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Full cost accessibility

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Abstract: Traditional accessibility evaluation fails to fully capture the travel costs, especially the external costs, of travel. This study develops a full cost accessibility (FCA) framework by combining the internal and external cost components of travel time, safety, emissions, and money. The example illustrated compares FCA by automobile and bicycle on a toy network to demonstrate the potential and practicality of applying the FCA framework on real networks. This method provides an efficient evaluation tool for transport planning projects.

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1 Introduction

Transport systems provide opportunities for people to participate in activities that are distributed over space and time. The concept of 'accessibility,' defined as the ease of reaching valuable destinations, provides a way to evaluate the performance of transport systems.

Accessibility has been long used in transport planning (Handy and Niemeier 1997; Hansen 1959). A very basic accessibility metric is cumulative opportunities, which measures the number of opportunities that can be reached within a given threshold (Ingram 1971; Vickerman 1974; Wachs and Kumagai 1973). It has been widely used to evaluate accessibility for different metropolitan areas and travel modes (Levinson 2013; Owen and Levinson 2014; Owen et al. 2014). In the gravity-based measure (or time-weighted cumulative opportunity), the attractiveness of the destinations in the calculation decreases with distance (or travel cost) from the origin (Hansen 1959; Iacono et al. 2010; Levinson and Kumar 1994). The utility-based accessibility measure, derived from the logsum of the multinomial logit model, incorporates travel behavior and decision-making preferences into accessibility measurement, and uses the corresponding utility to interpret accessibility (Ben-Akiva and Lerman 1985). However, the utility-based measure is harder to measure with empirical data, harder to explain since utility is an abstract value whose units lack physical meaning, and harder to compare between places and over time (El-Geneidy and Levinson 2006; LaMondia et al. 2010; Owen and Levinson 2012). Space-time accessibility considers time restrictions specifically (e.g., time-budget, required travel time, required participation time) (Song and Miller 2014; Wu and Miller 2001). Place-rank is a flow-based measure that does not require travel time, but does require origin-destination information (El-Geneidy and Levinson 2009).

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Accessibility is a reliable tool for comparing the effectiveness of proposed land-use and transport network scenarios in planning projects (Geurs and Van Wee 2004; Levine et al. 2017). Anderson et al. (2013) analyzed the accessibility of the combination of six land use and twelve network cases (both highway and transit). Moreover, accessibility significantly affects travel behavior (Kockelman 1997; Levinson 1998), real estate prices (Ibeas et al. 2012; Srour et al. 2002), and economic productivity (Melo et al. 2017).

Typically, accessibility has been analyzed from the perspective of the mean or expected travel time (Cui and Levinson 2016). It is thought reasonable not only because time is a critical cost factor affecting travelers' choice of mode, route, and departure time, but also because time is easier to understand and assess. Using only time cost, however, cannot capture the complete internal costs of travel since it disregards the costs of crashes, pollution intake, and out-of-pocket monetary cost. Moreover, external costs of urban transport, which are essential for policymakers to understand the full costs of travel (Mayeres et al. 1996), have been neglected in traditional accessibility measurement. These external costs, by definition, do not affect traveler decisions in the absence of specific policies; they nevertheless are real costs borne by society as a whole, and should be considered when using accessibility for evaluation. Full cost accessibility (FCA), introduced here, has the potential to change the ranking of investments and developments by incorporating the cost of externalities. Some projects may be more beneficial for individual travelers, while they impose external costs on society. Hence, knowing the full cost is necessary for stakeholders to properly evaluate transport projects.

In this paper we extend accessibility analysis to incorporate the full cost of travel to better align with evaluation goals in transport planning. This analysis allows us to evaluate accessibility across different cost aspects by applying alternate cost components and their combinations into accessibility metrics. This research combines the internal and external costs of time, safety, emission and money into a consistent accessibility analysis. The framework includes three stages: analyzing cost components of travel, proposing new path types, and performing FCA analysis. The framework allows us to:

- investigate the alternative cost components during urban travel, including both internal and external parts of costs,
- explore how each cost component affects travelers' choice, and
- evaluate component accessibility from different cost perspectives and evaluate FCA.

A toy network illustrates the FCA analysis framework.

The FCA framework, definition of path types, exposition of accessibility analyses, discussion of model inputs, results from a proof-of-concept, and the conclusion are in Sections 2-7 in turn.

2 FCA Analysis Framework

The 'internal cost' refers to what consumers pay directly for goods or services. In transport, internal cost is most typically represented as travel time, but also should consider crash risk, pollution intake, and out-of-pocket monetary cost. Rational economic agents are often assumed to choose the lowest internal cost during decision-making (Levinson and Gillen 1998). An 'external cost' occurs because of negative externalities, in which an externality refers to the "uncompensated impact of one person's actions on the well-being of a bystander" (Mankiw 2014). It is called a 'negative' externality if the impact is adverse. Negative externalities cause the full cost to exceed the internal cost, as Figure 1 shows. A social optimum including negative externalities has a higher price than one including only internal costs. Typically in transport, external costs include congestion delay imposed on others, increased crash risk to others, pollution emissions, noise, and road wear and tear in excess of road charges.

An 'external cost' is sometimes referred to as a 'social' cost, however we do not use the latter term to avoid confusion, as 'social' cost sometimes also refers to the combination of internal and external costs. Instead, we use 'full' costs as the term for the combined internal plus external costs, and 'external' cost for the costs the traveler does not bear (Jakob et al. 2006).

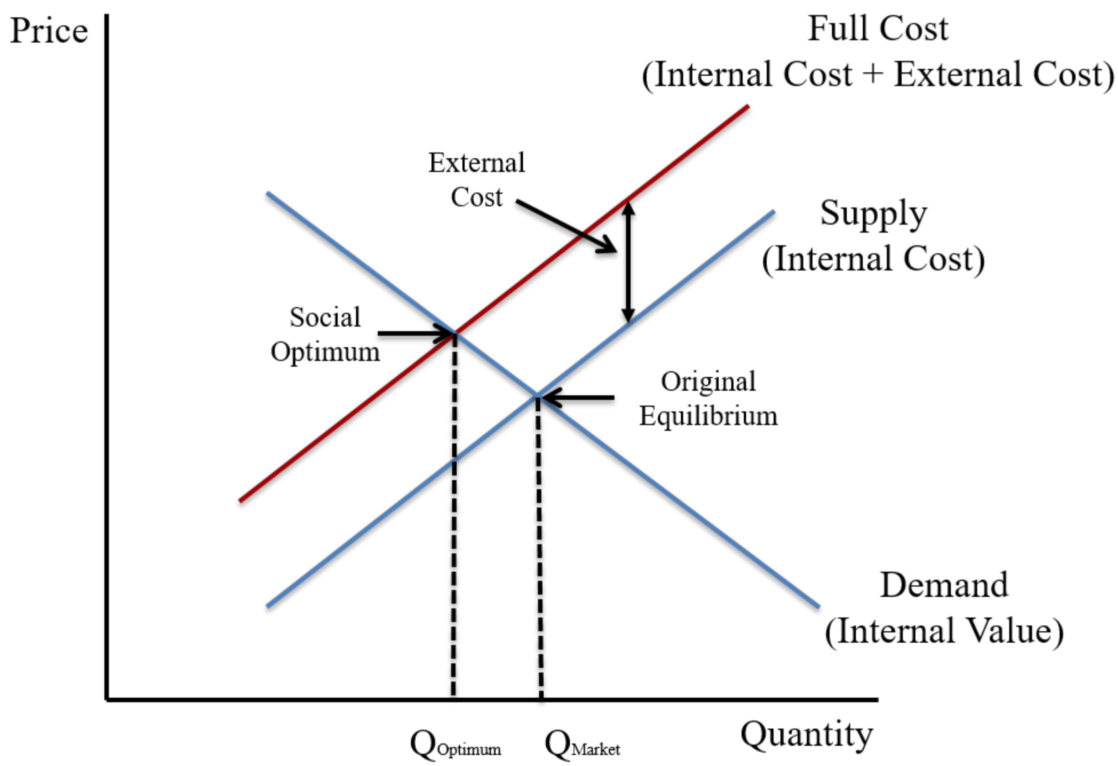


Figure 1: Internal and External Cost. Source: Mankiw (2014)

The full cost analysis framework comprises three stages: analyzing the component costs of travel, evaluating new path types, and measuring FCA, shown in Figure 2.

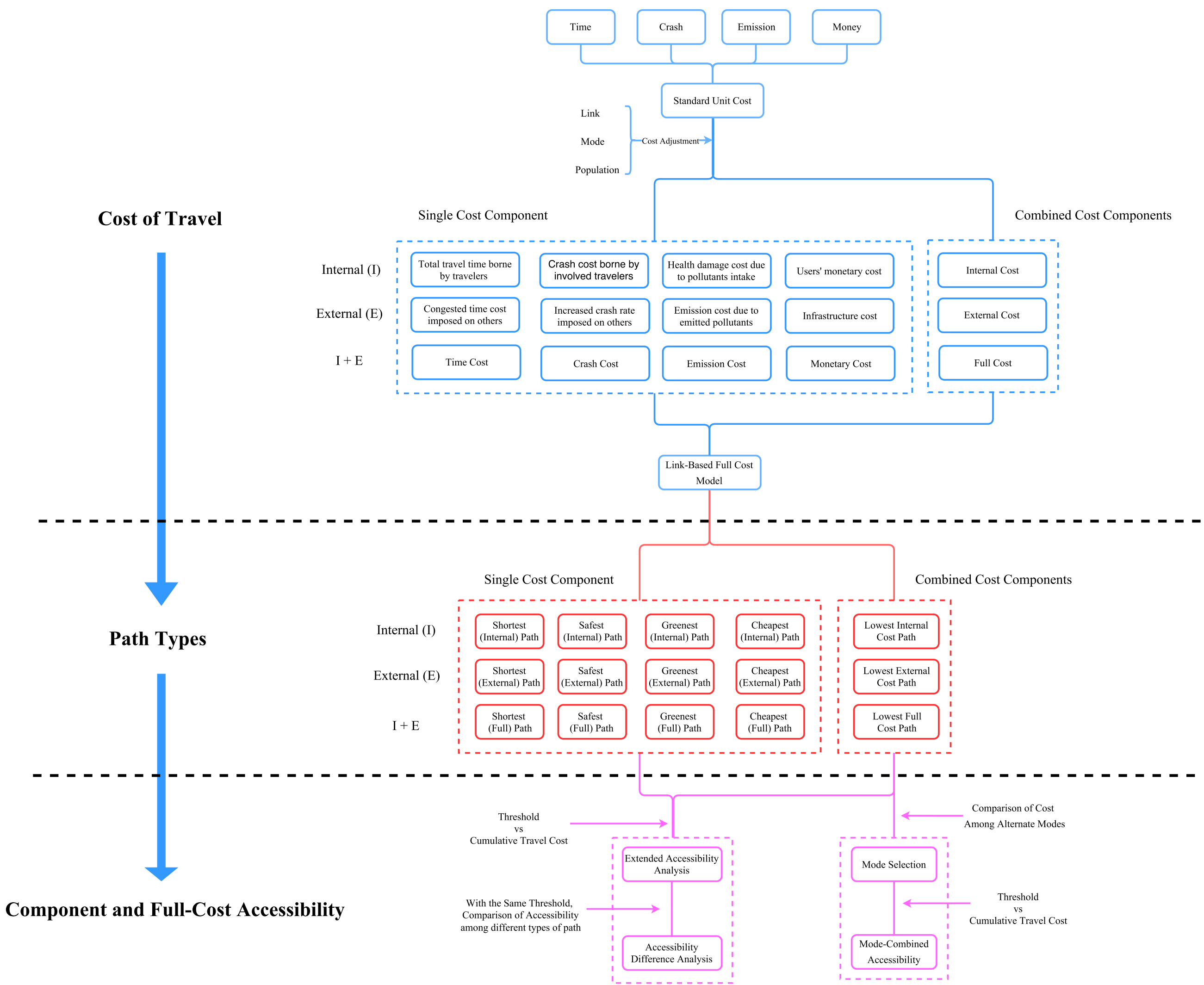


Figure 2: Full Cost Accessibility Framework

Full cost analysis emerged in transport in the 1990s (Delucchi 1997; Gillen and Levinson 1999; Greene and Jones 1997; Levinson and Gillen 1998; Levinson et al. 1997). For instance, from the perspective of travelers, there is a consensus that the full cost of highway transport considers user cost, infrastructure cost, time cost, crash cost, noise cost, and air pollution and global climate change cost. Other sometimes-reported costs, such as defense expenditures of the US in Middle Eastern countries (presumably to support the flow of petroleum) are more contentious. Boundaries have to be drawn, so costs intermediated by market transactions, like the pollution generated in the production of automobiles, which might or might not be internalized in the price of a car, are excluded, on the assumption, or hope, that those externalities have been properly priced. Without such boundaries, due to the networked nature of the world market economy, all externalities would have to be attributed at least in part to all goods, and double-counting would abound.

Based on review of the previous research, we consider four major cost components: time, crashes, emissions, and money (including noise costs, which are typically capitalized in land values), in which each contains internal and external elements. Analyzing travel costs at the individual level (disregarding the social benefit of transport systems overall, which instead we account for as the ability to reach opportunities), almost all the externalities are negative.

Focusing on auto travelers, the internal and external costs are defined as follows:

Travel time can be divided into congested and uncongested components, in which congested time implies the external cost imposed on others from the point-of-view of travelers, as additional vehicles on the roadways result in incremental delay borne by others (e.g., following travelers in the stream of traffic) (Levinson and Gillen 1998). Delay is highly related to traffic flow, which increases significantly as traffic flow reaches and exceeds capacity (Neuhold and Fellendorf 2014). Considering link properties, traffic and capacity, the marginal cost of travel time represents the external time cost. From the perspective of the road system, the congested time (delay) is fully internalized; however for each traveler, it is an external cost. The total travel time for a trip (personal travel time), including both congested and uncongested time, is the internal time cost borne by travelers, which also highly depends on the free-flow speed (Transportation Research Board 2010). Care needs to be taken to avoid double counting.

Vickrey (1968) proposed the crash externality as increased crash risk due to higher traffic flow, which implies a marginal cost of crashes (Edlin and Karaca-Mandic 2006). Jansson (1994) applied the definition of crash externality charges into an optimal road pricing scheme considering the marginal increases of crash risk for unprotected road users based on vehicle kilometers traveled. The internal part drivers need to pay for crashes is from the average crash rate, including both direct (e.g., medical, rehabilitation, and aftercare costs) and indirect costs (costs to police, for example) (Edlin and Karaca-Mandic 2006). Recognizing some of this cost is transferred to insurance costs is important to avoid double counting in a full cost accounting framework.

On-road emissions affect human health, vegetation, materials, aquatic ecosystems, visibility, and climate change, and categorizes as an external cost (Mayeres et al. 1996). Notably, damage to human health due to air pollution is the most expensive element. Small and Kazimi (1995) combined the exposure models with the health damage cost in the Los Angeles region, which provided a critical method for emission cost estimation, and implied that particulate matter is the primary cause of mortality and morbidity (Levinson and Gillen 1998). Hence, the external cost of emission from the perspective of travelers is measured by the health damage cost from emitted pollutants imposed on others. However, as an active agent in transport systems, the health risk of travelers due to exposure to pollutants is considered as the internal emission cost to travelers, which is measured by the quantity of pollution intake (breathed-in, in the case of air pollution).

The monetary cost of travel mainly comprises user and infrastructure costs (if we avoid double-counting for insurance and crashes). The user monetary cost, including fuel, vehicle ownership and maintenance, tolls and taxes and fares, and the like, could be totally internal for travelers (Barnes and Langworthy 2004). For the infrastructure cost, part of the expenditures, including capital, maintenance, administrative, and so on, are internalized and transferred to the user cost, through mechanisms like licensing and registration fees and user taxes (Levinson and Gillen 1998). But other costs, like road wear and tear, when they are uncompensated for by user taxes, are still external to travelers. Hence, the internal money cost for travelers covers all the components of the user cost during vehicle operation, while the external money cost is from the external infrastructure cost paid by others (except the part which is already internalized).

With sufficiently high taxes (e.g., on fuel, or as tolls, for instance with a Pigouvian Tax), it is certainly possible to internalize the externality, in other words, no net external costs. However that is empirically not the case at this time (Small et al. 2012), and externalities exist and result in implicit subsidies for travel.

For pedestrians and cyclists, the cost categories are the same as auto travelers, but the costs incurred differ. Pedestrians and bicyclists incur total travel time, crash cost due to exposure to crash risk, emission cost due to exposure to health risk and user operation cost borne by themselves as their internal cost, while they may generate congestion, marginally increase number of crashes for others, and require infrastructure funded by others as their external costs.

The external crash cost results from the marginal increases of crash cost due to an additional pedestrian or cyclist on the road, though the safety-in-numbers literature suggests additional pedestrians and bicyclists reduce the likelihood of a crash (Carlson et al. 2017; Murphy et al. 2017). These external costs may be considered in further studies for specific applications.

For transit passengers, the cost definitions would differ since they are not the owners of the vehicles and many of them need to share a same vehicle. A comprehensive framework is required to identify the parts of costs imposed on (internal cost) and imposed by (external cost) travelers (other parts of cost should be paid by the operators.). A comprehensive strategy is also required to assign those costs to each passenger. The framework and strategy of transit travel cost analysis on the perspective of passengers should be considered in future studies.

The total costs for each cost component can be measured as the sum of their corresponding internal and external costs, and the full costs would be the sum of the total costs for each cost components. To make sure each element in the cost analysis table are additive, all those cost elements would be monetized based on standard cost values, personal information, and link properties.

The cost analysis provides a method to estimate the internal, external, and full costs of link segments, and aggregate this to the scale of a complete road network.

3 Path Types

Individual travelers choose routes based on a number of factors, including trip-related factors, like travel time (and reliability), trip distance and tolls, and person-related factors, like drivers' urgency and experience (Ahn and Rakha 2008; Ben-Akiva et al. 1984; Tang and Levinson 2018; Zhu and Levinson 2015). Few travelers appear to consider minimizing the crash and emission cost, as, few, if any, travelers know these costs. The total internal, external and full costs of travel are considered in Figure 2.

- Shortest time path – the route with the lowest travel time costs. This is traditionally used in traffic assignment and route choice analysis, as well as most accessibility analyses.
  - The shortest time (internal) ($P_{t,int}$) path minimizes the private cost borne by travelers themselves, and is equivalent to the conventional User Equilibrium (UE) path.
  - The shortest time (external) path ($P_{t,ext}$) the external cost complement aims to minimize the congestion cost imposed on others.
  - The combined version of this ($P_{t,com}$) is equivalent to the traditional socially optimal (SO) path.
- Safest path – the route with the lowest crash costs. Dijkstra and Drolenga (2008) proposed the concept of 'Sustainably Safe Traffic', which encourages travelers to use safe roads as much as possible to reduce road crash casualties. Lord (2002) first defined the 'safest path' for individual

vehicles as the route that a driver would have the lowest probability of being involved in a crash based on a crash risk estimation model. The safest path can be compared with crash costs by using other paths (e.g., shortest time path) to show the crash cost savings. But it cannot be used alone to reflect travelers' actual route choices accurately (as most travelers wouldn't know this anyway, even if they valued safety highly).

  - The safest (internal) path ($P_{s,int}$) considers the personal crash costs.
  - The safest (external) path ($P_{s,ext}$) considers crash costs imposed on others.
  - The safest combined path is denoted by ($P_{s,com}$).

- Greenest path – the route with the lowest emission costs. Ahn and Rakha (2007) and Lena et al. (2002) believe that the economic measure of environmental externalities of travel would be lower if travelers took alternative routes that reduced pollution generation (other's exposure), and personal pollution intake. The greenest path is typically not the major concern for travelers when they choose routes (and again few would know what this was), but it allows an evaluation of on-road emissions overall. It also provides a measure of emission cost savings if travelers considered pollution when choosing routes, which would be achievable with Pigouvian Prices.
  - The greenest (internal) path ($P_{g,int}$) (or 'healthiest' path) minimizes intake of on-road emissions (Pollution intake may also include non-transport sources, but we neglect that in this analysis.).
  - The greenest (external) path ($P_{g,ext}$) is the route with the lowest monetized emissions.
  - The greenest combined path ($P_{g,com}$) includes both internal and external costs.
- Cheapest (least expensive) path – the route with the lowest monetary costs.
  - The least expensive internal cost path ($P_{l,int}$) includes out-of-pocket expenses like energy, tolls, parking, taxes.
  - The least expensive external cost path ($P_{l,ext}$) includes things like subsidized infrastructure costs.
  - The least expensive combined path ($P_{l,com}$) is the sum of the above.

The new path types are expressed as:

$$C_{k,ij,c,m} = \sum_{i \in P_{k,ij,m}} C_{z,c,m} \tag{1}$$

$$C_{ij,c,m} = min(C_{k,ij,c,m}) \tag{2}$$

Where:

$C_{z,c,m}$ is the cost of cost component c on link z by mode m,

$P_{k,ij,m}$ refers to the k^{th} path between origin i and destination j, by mode m,

k is a path considering one of the cost components (c): time (t), safety (s), greenness (g), monetary expense (l), or full cost (f) paths considering internal (int), external (ext), or combined (com) costs,

$C_{k,ij,c,m}$ is the travel cost of the k^{th} path for cost component c, by mode m,

$C_{ij,c,m}$ stands for the minimum travel cost between i and j for cost component c, by mode m.

4 Accessibility Analysis

Cumulative opportunity counts the number of opportunities that reachable within a given threshold (Vickerman 1974; Wachs and Kumagai 1973). Accessibility to jobs is expressed as:

$$A_{i,c,m} = \sum_{j} O_j f(C_{ij,c,m}) \tag{3}$$

$$f(C_{ij,c,m}) = \begin{cases} 1 & \text{if } C_{ij,c,m} \leq T_c \\ 0 & \text{if } C_{ij,c,m} > T_c \end{cases} \tag{4}$$

Where:

$A_{i,c,m}$ stands for the job accessibility of origin i, for cost category c by mode m

O_j stands for the number of opportunities (e.g., jobs) at destination j,

C_{ij} stands for the costs between origin i and destination j,

T_c represents the corresponding cost threshold for cost component c.

For FCA analysis, we use the cumulative opportunity measure to conduct component accessibility evaluations, accessibility difference measurements, and mode-combined accessibility analysis. The details follow.

4.1 Component Accessibility Evaluation

Component accessibility evaluation considers alternate internal and external cost components of travel in accessibility analysis, including time cost, crash cost, emission cost, monetary cost and their composite. It measures the number of opportunities, jobs, goods, or services, that can be reached in a given cost threshold.

All path types can be applied in the evaluations. At first, travel cost along the optimal path (e.g., time cost of the shortest path or crash cost of the safest path) is calculated for each origin to all the other destinations, which gives an origin-destination (OD) travel cost matrix. Comparing the cumulative travel costs with the corresponding predetermined cost threshold (time cost vs. time threshold, crash cost vs. crash cost threshold), the number of reachable opportunities is counted for each origin, which gives an accessibility metric. This calculation is conducted for time, crash, emission, monetary, and full costs, for internal, external and combined-costs, and for auto and non-auto travel. See Figure 2.

Accessibility measurements such as these may be useful for project evaluations with specific needs, such as using accessibility in the realm of crash costs for evaluations of safety improvement projects or connected/autonomous vehicles, or applying accessibility in the realm of emission costs for evaluating the wide application of electric vehicles.

4.2 Accessibility Difference Assessment

Accessibility difference assessment measures the penalties in terms of reduction in the number of destinations that can be reached for a given cost threshold. For instance, accessibility using the safest path under a 30 minute travel time threshold is significantly lower than the accessibility from the shortest path, indicating the accessibility loss of pursuing a safer route with higher travel time costs.

Accessibility difference assessment compares cost components, or the internal and external elements for each of them, with the same cost threshold. Note that travel costs along different path types (such as time cost of the safest path or time cost of the greenest path) need to be calculated to measure the accessibility for each component. Other calculations are the same as the FCA evaluations.

Accessibility Difference Assessment explains the trade-off of the costs and benefits between the private and public sectors. Travelers reach fewer job opportunities considering the full cost of travel with the same nominal cost threshold, as the implicit subsidies are exposed in the accessibility analysis.

4.3 Mode-combined Accessibility Analysis

Generally, accessibility analysis is conducted separately by mode (auto, transit, walk, or bike), which measures the ability to reach opportunities with a given mode to travel. For the conventional accessibility measurement, travel time usually represents the costs of trips and the order of needed travel time for these modes is clear in most contexts ($Walking > Bicycling > Transit > Autos$). Hence, the maximum accessibility is achieved with the fastest mode, almost always auto.

Based on the full cost of travel, for a given OD pair, the travel mode with the minimum total cost is selected. While this depends on the outcomes of the cost analysis and the context, in general, incorporating cost components beyond individual travel time makes non-auto modes more competitive. Applying the minimum total cost into the cost function provides a way to measure the mode-combined accessibility.

A mode-combined accessibility analysis comprehensively evaluates the effectiveness of network operation. It is calculated as the full cost of different modes along their lowest full cost path.

C_{ij} is measured as:

$$C_{ij,c} = min(C_{ij,c,m}) \forall m \in M \tag{5}$$

Where:

M is the set of all modes m.

The mode with the lowest full cost for each OD pair is selected. This full cost gives the impedance in the accessibility measurement, which provides a full cost minimizing, multi-modal accessibility analysis.

In this paper, the total internal cost, and the full costs are compared in the mode-combined accessibility analysis.

5 Model Inputs

A 10×10 toy network is constructed to illustrate the FCA process. This network includes 100 vertices (nodes) and 180 edges (links) (Figure 3). The nodes are named based on their coordinates, and the links are identified by their nodes.

5.1 Network Modeling

The following assumptions are applied for network modeling:

1. Length of links: 1 km;
2. Free-flow speed: 60 km/h;
3. Capacity: 2000 veh/h;
4. Number of jobs for each node: 1,000;
5. Flow on each link: randomly assigned with a range of [400-51,000] [1].

Note that network modeling parameters and cost function specifications were calibrated based on corresponding data in Minnesota for illustration only. The FCA analysis framework is not location specific.

5.2 Automobile Cost Functions

To model the costs of autos for each link, speed, number of crashes, and emissions were estimated based on the traffic flow. The estimated (average cost) values were directly used to measure the corresponding internal costs, while the marginal costs were used for the external costs.

[1] The range was determined based on the 5th and 95th percentile AADT of local links in Minneapolis-St.Paul Metropolitan Area (Source: MnDOT (Minnesota Department of Transportation 2016b)), in which the 5th percentile AADT shows the AADT on links which are the lowest 5% of those records and the 95th percentile AADT represents the highest 5%.

5.2.1 Time costs

The standard Bureau of Public Roads (BPR) link performance function was used to estimate the speed of each link, which is given as (U.S. Department of Commerce, Bureau of Public Roads 1964),

$$U_Q = \frac{U_0}{[1+\alpha(Q/Q_0)^{\beta}]} \tag{6}$$

This function assumes that speed U_Q decreases from free-flow speed U_0 based on the ratio of flow (Q) to capacity (Q_0). The coefficients α and β are usually set as 0.15 and 4.

A unit time value for business trip ($24.1/h for auto (U.S. Department of Transportation 2014)) was used to monetize travel time.

5.2.2 Crash Cost

A safety performance function (SPF) is used to estimate the number of crashes for each link (N) (American Association of State Highway and Transportation Officials (AASHTO) 2010). Using negative binomial regression, the function is expressed as

$$N = exp(\beta_0)Q^{\beta_1} * L^{\beta_2} \tag{7}$$

Where:

L: Segment length;

Q: Daily traffic (AADT).

Table 1 estimates the models.

5.2.3 Emission Cost

Polynomial regression models estimate both internal and external emission costs:

$$E = \epsilon_0 + \epsilon_1 t + \epsilon_2 Q + \epsilon_3 Q^2 \tag{8}$$

Where:

t: Travel time needed for each link.

Quantities of pollutants were estimated by the authors using the EPA Motor Vehicle Emission Simulator (MOVES) for each link in the Twin Cities. The unit health damage cost and climate change cost per metric ton were estimated by McGarity (2012) (NO_x: $6,700; PM: $306,500; SO_2: $39,600; CO_2:$22), which represents the damage cost reductions per ton of emissions of each pollutant that is avoided. An intake fraction of 10 per million was used to assess the internal emission cost of travelers (Marshall et al. 2005).

The estimates from the emission cost model are displayed in Table 2.

5.2.4 Other Costs

1. Vehicle Operating Cost: $0.155/km (Minnesota Department of Transportation 2015);
2. Infrastructure Cost: $0.0287/veh-km (Levinson and Gillen 1998);
3. Noise Cost: $0.000622/veh-km (McGarity 2012).

Time cost (mean: $0.48/veh-km) and monetary cost (mean: $0.18/veh-km), including both internal and external parts, account for a higher percentage (around 90%) of the full cost of travel for the toy network. Safety cost (mean: $0.059/veh-km) and emission cost (mean: $0.020/veh-km) are quite low. It is highly unlikely many travelers would be persuaded to shift routes to the safest or the greenest path. However, the costs cannot be ignored, especially for links with higher crash risks or emission concentrations. In addition, the internal cost (mean: $0.65/veh-km) is much higher than the external one (mean: $0.17/veh-km).

Table 1: Estimates of Safety Performance Function (SPF)

		Coef.	SE	Signif	AIC	Pseudo R^2
Fatal	Intercept	-6.15605	0.78343	***		
[$\$10,600,000$]	Log(Q)	0.20301	0.09345	*	822.14	0.024
	Log(L)	0.55331	0.13923	***		
Injury Type A	Intercept	-4.705	0.31069	***		
[$\$570,000$]	Log(Q)	0.28244	0.03689	***	4366.9	0.032
	Log(L)	0.51232	0.05379	***		
Injury Type B	Intercept	-3.51676	0.18945	***		
[$\$170,000$]	Log(Q)	0.33686	0.02278	***	12783	0.033
	Log(L)	0.52125	0.03159	***		
Injury Type C	Intercept	-3.54922	0.16921	***		
[$\$83,000$]	Log(Q)	0.44891	0.02044	***	20091	0.032
	Log(L)	0.52909	0.02725	***		
Property Damage Only	Intercept	-1.8872	0.125	***		
[$\$7,600$]	Log(Q)	0.4079	0.0152	***	39227	0.025
	Log(L)	0.4729	0.0196	***		

Note: Unit crash values per crash type shown in [brackets]. Source: Crash value costs (Minnesota Department of Transportation 2015). Models estimated by authors using data from the Minneapolis-St.Paul Metropolitan area (the Twin Cities) for 2002 to 2014, source (Minnesota Department of Transportation 2016a). The sample size is 10,740, which refers to the number of local links in the Twin Cities area based on TomTom road network.

5.3 Bicycle Costs

To illustrate the mode-combined accessibility analysis, biking is selected as the alternate mode.

The travel cost of biking is assumed as below:

1. Time Cost: The speed is assumed as 20km/h and unit time value for business trips was set as $15.00 (Lyons and Urry 2005).
2. Crash Cost: The internal crash cost of biking is set as the same as autos, while the external cost is set as 0.
3. Emission Cost: The internal emission cost of biking is set as the same as autos, while the external cost is set as 0.
4. Other Cost: All other costs, such as operation, parking, and noise are set to 0.

Table 2: Estimates of Emission Cost

Variable	Internal Emission Cost			External Emission Cost		
	Coef.	SE	Signif	Coef.	SE	Signif
Intercept	-4.83E-02	6.55E-04	***	-2.247E+00	5.732E-02	***
t	9.43E-02	5.47E-04	***	3.083E+00	4.784E-02	***
Q	2.21E-07	5.20E-08	***	4.356E-04	4.549E-06	***
Q^2	-1.01E-12	4.13E-13	*	-8.122E-10	3.618E-11	***
R^2	0.383			0.464		

6 Results

6.1 Path Types

Figure 3 shows the new path types and their travel costs on the toy network from Node (0,9) to Node (9,0) (The cheapest path cannot be searched based on the assumptions that all the edges have uniform operating cost).

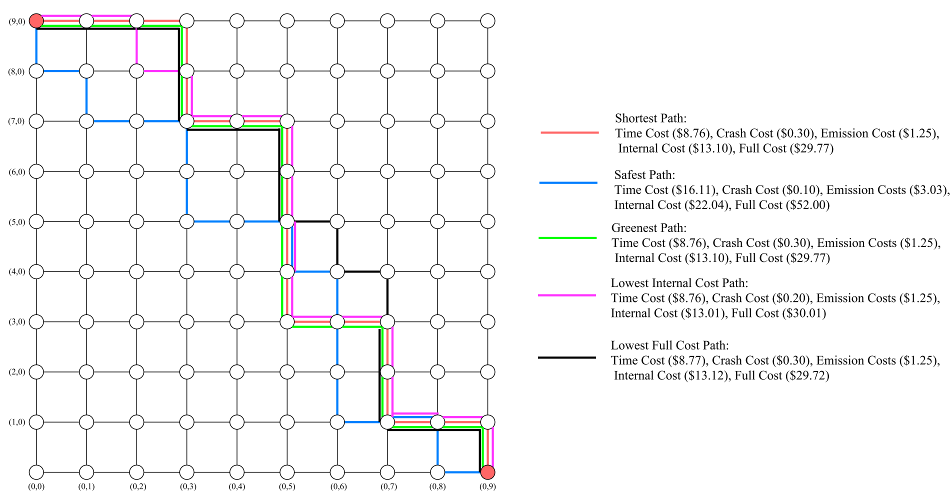


Figure 3: Path Types of Path for Origin (0,9) and Destination(9,0)

The route choice based on time cost, the traditional travel cost component, significantly differs from safest path, which has a time cost that in this example is about twice the shortest path. The lowest internal cost path and the lowest full cost path, which include time cost, have more overlaps with the shortest one. In the example, the greenest path exactly coincides with the shortest path, while we expect differences on a larger network.

Calculating the travel costs of each path type (as Figure 3 shows) from origins to all the other destinations, we measure the accessibility, accessibility differences, and mode-combined accessibility.

6.2 Component Accessibility Analysis

Figure 4 displays the accessibility of Node (0,0) for alternate cost components, subject to a $5 cost threshold. For illustration, we used $5 *time cost threshold* to measure the accessibility based on the shortest path, but $5 *crash cost threshold* to measure that based on the safest path, and so on.

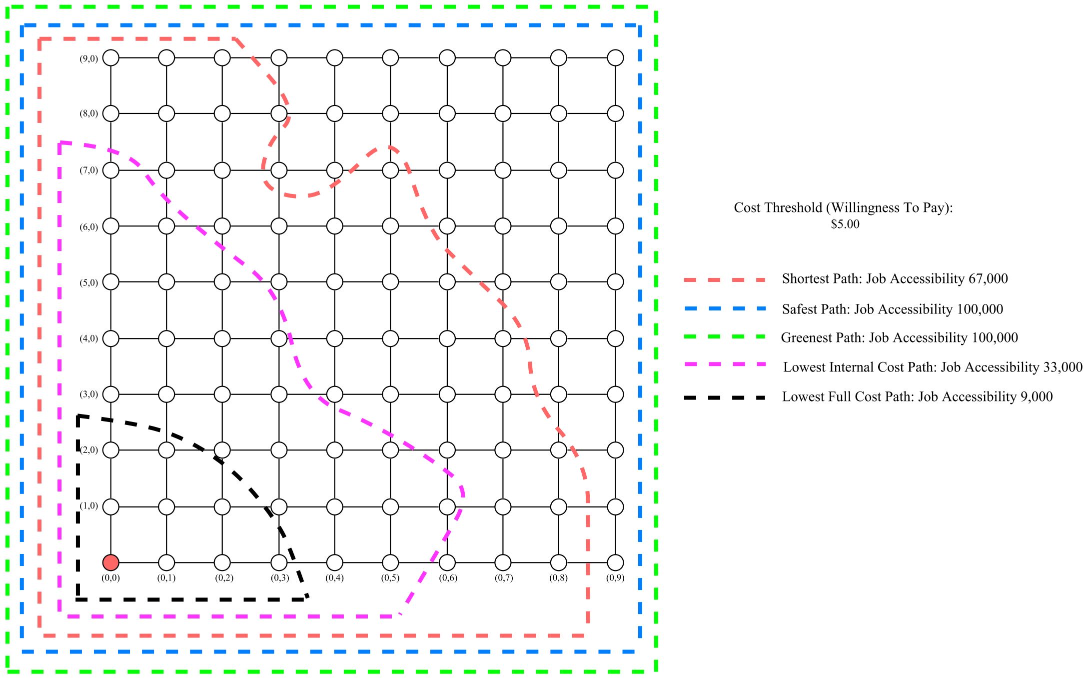


Figure 4: Component and FCA Analysis: Accessibility of Node(0,0) at Iso-Cost Threshold of $5

The curves on the figure refer to the isocost lines. Travelers from Node(0,0) pay less than $5 of each cost component to reach the nodes within the curves, based on the corresponding paths. The accessibility for Node(0,0) is shown in the legend.

In $5, travelers from Node (0,0) can reach all the job opportunities on the network by using $5 of safety on the safest path and $5 of pollution on the greenest path. The accessibility based on other path types are much lower, especially the lowest full cost path. This is consistent with the cost analysis results: time cost is much higher than safety and emission cost. Full cost adds all the other cost components.

6.3 Accessibility Difference Analysis

Figure 5 shows accessibility differences of Node (0,0) by comparing the accessibility metrics based on different cost components with the same full cost threshold of $16. For illustration, we used $16 *full cost threshold* to measure the accessibility based on all different path types.

Within the full cost threshold (Figure 5), it is shown that, in $16, using the lowest full cost path would have the highest job accessibility (60,000) since it is the optimal path to minimize full costs. Using other path types would make the trips more expensive, which results in an accessibility loss. For Node(0,0), the accessibility loss by using the shortest path, safest path, greenest path and the lowest internal cost path is 1,000, 34,000, 3,000 and 1,000 respectively.

6.4 Mode-combined Accessibility Analysis

Figure 6 displays the lowest internal cost path and the lowest full cost path by both auto and biking from Node (0,9) to Node (9,0) (The lowest full cost path by biking is the same as the lowest internal cost path since the external costs were set as 0.).

The results indicate that driving shows advantages over bicycling if travelers only considered the internal cost even in this small toy network. The full cost of bicycling, however, is much lower than driving. Depending on the mode and route choice rules in the mode-combined accessibility measure-

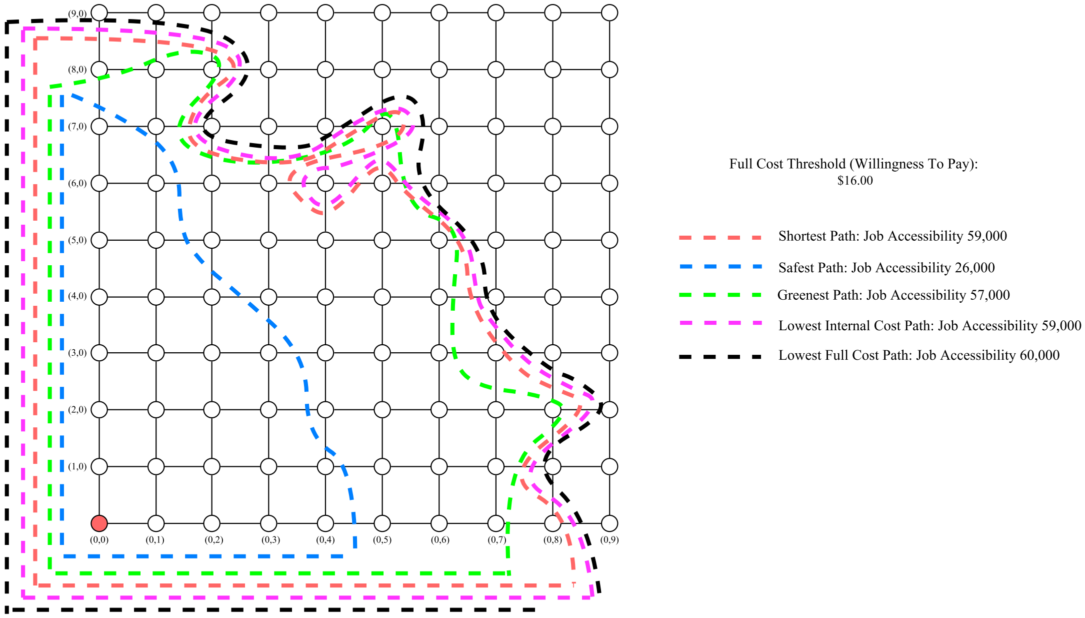


Figure 5: Accessibility Difference Analysis: $16 Full Cost Isocost Lines for Travelers from Node(0,0) Using Different Paths. The accessibility for Node(0,0) is shown in the legend.

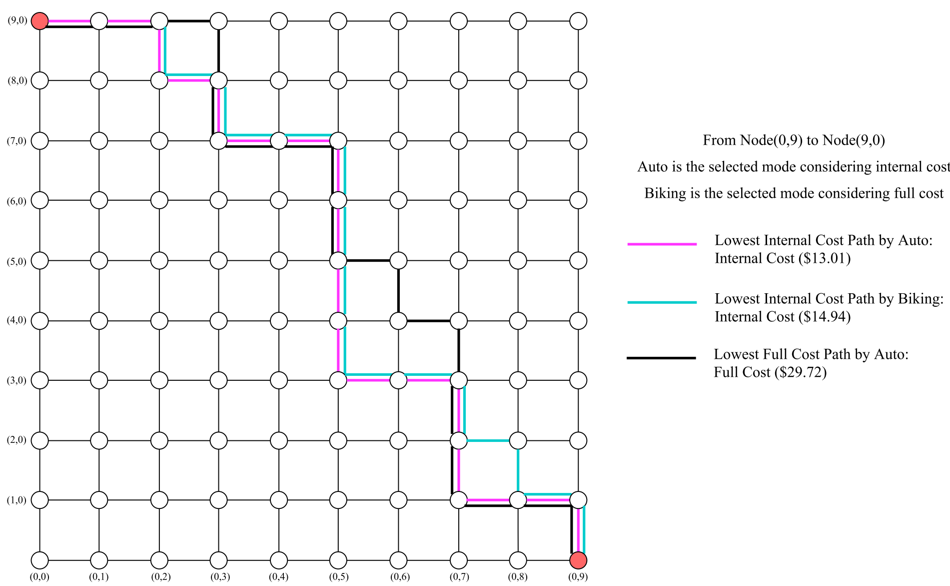
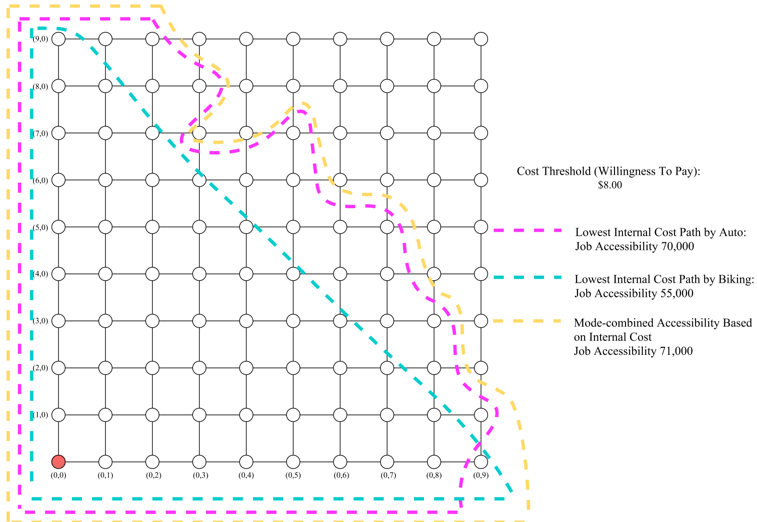


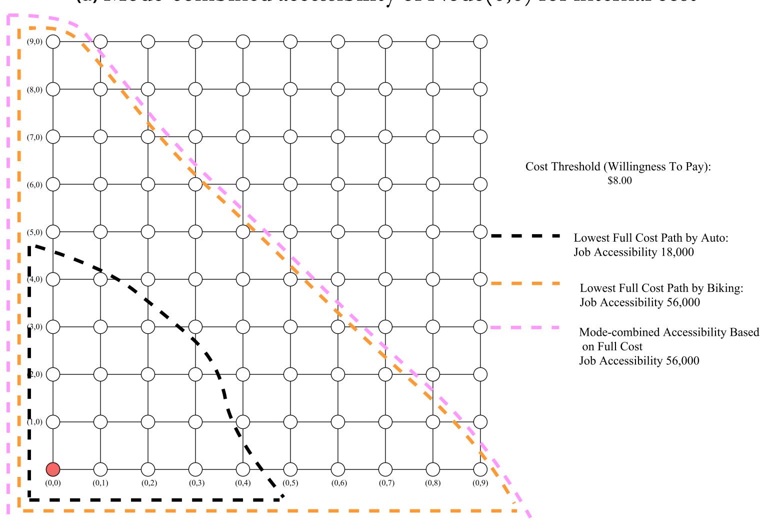
Figure 6: Types of Paths by Autos and Biking

ment, if the internal cost is considered, auto would be the preferred mode and the lowest internal cost path by auto would be the preferred route. While if the full cost is considered, biking would be the preferred mode and the lowest full cost path by biking would be the preferred route.

Figure 7 shows the mode-combined accessibility for the internal cost (Figure 7(a)) and full cost (Figure 7(b)) respectively for a cost threshold of $8. Again, the curves refer to the isocost lines of the cost threshold, and the accessibility is shown in the legends.



(a) Mode-combined accessibility of Node(0,0) for internal cost



(b) Mode-combined accessibility of Node(0,0) for full cost

Figure 7: Mode-combined accessibility of Node(0,0) within $8.00

Mode-combined accessibility can be no lower than the accessibility of a single mode, in this case bike, and may be higher if one mode is better for certain OD pairs, and another mode is better for others.

7 Conclusion

This paper develops a full cost framework incorporating alternate cost components into accessibility evaluations. The framework estimates the cost of travel, evaluates new path types, and measures accessibility. The key cost components considered here are time, safety, emission, and monetary costs. This analysis of the component costs of travel, as well as the full cost, contrasts with most traditional accessibility metrics, which comprise internal time (and sometimes money (El-Geneidy et al. 2016) cost).

The cost analysis distinguishes the internal and external costs of travel for the key cost components, and implements a link-based full cost model applied to a test road network. We believe it provides a useful tool for travel cost assessment.

The new path types, including the safest and greenest paths, in addition to the traditional shortest travel time and least expensive (monetary) paths, test alternative route choices. The new full cost path type considers the route if travelers were to consider the external costs imposed on others in their decisions. It allows the measurement of how much society would save if the optimal path were selected.

Component and FCA evaluation shows the number of opportunities that can be reached for given cost thresholds. It can be used to evaluate transport services and land-use development and to monitor the changes for each cost component.

A mode-combined accessibility analysis uses the travel mode with the lowest travel cost for each OD pair in accessibility calculations. In conventional accessibility analysis, travel by automobile has the highest accessibility (considering only travel time) for almost every origin. However when looking at full costs, that no longer holds. Compared with the accessibility by a single mode, mode-combined accessibility demonstrates that the presence of multiple modes can improve accessibility, when different modes better serve different OD pairs.

This framework also has implications for accessibility-based planning, as the use of full costs rather than internal costs has the potential to change the ranking of investments and developments. While some projects may reduce internal costs for travelers, they often do so at the expense of greater externalities or infrastructure costs. Here both of those are incorporated, and so investments that are socially more beneficial or less costly may rank higher.

A toy network was built in this paper to illustrate the implementation of the framework, which demonstrates the potential and practicality of applications in real networks.

In real-world applications, a large amount of data is required for the link-based cost analysis and accessibility measurement. GIS shapefiles of road networks showing their geographical structures are needed, which provide network datasets, including geometric properties like segment length. Link-based traffic data, travel speed and traffic flow, is required not only for the time cost assessment, but also for the safety and emission cost estimations. Crash count data is also needed for safety cost analysis. Spatial distributions of opportunities is required for accessibility calculations, which describes the number of opportunities in each destination. Details for the required data can be found in our studies of extending accessibility analysis for the Minneapolis – St. Paul Metropolitan area (Cui and Levinson 2017, 2018; Cui et al. 2017).

We used basic cost functions for the toy network as proof-of-concept. In applications, we expect more sophisticated analysis will be employed. This might include accounting for link interdependencies.

Future studies should extend the framework to transit, especially for the cost analysis part, to identify the internal and external costs from the perspective of passengers. Moreover, a full-benefit analysis could be conducted. It is believed, for instance, that health is improved by travel on non-motorized modes. Happiness might also vary by mode, and so could be reflected in different ways of assessing value of time. This could be considered in the analysis.

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References

Ahn, K. and H. Rakha. 2007. Field evaluation of energy and environmental impacts of driver route choice decisions. In *Intelligent Transportation Systems Conference, 2007. ITSC 2007*, pp. 730–735. IEEE.

Ahn, K. and H. Rakha. 2008. The effects of route choice decisions on vehicle energy consumption and emissions. *Transportation Research Part D: Transport and Environment*, 13(3):151–167.

American Association of State Highway and Transportation Officials (AASHTO). 2010. Highway safety manual.

Anderson, P., D. Levinson, and P. Parthasarathi. 2013. Accessibility futures. *Transactions in GIS*, 17(5):683–705.

Barnes, G. and P. Langworthy. 2004. Per mile costs of operating automobiles and trucks. *Transportation Research Record: Journal of the Transportation Research Board*, (1864):71–77.

Ben-Akiva, M., M. Bergman, A. J. Daly, and R. Ramaswamy. 1984. Modeling inter-urban route choice behaviour. In *Proceedings of the 9th International Symposium on Transportation and Traffic Theory*, pp. 299–330. VNU Science Press Utrecht, The Netherlands.

Ben-Akiva, M. E. and S. R. Lerman. 1985. *Discrete choice analysis: theory and application to travel demand*, volume 9. Cambridge, MA: MIT Press.

Carlson, K., A. Ermagun, B. Murphy, A. Owen, and D. M. Levinson. 2017. Safety in numbers and safety in congestion for bicyclists and motorists at urban intersections. Working paper.

Cui, M. and D. Levinson. 2016. Accessibility and the ring of unreliability. *Transportmetrica A: Transport Science*, pp. 1–18.

Cui, M. and D. M. Levinson. 2017. The safest path: Analyzing the effects of crash costs on route choice and accessibility. In *96th Annual Meeting of Transportation Research Board, Washington D.C., 2017*.

Cui, M. and D. M. Levinson. 2018. The healthiest vs. greenest path: Comparing the effects of internal and external costs of motor vehicle pollution on route choice. In *97th Annual Meeting of Transportation Research Board, Washington D.C., 2018*.

Cui, M., A. Owen, and D. Levinson. 2017. Exploring and expanding accessibility metrics for transportation planning, Phase 2 extending accessibility analysis. Technical report, Accessibility Observatory, University of Minnesota, Minneapolis.

Delucchi, M. A. 1997. The annualized social cost of motor-vehicle use in the us, 1990-1991. Technical report, UC Berkeley University of California Transportation Center, Berkeley, CA.

Dijkstra, A. and H. Drolenga. 2008. Safety effects of route choice in a road network: Simulation of changing route choice. Technical report, SWOV Institute for Road Safety Research, The Hague.

Edlin, A. S. and P. Karaca-Mandic. 2006. The accident externality from driving. *Journal of Political Economy*, 114(5):931–955.

El-Geneidy, A. and D. Levinson. 2009. Place rank: A flow-based accessibility measure.

El-Geneidy, A., D. Levinson, E. Diab, G. Boisjoly, D. Verbich, and C. Loong. 2016. The cost of equity: Assessing transit accessibility and social disparity using total travel cost. *Transportation Research Part A: Policy and Practice*, 91:302–316.

El-Geneidy, A. M. and D. M. Levinson. 2006. Access to destinations: Development of accessibility measures. Technical report, University of Minnesota, Minneapolis.

Geurs, K. T. and B. Van Wee. 2004. Accessibility evaluation of land-use and transport strategies: review and research directions. *Journal of Transport Geography*, 12(2):127–140.

Gillen, D. and D. Levinson. 1999. Full cost of air travel in the California corridor. *Transportation Research Record: Journal of the Transportation Research Board*, (1662):1–9.

Greene, D. L. and D. W. Jones. 1997. *The Full Costs and Benefits of Transportation: Contributions to Theory, Method and Measurement; with 62 Tables*. Springer Science & Business Media.

Handy, S. and D. Niemeier. 1997. Measuring accessibility: an exploration of issues and alternatives. *Environment and Planning A*, 29:1175–1194.

Hansen, W. G. 1959. How accessibility shapes land use. *Journal of the American Institute of Planners*.

Iacono, M., K. J. Krizek, and A. El-Geneidy. 2010. Measuring non-motorized accessibility: issues, alternatives, and execution. *Journal of Transport Geography*, 18(1):133–140.

Ibeas, Á., R. Cordera, L. dell'Olio, P. Coppola, and A. Dominguez. 2012. Modelling transport and real-estate values interactions in urban systems. *Journal of Transport Geography*, 24:370–382.

Ingram, D. R. 1971. The concept of accessibility: A search for an operational form. *Regional studies*, 5(2):101–107.

Jakob, A., J. L. Craig, and G. Fisher. 2006. Transport cost analysis: a case study of the total costs of private and public transport in Auckland. *Environmental Science & Policy*, 9(1):55–66.

Jansson, J. O. 1994. Accident externality charges. *Journal of Transport Economics and Policy*, pp. 31–43.

Kockelman, K. 1997. Travel behavior as function of accessibility, land use mixing, and land use balance: Evidence from San Francisco Bay Area. *Transportation Research Record: Journal of the Transportation Research Board*, (1607):116–125.

LaMondia, J. J., C. E. Blackmar, and C. R. Bhat. 2010. Comparing transit accessibility measures: A case study of access to healthcare facilities. In *90th Annual Meeting of Transportation Research Board, Washington D.C., 2011*.

Lena, T., V. Ochieng, M. Carter, J. Holguín-Veras, and P. Kinney. 2002. Elemental Carbon and PM 2.5 Levels in an Urban Community Heavily Impacted by Truck Traffic. *Environmental Health Perspectives*, 110(10):1009–1016.

Levine, J., L. Merlin, and J. Grengs. 2017. Project-level accessibility analysis for land-use planning. *Transport Policy*, 53:107–119.

Levinson, D. 1998. Accessibility and the journey to work. *Journal of Transport Geography*, 6(1):11–21.

Levinson, D. 2013. Access across america: Auto 2013. Technical report, Center of Transportation Studies, University of Minnesota, Minneapolis.

Levinson, D. and D. Gillen. 1998. The full cost of intercity highway transportation. *Transportation Research Part D: Transport and Environment*, 3(4):207–223.

Levinson, D. and A. Kumar. 1994. Multi-modal trip distribution: Structure and application. *Transportation Research Record: Journal of the Transportation Research Board*, 1446:124–131.

Levinson, D., J. M. Mathieu, D. Gillen, and A. Kanafani. 1997. The full cost of high-speed rail: an engineering approach. *The Annals of Regional Science*, 31(2):189–215.

Lord, D. 2002. Application of accident prediction models for computation of accident risk on transportation networks. *Transportation Research Record: Journal of the Transportation Research Board*, (1784):17–26.

Lyons, G. and J. Urry. 2005. Travel time use in the information age. *Transportation Research Part A: Policy and Practice*, 39(2):257–276.

Mankiw, G. N. 2014. *Principles of macroeconomics*. Cengage Learning.

Marshall, J. D., S.-K. Teoh, and W. W. Nazaroff. 2005. Intake fraction of nonreactive vehicle emissions in US urban areas. *Atmospheric Environment*, 39(7):1363–1371.

Mayeres, I., S. Ochelen, and S. Proost. 1996. The marginal external costs of urban transport. *Transportation Research Part D: Transport and Environment*, 1(2):111–130.

McGarity, T. O. 2012. Final regulatory impact analysis: Corporate average fuel economy for MY 2017-MY 2025 Passenger cars and light trucks. Technical report, US Department of Transportation, Washington, DC.

Melo, P. C., D. J. Graham, D. Levinson, and S. Aarabi. 2017. Agglomeration, accessibility and productivity: Evidence for large metropolitan areas in the US. *Urban Studies*, 54(1):179–195.

Minnesota Department of Transportation. 2015. Benefit-cost analysis for transportation projects. URL http://www.dot.state.mn.us/planning/program/benefitcost.html.

Minnesota Department of Transportation. 2016a. Traffic engineering, crash data. URL http://www.dot.state.mn.us/trafficeng/safety/crashdata.html.

Minnesota Department of Transportation. 2016b. Traffic forecasting and analysis. URL http://www.dot.state.mn.us/traffic/data/.

Murphy, B., D. M. Levinson, and A. Owen. 2017. Evaluating the safety in numbers effect for pedestrians at urban intersections. *Accident Analysis & Prevention*, 106:181–190.

Neuhold, R. and M. Fellendorf. 2014. Volume delay functions based on stochastic capacity. *Transportation Research Record: Journal of the Transportation Research Board*, (2421):93–102.

Owen, A. and D. Levinson. 2012. Access to destinations: Annual accessibility measure for the Twin Cities Metropolitan Region. Technical report, Minnesota Department of Transportation, St. Paul.

Owen, A. and D. Levinson. 2014. Access across America: Transit 2014. Technical report, Accessibility Observatory, University of Minnesota, Minneapolis.

Owen, A., D. Levinson, and B. Murphy. 2014. Access across America: Walking 2014. Technical report, Accessibility Observatory, University of Minnesota, Minneapolis.

Small, K. A. and C. Kazimi. 1995. On the costs of air pollution from motor vehicles. *Journal of Transport Economics and policy*, pp. 7–32.

Small, K. A., C. Winston, and C. A. Evans. 2012. *Road work: A new highway pricing and investment policy*. Washington, DC: Brookings Institution Press.

Song, Y. and H. J. Miller. 2014. Simulating visit probability distributions within planar space-time prisms. *International Journal of Geographical Information Science*, 28(1):104–125.

Srour, I., K. Kockelman, and T. Dunn. 2002. Accessibility indices: Connection to residential land prices and location choices. *Transportation Research Record: Journal of the Transportation Research Board*, (1805):25–34.

Tang, W. and D. M. Levinson. 2018. An empirical study of the deviation between actual and shortest travel time paths. *ASCE Journal of Transportation Engineering, Part A: Systems*, 144(8).

Transportation Research Board. 2010. Highway Capacity Manual.

U.S. Department of Commerce, Bureau of Public Roads. 1964. *Traffic Assignment Manual*. U.S. Government Print Office.

U.S. Department of Transportation. 2014. Revised departmental guidance on valuation of travel time in economic analysis. Technical report, U.S. Department of Transportation, Office of the Secretary of Transportation.

Vickerman, R. W. 1974. Accessibility, attraction, and potential: A review of some concepts and their use in determining mobility. *Environment and Planning A*, 6(6):675–691.

Vickrey, W. 1968. Automobile accidents, tort law, externalities, and insurance: An economist's critique. *Law and Contemporary Problems*, 33(3):464–487.

Wachs, M. and T. G. Kumagai. 1973. Physical accessibility as a social indicator. *Socio-Economic Planning Sciences*, 7(5):437–456.

Wu, Y.-H. and H. J. Miller. 2001. Computational tools for measuring space-time accessibility within dynamic flow transportation networks. *Journal of Transportation and Statistics*, 4(2/3):1–14.

Zhu, S. and D. Levinson. 2015. Do people use the shortest path? An empirical test of wardrop's first principle. *PloS one*, 10(8):e0134322.