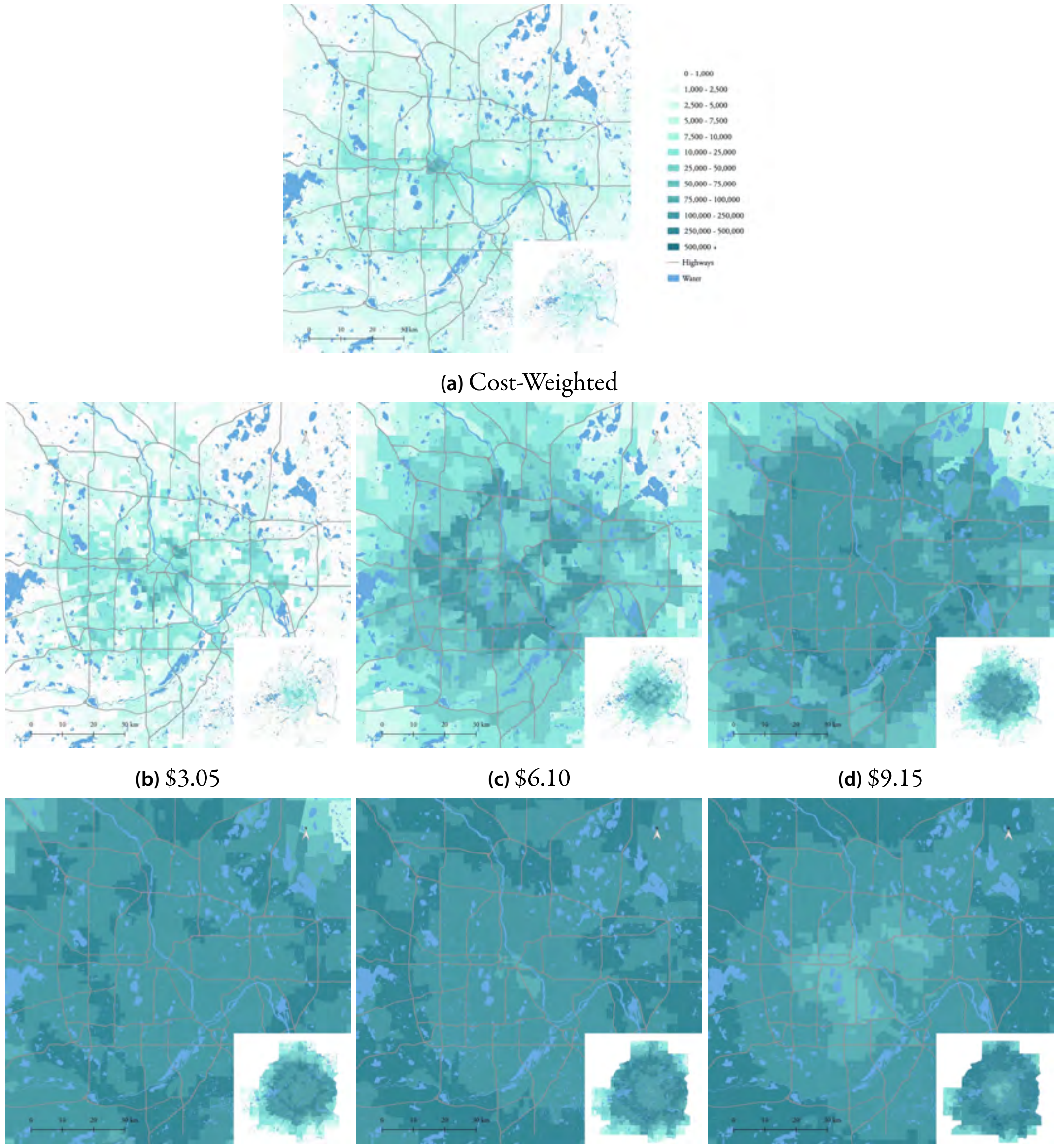


(b) Internal Cost Accessibility

Figure 10: Cost-Weighted Time-Based and Internal Cost Accessibility by Auto

Figure 11 compares the internal cost accessibility with the full cost accessibility (internal - full) based on the cost-weighted results and with the corresponding cost thresholds ranging from \$3.05 to \$18.30. Table 6 shows the regression results of the differences on the Euclidean distance to downtown Minneapolis(D_{MN}) and downtown St. Paul (D_{SP}).

Figure 12 shows the internal cost accessibility loss using the shortest travel time path, compared to the internal cost accessibility using the lowest internal cost path (lowest internal cost path - shortest travel time path), which explains the accessibility reductions from failing to consider the internal cost factors other than travel time. Table 7 shows the regression of the accessibility loss on the Euclidean distance to downtown Minneapolis(D_{MN}) and downtown St. Paul (D_{SP}).

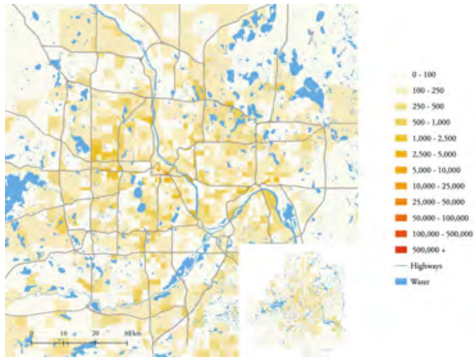


(a) Cost-Weighted

(b) \$3.05 **(c)** \$6.10 **(d)** \$9.15

(e) \$12.20 **(f)** \$15.25 **(g)** \$18.30

Figure 11: Differences between the Internal Cost and Full Cost Accessibilities Based on the Cost-Weighted Results and with the Corresponding Cost Thresholds [\$3.05 to \$18.30] (Internal Cost Accessibility - Full Cost Accessibility)

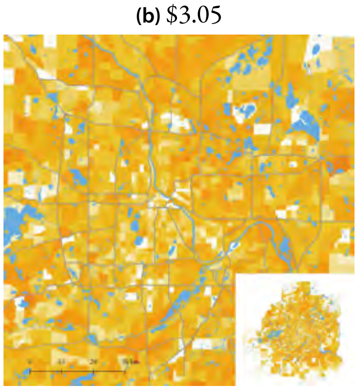


(a) Cost-Weighted

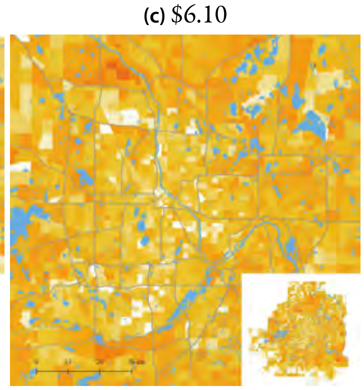
(b) $3.05

(c) $6.10

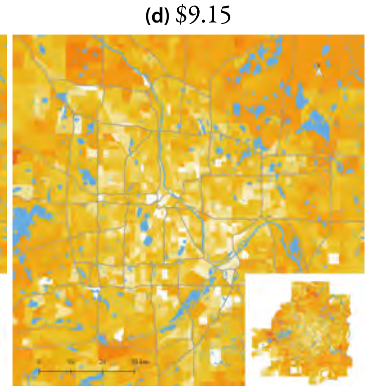
(d) $9.15



(e) $12.20



(f) $15.25



(g) $18.30

Figure 12: Internal Cost Accessibility Loss Using the Shortest Travel Time Path Compared with the Lowest Internal Cost Path, Based on the Cost-Weighted Results and with the Internal Cost Threshold [$3.05 to $18.30] (Lowest Internal Cost Path - Shortest Travel Time Path)

Table 6: Regression of the Internal Cost vs. Full Cost Accessibility Differences on the Euclidean Distance to Downtown Minneapolis and Downtown St. Paul

	$3.05		$6.10		$9.15		$12.20		$15.25		$18.30		Cost-Weighted	
	Est	Signif.	Est	Signif.	Est	Signif.	Est	Signif.	Est	Signif.	Est	Signif.	Est	Signif.
Intercept	2.36E+04	***	1.38E+05	***	2.35E+05	***	2.09E+05	***	5.58E+04	***	-9.34E+04	***	2.03E+04	***
D_{MN}	-1.25E+00	***	-4.38E+00	***	-5.42E+00	***	3.96E+00	***	1.55E+01	***	1.90E+01	***	-9.90E-01	***
D^2_{MN}	1.73E-05	***	4.07E-05	***	1.76E-05	**	-1.51E-04	***	-3.05E-04	***	-2.79E-04	***	1.43E-05	***
D_{SP}	-6.61E-02		-1.72E+00	***	-1.34E+00	***	-1.45E+00	***	9.48E-01	**	5.32E+00	***	-1.19E-01	**
D^2_{SP}	7.25E-08		2.22E-05	***	1.56E-05	***	1.08E-05	.	-2.50E-05	***	-9.29E-05	***	6.26E-07	
Adj R^2	0.323		0.566		0.628		0.522		0.520		0.632		0.303	

*** p-value<0.001, ** p-value<0.01, * p-value<0.05, . p-value <0.1

Table 7: Regression of Internal Cost Accessibility Loss Using the Shortest Travel Time Path on the Euclidean Distance to Downtown Minneapolis and Downtown St. Paul

	$3.05		$6.10		$9.15		$12.20		$15.25		$18.30		Cost-Weighted	
	Est	Signif.	Est	Signif.	Est	Signif.	Est	Signif.	Est	Signif.	Est	Signif.	Est	Signif.
Intercept	8.13E+02	***	3.40E+03	***	3.67E+03	***	2.10E+03	***	-1.48E+03	***	-4.24E+03	***	4.55E+02	***
D_{MN}	-3.47E-02	***	-1.36E-01	***	–	–	2.70E-01	***	4.32E-01	***	4.05E-01	***	-1.79E-02	***
D^2_{MN}	4.78E-07	***	1.28E-06	***	-1.16E-06	***	-5.34E-06	***	-5.90E-06	***	-3.65E-06	***	2.33E-07	***
D_{SP}	-9.83E-03	*	–	–	-3.27E-02	*	-3.20E-02	**	1.09E-01	***	2.37E-01	***	-1.72E-03	*
D^2_{SP}	9.67E-08		–	–	2.40E-07		–	–	-2.72E-06	***	-4.22E-06	***	–	–
Adj R^2	0.047		0.086		0.076		0.069		0.103		0.157		0.064	

1. *** p-value<0.001, ** p-value<0.01, * p-value<0.05, . p-value <0.1;
2. – Excluded independent variable, adding which would decrease the Adj R^2.