Full Cost Accessibility

A THESIS
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BY

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David Levinson

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Abstract

Accessibility measures the ease of reaching destinations, and is the product of a function of the cost of travel between two points and the number of opportunities at the destination. That cost is usually represented as individual travel time, and occasionally as time and out-of-pocket monetary costs. Thus, it fails to fully capture travel costs, especially the external costs, of travel. This study develops a full cost accessibility (FCA) framework combining the internal and external cost components of travel with accessibility evaluations, to provide an efficient evaluation tool for transport planning projects.

The FCA framework includes three major steps: analyzing cost components of travel, proposing new path types, and performing FCA analysis. The cost analysis distinguishes the internal and external costs of travel for alternate cost components and proposes a link-based cost model applied to each road segment in a metropolitan road network. The new path types, including the Safest and Greenest/Healthiest paths, in addition to the traditional Shortest Travel Time and Cheapest (least expensive) paths, are proposed to translate link costs into trip costs by selecting the routes with the lowest cost. For the FCA analysis, we measure the number of opportunities that can be reached in a given cost threshold.

The key cost components for travelers are categorized as time costs, safety costs, emission costs, and monetary costs. The Minneapolis - St. Paul Metropolitan (Twin Cities) region was selected as the study area to implement the FCA framework based on each of those key cost components. Our major findings indicate:

1. The average full cost of travel is $0.68/veh-km in the Twin Cities region. Time and monetary costs account for approximately 85% of the total. It is unlikely that travelers will shift their route significantly to consider safety and emissions.

2. Except for the infrastructure cost, highways are more cost-effective than other surface roadways considering all the other cost components, and the internal and full costs.

3. Most new path types show largely the same spatial distribution as the shortest travel time path. However, the healthiest path, concerning the emission intake cost, detours...
to exurban areas where the on-road concentrations are lower; the lowest infrastructure
cost path detours to local surface roadways where the infrastructure expenses are
lower.

4. Job accessibility measurements based on different cost components show similar spa-
tial distribution patterns. Accessibility decreases with the distance to the downtown
area. Slight differences exist depending on the properties of cost components.

5. Accessibility difference assessment reveals a cost-benefit trade-off showing that trav-
elers will save $0.24/veh-km of full cost on average based on the lowest full cost path
rather than the shortest travel time path by paying a time-weighted accessibility loss
of 191 jobs.

This dissertation demonstrates the practicability of FCA framework in metropolitan
areas.
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## Symbolization

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<td>$A_{O,c,m}$</td>
<td>Accessibility of origin $O$ considering cost component $c$ by mode $m$</td>
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<tr>
<td>$B$</td>
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<td>Emission cost borne by travelers themselves</td>
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<td>The greenest (combined) path</td>
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<tbody>
<tr>
<td>$P_{l,int}$</td>
<td>The cheapest (internal) path or the lowest monetary cost path</td>
</tr>
<tr>
<td>$P_{l,ext}$</td>
<td>The cheapest (external) path or the lowest infrastructure cost path</td>
</tr>
<tr>
<td>$P_{l,com}$</td>
<td>The cheapest (combined) path</td>
</tr>
<tr>
<td>$P_{OD,k,m}$</td>
<td>The $k^{th}$ path between O and D by mode m</td>
</tr>
<tr>
<td>$P_{OD,k}$</td>
<td>The $k^{th}$ path between O and D</td>
</tr>
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<tr>
<td>$P_{s,ext}$</td>
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<td>$P_{s}$</td>
<td>The safest path</td>
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</tr>
<tr>
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<td>Vehicle-kilometer of travel by truck</td>
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<tr>
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<td>Capacity</td>
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<td>$R_b$</td>
<td>Breathing rate</td>
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<td>$R_{i_f,z}$</td>
<td>Probability of type $z$ crashes happened on link $i_f$</td>
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<td>$R_g$</td>
<td>Intake fraction, the fraction of emissions that are inhaled by exposed people</td>
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<td>$R_{v_t}$</td>
<td>truck percentage on highways</td>
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<td>Transport system’s internal cost</td>
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<tr>
<td>$S_E$</td>
<td>Transport system’s external cost</td>
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<td>Time threshold</td>
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<td>Unit emission cost of CO$_2$, $22/\text{ton} \ (2010 \ \text{US dollar})$</td>
</tr>
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<td>Unit emission cost</td>
</tr>
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<td>$u_{g,p}$</td>
<td>Unit emission cost of pollutant $p$</td>
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<td>Unit intake-emission cost of pollutant $p$</td>
</tr>
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<td>Price of labor</td>
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<td>$u_B$</td>
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<td>$u_s$</td>
<td>Unit crash cost</td>
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<tr>
<td>$u_{s,p}$</td>
<td>Unit crash cost per injured person</td>
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<tr>
<td>$u_{s,v}$</td>
<td>Unit crash cost per involved vehicle</td>
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<td>$u_{s,z}$</td>
<td>Unit crash cost per vehicle involved in a type $z$ crash</td>
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<td>Per injured person based crash cost in a type $z$ crash</td>
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<td>$u_{s,v,z}$</td>
<td>Per crashing vehicle based crash cost in a type $z$ crash</td>
</tr>
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<td>$U$</td>
<td>Urban roadways</td>
</tr>
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<td>Traffic speed</td>
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<tr>
<td>$V_i$</td>
<td>Traffic speed on link $i$</td>
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<tr>
<td>$V_Q$</td>
<td>Traffic speed associated with traffic flow $Q$</td>
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<td>$V_{Var}$</td>
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<td>Width of roads</td>
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<tr>
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<tr>
<td>$W_{snow}$</td>
<td>Road surface feature is snow</td>
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<td>Emission cost imposed on other motorized travelers</td>
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<td>Health damage cost vehicle $k$ imposes on $q$</td>
</tr>
<tr>
<td>$X_s$</td>
<td>Crash cost imposed on other motorized travelers</td>
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<td>Increased crash cost due to vehicle $k$ imposed on vehicle $q$</td>
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<td>Time cost imposed on other motorized travelers</td>
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<td>Cost imposed on other non-motorized travelers</td>
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<td>Emission cost imposed on other non-motorized travelers</td>
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<td>$z$</td>
<td>Crash severity</td>
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<tr>
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<td>Cost imposed on other non-travelers</td>
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<td>Emission cost imposed on other non-travelers</td>
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<td>$Z_s$</td>
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<td>$Z_t$</td>
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<tr>
<td>$\alpha, \beta, \epsilon$</td>
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<tr>
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<td>Threshold values to illustrate crash severity</td>
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<td>$\varepsilon$</td>
<td>Random error term</td>
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<tr>
<td>( \rho_{p,i}(t) )</td>
<td>Concentrations of pollutant ( p ) of link ( i ), which varies with time</td>
</tr>
<tr>
<td>( \rho_{p,i,j}(t) )</td>
<td>Off-road concentration of block ( j ) contributed by emissions ( p ) from link ( i )</td>
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Chapter 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.

The term accessibility reflects the correlations between the cost and benefits of travel and combines them into a single metric, which represents the strengths and weaknesses of interactions of the transport network and land-use, that should be considered in transport planning.

A very basic accessibility metric is cumulative opportunities, which measures the number of opportunities reachable within a given threshold (Vickerman 1974, Wachs & Kumagai 1973, Ingram 1971, Wickstrom 1971). Figure 1.1 displays the accessibility to jobs with a given time threshold setting as 20, 30, and 40 minutes respectively, based on the cumulative opportunity measure. It illustrates the trade-off between a traveler cost and benefit that can be achieved since an increased travel time threshold allows reaching more job opportunities overall, where the travel time threshold represents a given time cost of travel.

Accessibility is a reliable tool for comparing the effectiveness of proposed land-use and transport network scenarios in planning projects. Anderson et al. (2013) analyzed the accessibility of scenarios with the combination of six land use and twelve networks cases (both highway and transit). Moreover, accessibility significantly affects different aspects of travel behavior. Levinson (1998) and Kockelman (1997) examined the critical influences
of accessibility on travelers’ behaviors of commuting duration, vehicle kilometers traveled, automobile ownership, and mode choice, while others have considered real estate prices (Srour et al. 2002, Ibeas et al. 2012) and economic productivity (Melo et al. 2017).

Figure 1.1: Traditional Time-based Job Accessibility by Auto in Different Time Thresholds using median speeds

(a) 20 min

(b) 30 min

(c) 40 min

Typically, accessibility has been analyzed from the perspective of the mean or expected travel time (Cui & Levinson 2018a). 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 measurements. 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 evaluate transport projects properly.

In this dissertation, 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.
Chapter 2

Literature Review

2.1 Accessibility

2.1.1 Definition

The concept of accessibility, literally, means the ability to access, in which access is the act of approaching something (El-Geneidy et al. 2006). It was introduced into transport planning field in 1959 by Hansen (1959) and it is widely believed that a higher accessibility reflects a more effective transport system (Cervero et al. 1997, Cheng & Bertolini 2013, El-Geneidy et al. 2006, Hansen 1959, Levinson 1998, Martellato & Nijkamp 1998, Owen & Levinson 2012, Páez et al. 2012).

Accessibility has been defined in several ways, which, however, reflects subtle variations (Ganning 2014). A well-known definition of accessibility was offered by Hansen (1959) as the “potential of opportunities for interaction”. Levine & Garb (2002) defined accessibility as the “ease of reaching destinations”. Seeing accessibility as indicators for the impact of land-use and transport system developments, Geurs & Van Wee (2004) defined accessibility as “the extent to which land-use and transport systems enable (groups of) individuals to reach activities or destinations by means of a (combination of) transport mode(s)”.

Bhat et al. (2000) proposed a qualitative definition that “accessibility is a measure of the ease of an individual to pursue an activity of a desired type, at a desired location, by a desired mode, and at a desired time”.

The term mobility is often misused with accessibility, which measures the ability to
move from one place to another (Handy 1994, Hansen 1959). A high level of mobility does not necessarily reflect a high level of accessibility. Great accessibility can be achieved even though mobility is constrained if many destinations are close by. Accessibility may be poor even though mobility is high if potential destinations are remote (Levine & Garb 2002, Stopher 2004). Consider the comparison between Manhattan and Manitoba (El-Geneidy et al. 2006), travel in Manhattan can reach many opportunities even with a lower-level of mobility, while in contrast, the accessibility is quite low in Manitoba where the travel speed is high. As Levine & Garb (2002) state, mobility reflects the cost of travel per kilometer, while accessibility reflects the cost of travel per destination.

Geurs & Van Wee (2004) summarized four types of components of accessibility from these different definitions. The land-use component indicates the spatial distribution of supply and demand of opportunities at destinations and origins correspondingly. The transportation component describes the cost of travel for an individual covering an origin and a destination, e.g., time cost, monetary cost. The temporal component reflects the time constraints for individuals to participate in desired activities. The individual component illustrates individuals' needs, abilities, and opportunities. Hence, accessibility is a comprehensive indicator that investigates the changes in land use, transport networks, time constraints, and personal capability.

However, accessibility cannot be presented without mobility since the opportunities are distributed over time and space (El-Geneidy et al. 2006). Accessibility can be improved by increasing the mobility (Berdica 2002). Generally, in the US, the accessibility, for a given origin, is much higher by autos than by transit or walk due to faster speeds (and lower wait times in comparison with transit) for automobiles.

### 2.1.2 Accessibility Measures

Various methods have been proposed to measure accessibility. Focusing on the usability in evaluations of alternative land-use and transport policies, Handy & Niemeier (1997) have reviewed the cumulative opportunity measures, gravity-based measures and utility-based measures for planners to use, which are all classified as location-based measures by Geurs & Van Wee (2004). A complement to this, Geurs & Van Wee (2004) have also
reviewed accessibility measures from other three perspectives, including infrastructure-based measures, person-based measures, and utility-based measures, according to criteria like theoretical basis, interpretability, and data requirement. The infrastructure-based measures, however, are more like measures of mobility, as the results only consider the travel cost, such as travel time, without a land-use input, which is not our focus. Other accessibility measures are discussed here in detail.

The cumulative opportunity measure counts the number of opportunities that can be reached within a predetermined travel cost threshold, (Vickerman 1974, Wachs & Kumagai 1973, Ingram 1971, Wickstrom 1971). It is a very basic method that is simple to calculate due to a binary cost function comparing the travel costs with the thresholds. It has been commonly used in accessibility measurements, as the study ‘Access Across America’ used the cumulative opportunity measure to assess accessibilities for around 50 metropolitan areas by auto, transit and walking (Owen et al. 2014, Levinson 2013, Owen & Levinson 2014).

Advantageously, the cumulative opportunity measure is straightforward to interpret, as it directly shows the count of reachable opportunities. In addition, it is sensitive to the changes in transport network or land use, which makes it a useful way to evaluate the effectiveness of planning projects. It is also easy to communicate to policymakers and the public. But the binary cost function does not consider the impedance of reaching destinations or the attractiveness of them and creates artificial distinctions between destinations with similar travel costs (Owen & Levinson 2012, El-Geneidy et al. 2006).

The gravity-based measure, which was derived from the gravity model for trip distribution, is also commonly used in accessibility measurement (Handy & Niemeier 1997). Similar to the cumulative opportunity measure, it counts the total potential opportunities as well, but expecting the accessibility to decrease with a farther distance (or a higher travel cost) from the origins (Hansen 1959, Vickerman 1974, Ingram 1971). This measure considers the cost impedance in the calculation that an opportunity will contribute to accessibility more if it costs less to reach.

The application of the gravity-based measure is more complex due to the impedance function. First, even though the negative exponential function is often recommended for gravity-based measures to represent travelers’ behavior, it may not be the best fit, which
makes it necessary to test the accuracy before using it empirically. Second, the parameter values in the impedance function need to be specified for each mode, trip purpose, and region. In addition, the gravity-based measure does not correspond to the attractiveness of destinations as well and assumes all the facilities of a given type and size are equivalent. It is difficult to compare places and times with gravity-based measures. However, the gravity-based measure combines observed travelers behavior into the accessibility indexes via the impedance function, which improves the accuracy of the accessibility evaluation and avoids the artificial distinctions between destinations generated by the cumulative opportunity measure (Handy & Niemeier 1997, Owen & Levinson 2012).

Anderson et al. (2013) proposed a time-weighted accessibility measure combining the cumulative opportunity measures with impedance functions (defined by Levinson & Kumar (1995)), which mitigates the artificial distinctions. Basically, it weighs the donut accessibility (e.g. $A_{20\text{min}} - A_{10\text{min}}$) based on the time threshold (e.g. 20 min). This essentially replicates a gravity-based measure if the donuts are thin enough.

The space-time accessibility is a person-based measure, which incorporates individuals’ spatial constraints, e.g., fixed activity locations, and temporal constraints, for instance, time-budget, required travel time, and required participation time, into accessibility analysis based on the space-time primes or time-geographical framework (Hägerstrand 1970, Miller 1991, Wu & Miller 2001, Miller & Wu 2000). The space-time accessibility counts the potential areas of opportunities that can be reached with personal time constraints, which has theoretical advantage that considers individual variations in accessibility. However, the applications of this measure are restricted to a relatively small region since it requires detailed individual activity-travel data. The computational intensity is another burden for its application to a higher geographical scale (Geurs & Van Wee 2004, Kwan 1998).

The utility-based measure was derived first based on the multinomial logit model, which incorporates individuals’ travel behavior and decision-making preferences into accessibility measurements, and uses the corresponding utility to interpret accessibility (Ben-Akiva & Lerman 1985). The utility-based measure not only accounts for the travel impedance and attractiveness of destinations but differentiates them by individuals. It gives different evaluations of accessibility for people living in the same analysis area based on the utilities of destinations and the characteristics of the individuals (Owen & Levinson 2012). Miller
(1999) combined the space-time accessibility with the utility-based measure, which reconciles space-time prisms, destination attractiveness, and welfare providing to individuals.

Similar to the space-time accessibility, the utility-based measure requires the detailed travel behavior data to show travelers’ actual preference and destination attractiveness data to measure the utility (Owen & Levinson 2012). It is not suitable for an application on a larger geographical scale. In addition, the accessibility is harder to interpret based on this measure since utility is an abstract value without any units (El-Geneidy et al. 2006, LaMondia et al. 2010), though it can be monetized since a value of time can often be estimated if the function is specified appropriately.

Place rank is a flow-based accessibility measure that embeds the impedance and attractiveness of destinations into traffic flow dataset based on origin-destination information (El-Geneidy & Levinson 2011). It measures the level of accessibility of a zone by the number of people who travel to the zone for valuable opportunities and the power of each person’s contribution depends on the attractiveness of the zone as an origin (number of people originating in the zone).

The major advantage of place rank is that the cost of travel does not need to be measured, such as travel time, since it has been incorporated in the process of calculation. The data for work travel, the origins and destinations for each worker, used in place rank could be collected by the US Census Bureau, for instance. But, for areas without OD information or for other activities that lack data, the application of this measure is limited (El-Geneidy & Levinson 2011).

2.1.3 Accessibility Measurements by Modes and Destinations

Accessibility varies across modes. Generally, analysts focus on auto and transit for motorized modes, bicycle and walk for non-motorized modes, among which, however, motorized modes are more highly considered since auto and transit are the most commonly used modes, especially for commuting trips (McKenzie 2014). Moreover, considering different trip purposes (opportunities), accessibility to jobs is widely considered the most significant, since commuting trips play a vital role in workers’ daily travel. Tilahun & Fan (2014) identified competitive industrial clusters and measured the accessibility to job clusters.

‘Access Across America’ generates the rankings of job accessibility by auto, transit, and
walking separately for metropolitan areas across the United States with different settings of travel time thresholds (Owen et al. 2014, Levinson 2013, Owen & Levinson 2014). As expected, the rankings are relatively stable for using different modes that major metropolitan areas, like New York, Los Angeles, and Chicago, have a higher ranking of accessibility by all modes. For a realistic time threshold, accessibility by auto is much higher than by transit and walking. Similarly, Shen (2006) found that job accessibility for transit passengers is significantly lower than that for auto users, especially for US cases (Boston and Los Angeles).

Other types of opportunities in accessibility studies include retail, school, restaurants, and so on. For instance, Iacono et al. (2010) applied an integral accessibility measure to evaluate the accessibility to restaurants by walking and accessibility to shopping by bicycling in South Minneapolis and proposed that higher accessibility to such activities could improve the general quality of life.

2.2 Cost of Travel

2.2.1 Internal vs. External Costs

For transport systems, it is unavoidable that travel imposes both internal and external costs due to the interaction among travelers and interdependence with other systems.

Travel time can be divided into congested and uncongested components, in which congested time implies the external cost imposed by others from the point-of-view of travelers since each additional vehicle on the roadways results in incremental delay borne by others (following travelers) (Levinson & Gillen 1998). Delay is highly related to traffic flow and increases significantly as traffic flow reaches and exceeds capacity (Neuhold & Fellendorf 2014, Levinson & Gillen 1998). Considering the link properties, traffic, and capacity, the marginal cost of travel time could be used to measure the external time 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

1From the perspective of the road system, the congested time (delay) is fully internalized, however for each traveler, which is the relevant decision unit here, it is an internal cost. This is an important distinction for evaluation, which we revisit later in the dissertation.
speed (Transportation Research Board 2010).

For crash costs, generally, the external charges refer to the costs that are imposed on society instead of the road users from the perspective of transport systems. Jakob et al. (2006) pointed that, in New Zealand, direct costs (e.g. medical, rehabilitation, aftercare costs) and part of the indirect costs (e.g. costs to police) are internalized and funded by road user charges, levies on petrol, and vehicle registration fees, but others, such as loss of production, non-market cost, and humanitarian, are totally external. In the US context, many of these costs are covered by insurance, and so internalized. However, these costs are assessed, and thus perceived, as fixed costs, unrelated to the amount of travel, at least in the short run. It would be possible to charge for them so that they are perceived as variable costs and thus enter into the trip-making calculus. Considering the individual level of cost, similar to travel time, Vickrey (1968) proposed the externality as an increased crash risk due to higher traffic flow, which implies a marginal cost of crashes (Edlin & 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 and indirect costs (Edlin & Karaca-Mandic 2006). Recognizing this is transferred to insurance costs is essential to avoid double counting in a full cost accounting framework.

On-road emission is more likely to be categorized into external costs, which affect human health, vegetation, materials, aquatic ecosystems, visibility, climate changes, and so on (Mayeres et al. 1996). Notably, damage to human health due to air pollution is the most expensive element. Small & Kazimi (1995) combined the exposure models with the health damage cost regarding 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 & Gillen 1998). Hence, the external cost of emission from the perspective of travelers could be measured by the health damage cost from emitted pollutants imposing on others. Moreover, as an active agent in transport systems, the internal emission cost for a traveler could be considered as the health damage cost borne due to pollution intake during trips.

The monetary cost of travel mainly includes user cost and infrastructure cost (if we
avoid double-counting for insurance and crashes). User car operation and maintenance costs, covering the cost of gas, oil, maintenance, and so on, is totally internal for travelers considering both average and marginal cost. Anderson & McCullough (2000, 2003) classified the infrastructure cost and other costs borne by any level of government as a new category, governmental cost. From the view of internal and external costs, part of the expenditures of infrastructure, including capital, maintenance, administrative, and so on, are internalized and transferred to the user cost, like license, registration, and taxes. Levinson & Gillen (1998) measured the infrastructure costs and distinguished the long run and short run total infrastructure expenditures where capital cost is considered as fixed for a short run estimation while it varies in a long run cost model. Many infrastructure costs are not paid directly by travelers, but instead through general taxation, and need to be accounted for. In addition, road wear and tear varies with the number and kinds of vehicles and may not be fully recovered by each traveler. 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).

2.2.2 Costs across Modes, Links, and Populations

The travel cost of all the components differ across traffic modes, links, and populations (for instance, we expect different individuals have different values of travel time savings or statistical values of life, depending on demographic variables such as income, age, and gender – and even that varies within individuals based on context), which implies different mode choice and route choice among seemingly similarly situated individuals.

Among modes, auto and transit costs vary due to their distinct properties and corresponding unit costs. Considering the average travel speed, for instance, generally, transit takes longer than driving. Travel time unit costs, moreover, varies with the trip purposes, distance, comfort, and so on. Travelers will be more willing to pay to shorten the time for business travels, long-distance travels, or more uncomfortable travels (US Department of Transportation, Office of the Secretary of Transportation 2016). And regarding the crash severity, there are fewer fatal and injury crashes caused by transit compared with automobiles or light trucks (Minnesota Department of Public Safety 2014). But the number of
fatalities or injuries involved in a crash causes the major differences in the unit cost per crash. The unit operating and emission costs also vary across modes (Reichert 2006).

The attributes of links significantly affect traffic properties, like length, speed, flow, and functional classifications, which, similar to traffic modes, play vital roles in costs. American Association of State Highway and Transportation Officials (AASHTO) (2010) applied the annual average daily traffic (AADT) and the segment length as the basic variables to estimate crash count, which is statistically significant. Motor Vehicle Emission Simulator (MOVES), developed by US Environmental Protection Agency (2015a) (EPA), asks for link inputs, including length, traffic flow, average speed, and road grade, to simulate link level emissions. Roadway conditions, like pavement roughness, also affect vehicles’ operating cost (e.g., maintenance, tire, repair, and depreciation costs). And the road classifications, ‘city’ versus ‘highway’, affect energy consumption as well (Barnes & Langworthy 2004).

Value of travel time savings (VTTS or VoT) is a critical factor to assess the time cost of travel, which is significantly affected by personal income. US Department of Transportation, Office of the Secretary of Transportation (2016) illustrates that a specified percentage of hourly income could be used to determine the value of time savings during traveling. Commonly, an income elasticity of 1.0 is applied to estimate the value of travel time savings to new times and locations for business travel, while personal travel has a lower elasticity. Gwilliam (1997) suggested using the value of 30 percent of household income for commuting and other non-work trips.

Value of a statistical life (VSL) refers to the amount that people are willing to pay for fatal risk reduction to save one life (Miller 2000), which is the key cost component in crashes and commonly considered to estimate the health damage cost of emission (Trottenberg & Rivkin 2014). VSL also varies significantly across ages and income. The findings of Aldy & Viscusi (2008) explain that VSL exhibits an inverted-U shaped relationship with age, where VSL rises from $3.2 million (age 18-24) to $9.9 million (age 35-44) and declines to $3.8 million (age 55-62). A higher income does directly result in a higher VSL, and the elasticity of income regarding to VSL ranges from 0.85 to 1.00 across counties (Miller 2000). Viscusi & Aldy (2003) estimate income elasticity averaging 0.55, but demonstrate a positive effect on VSL as well.
Chapter 3

FCA Analysis Framework

The *internal cost* refers to what consumers pay directly for goods or services. In transport, the 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 & 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 3.1 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 risks 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 the 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).

The full cost analysis framework comprises three stages: analyzing the component costs of travel, evaluating new path types, and measuring FCA, shown in Figure 3.2.
Figure 3.2: Full Cost Accessibility (FCA) Framework
3.1 Cost Analysis

Full cost analysis emerged in transport in the 1990s (Delucchi 1997, Greene & Jones 1997, Levinson & Gillen 1998, Levinson et al. 1997, Gillen & Levinson 1999). 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 the 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 & Gillen 1998). Delay is highly related to traffic flow, which increases significantly as traffic flow reaches and exceeds capacity (Neuhold & 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 risks due to higher traffic flow, which implies a marginal cost of crashes (Edlin & 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 and indirect costs (Edlin & 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 are categorized as an external cost (Mayeres et al. 1996). Notably, damage to human health due to air pollution is the most expensive element. Small & 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 & 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 & 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 & 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 operations, 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 the 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 the 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 from 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.
3.2 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 & Rakha 2008, Ben-Akiva et al. 1984, Zhu & Levinson 2015, Tang & Levinson 2015). Few travelers appear to consider minimizing the crash and emission costs, as, few, if any, travelers know these costs. The total internal, external and full costs of travel are considered in Figure 3.2.

- **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) path* \( (P_{t,int}) \) 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.

- **Safest path** – the route with the lowest crash costs. Dijkstra & 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, say the 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 \((P_{s,com})\).

- **Healthiest/Greenest path** – the route with the lowest emission costs. Ahn & 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 healthiest or 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 healthiest path** \((P_{g,int})\) minimizes intake of on-road emissions (Pollution intake may also include non-transport sources, but we neglect that in this analysis.).

  - **The greenest 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/infrastructure costs.

  - **The least expensive internal cost path** or the **lowest monetary cost path** \((P_{l,int})\) includes out-of-pocket expenses like energy, tolls, parking, taxes.

  - **The least expensive external cost path** or the **the lowest infrastructure 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:

\[
C_{OD,k,c,m} = \sum_{i \in P_{OD,k,m}} C_{c,i,m} \quad (3.1)
\]

\[
C_{OD,c,m} = \min(C_{OD,k,c,m}) \quad (3.2)
\]
Where:

\( C_{c,i,m} \): Cost of cost component \( c \) on link \( i \) by mode \( m \);

\( P_{OD,k,m} \): The \( k^{th} \) path between origin \( O \) and destination \( D \) by mode \( m \);

\( k \): 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;

\( C_{OD,k,c,m} \): Travel cost of the \( k^{th} \) path between \( O \) and \( D \) for cost component \( c \), by mode \( m \);

\( C_{OD,c,m} \): The minimum travel cost between \( O \) and \( D \) for cost component \( c \), by mode \( m \).

### 3.3 Accessibility Analysis

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

\[
A_{O,c,m} = \sum_{D} J_D f(C_{OD,c,m})
\]  

(3.3)

\[
f(C_{OD,c,m}) = \begin{cases} 
1 & \text{if } C_{OD,c,m} \leq T_c \\
0 & \text{if } C_{OD,c,m} > T_c 
\end{cases}
\]  

(3.4)

Where:

\( A_{O,c,m} \): Job accessibility of origin \( O \), for cost category \( c \) by mode \( m \);

\( J_D \): Number of opportunities (e.g. jobs) at destination \( D \);

\( C_{OD,c,m} \): Costs between origin \( O \) and destination \( D \) for cost category \( c \) by mode \( m \);

\( T_c \): The corresponding cost threshold for cost component \( c \).

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

#### 3.3.1 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, the travel cost along the optimal path, such as time cost of the shortest path and 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 3.2.

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 applications of electric vehicles.

### 3.3.2 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 with different path types, for instance, time cost of the safest path or time cost of the greenest path, need to be calculated to measure the accessibility of 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.
3.3.3 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 with their lowest full cost path.

\[ C_{OD,F} = \min_{m \in M}(C_{OD,F,m}) \forall m \in M \]  

Where:

\[ M: \text{The set of all modes } m. \]

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.
Chapter 4

An Illustration of the FCA Framework

A toy network is constructed to illustrate the FCA analysis framework.

4.1 Model Inputs

A $10 \times 10$ toy network is constructed to illustrate the FCA process. This network includes 100 vertices (nodes) and 180 edges (links) (Figure 4.1). The nodes are named based on their coordinates, and the links are identified by their nodes.

4.1.1 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 $[400-51,000]$.  

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

### 4.1.2 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.

#### 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 (US Department of Commerce, Bureau of Public Roads 1964),

$$V_Q = \frac{V_0}{1 + \alpha(Q/Q_0)^\beta}$$  

(4.1)

This function assumes that speed $V_Q$ decreases from free-flow speed $V_0$ based on the ratio of flow ($Q$) to capacity ($Q_0$). The coefficients $\alpha$ and $\beta$ are usually set as 0.15 and 4.

A unit time value for business trips ($24.10/h for auto (US Department of Transportation 2014a)) was used to monetize the travel time.

#### 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 regressions, the function is expressed as

---

1The 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 2016d)), 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%. 

\[ N = \exp(\beta_0)Q^{\beta_1} \times L^{\beta_2} \] (4.2)

Where:
- \( L \): Segment length;
- \( Q \): Daily traffic (AADT).

Table 4.1 estimates the models.
### Table 4.1: Estimates of Safety Performance Function (SPF)

<table>
<thead>
<tr>
<th></th>
<th>Est.</th>
<th>S.E.</th>
<th>Signif.</th>
<th>AIC</th>
<th>Pseudo R²</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fatal</strong></td>
<td>Intercept</td>
<td>-6.156</td>
<td>0.783</td>
<td>***</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Log(Q)</td>
<td>0.203</td>
<td>0.093</td>
<td>*</td>
<td>822</td>
</tr>
<tr>
<td></td>
<td>Log(L)</td>
<td>0.553</td>
<td>0.139</td>
<td>***</td>
<td></td>
</tr>
<tr>
<td><strong>[$10,600,000]</strong></td>
<td>Log(Q)</td>
<td>0.203</td>
<td>0.093</td>
<td>*</td>
<td>822</td>
</tr>
<tr>
<td></td>
<td>Log(L)</td>
<td>0.553</td>
<td>0.139</td>
<td>***</td>
<td></td>
</tr>
<tr>
<td><strong>Injury Type A</strong></td>
<td>Intercept</td>
<td>-4.705</td>
<td>0.311</td>
<td>***</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Log(Q)</td>
<td>0.282</td>
<td>0.037</td>
<td>***</td>
<td>4,367</td>
</tr>
<tr>
<td></td>
<td>Log(L)</td>
<td>0.512</td>
<td>0.054</td>
<td>***</td>
<td></td>
</tr>
<tr>
<td><strong>[$570,000]</strong></td>
<td>Log(Q)</td>
<td>0.282</td>
<td>0.037</td>
<td>***</td>
<td>4,367</td>
</tr>
<tr>
<td></td>
<td>Log(L)</td>
<td>0.512</td>
<td>0.054</td>
<td>***</td>
<td></td>
</tr>
<tr>
<td><strong>Injury Type B</strong></td>
<td>Intercept</td>
<td>-3.517</td>
<td>0.189</td>
<td>***</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Log(Q)</td>
<td>0.337</td>
<td>0.023</td>
<td>***</td>
<td>12,783</td>
</tr>
<tr>
<td></td>
<td>Log(L)</td>
<td>0.521</td>
<td>0.032</td>
<td>***</td>
<td></td>
</tr>
<tr>
<td><strong>[$170,000]</strong></td>
<td>Log(Q)</td>
<td>0.337</td>
<td>0.023</td>
<td>***</td>
<td>12,783</td>
</tr>
<tr>
<td></td>
<td>Log(L)</td>
<td>0.521</td>
<td>0.032</td>
<td>***</td>
<td></td>
</tr>
<tr>
<td><strong>Injury Type C</strong></td>
<td>Intercept</td>
<td>-3.549</td>
<td>0.169</td>
<td>***</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Log(Q)</td>
<td>0.449</td>
<td>0.020</td>
<td>***</td>
<td>20,091</td>
</tr>
<tr>
<td></td>
<td>Log(L)</td>
<td>0.529</td>
<td>0.027</td>
<td>***</td>
<td></td>
</tr>
<tr>
<td><strong>[$83,000]</strong></td>
<td>Log(Q)</td>
<td>0.449</td>
<td>0.020</td>
<td>***</td>
<td>20,091</td>
</tr>
<tr>
<td></td>
<td>Log(L)</td>
<td>0.529</td>
<td>0.027</td>
<td>***</td>
<td></td>
</tr>
<tr>
<td><strong>Property Damage Only</strong></td>
<td>Intercept</td>
<td>-1.887</td>
<td>0.125</td>
<td>***</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Log(Q)</td>
<td>0.408</td>
<td>0.015</td>
<td>***</td>
<td>39,227</td>
</tr>
<tr>
<td></td>
<td>Log(L)</td>
<td>0.473</td>
<td>0.020</td>
<td>***</td>
<td></td>
</tr>
<tr>
<td><strong>[$7,600]</strong></td>
<td>Log(Q)</td>
<td>0.408</td>
<td>0.015</td>
<td>***</td>
<td>39,227</td>
</tr>
<tr>
<td></td>
<td>Log(L)</td>
<td>0.473</td>
<td>0.020</td>
<td>***</td>
<td></td>
</tr>
</tbody>
</table>

Note: Unit crash values per crash type shown in [brackets]. Source: Crash value costs recommended by 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 (2016b). The sample size is 10,740, which refers to the number of local links in the Twin Cities area based on the TomTom road network.

**Emission Cost**

Polynomial regression models estimate both internal and external emission costs:
\[ C_g = \epsilon_0 + \epsilon_1 t + \epsilon_2 Q + \epsilon_3 Q^2 \]  

(4.3)

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 models are displayed in Table 4.2.

Table 4.2: Estimates of Emission Cost

<table>
<thead>
<tr>
<th>Variable</th>
<th>Internal Emission Cost</th>
<th>External Emission Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>-4.83E-02</td>
<td>6.55E-04</td>
</tr>
<tr>
<td>( t )</td>
<td>9.43E-02</td>
<td>5.47E-04</td>
</tr>
<tr>
<td>( Q )</td>
<td>2.21E-07</td>
<td>5.20E-08</td>
</tr>
<tr>
<td>( Q^2 )</td>
<td>-1.01E-12</td>
<td>4.13E-13</td>
</tr>
<tr>
<td>( R^2 )</td>
<td></td>
<td>0.383</td>
</tr>
</tbody>
</table>

Other Costs

1. Vehicle Operating Cost: \$0.155/km (Minnesota Department of Transportation 2015);

2. Infrastructure Cost: \$0.0287/veh-km (Levinson & 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).

### 4.1.3 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 & 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.

### 4.2 Results

#### 4.2.1 Path Types

Figure 4.1 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 a uniform operating cost).
The route choice based on time cost, the traditional travel cost component, significantly differs from the 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 4.1 shows) from origins to all the other destinations, we measure the accessibility, accessibility differences, and mode-combined accessibility.

### 4.2.2 Component Accessibility Analysis

Figure 4.2 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 4.2: 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. The full cost adds all the other cost components.
4.2.3 Accessibility Difference Analysis

Figure 4.3 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 4.3), 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 the full cost. 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.
4.2.4 Mode-combined Accessibility Analysis

Figure 4.4 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).

![Diagram showing types of paths by auto and biking](image-url)

*Figure 4.4: Types of Paths by Auto and Biking*

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 measurement, 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 4.5 shows the mode-combined accessibility for the internal cost (Figure 4.5a) and full cost (Figure 4.5b) 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.

Figure 4.5: 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.
Chapter 5

Full Cost Allocation for Automobiles

This chapter develops methods for combining cost components and internal and external costs while addressing double counting problems.

5.1 Combining Internal and External Costs for Each Component

The theory of total cost analysis provides rules for combining internal and external costs for each component in the FCA framework addressing the double-counting problems it may have if internal and external costs are added. In the framework of FCA analysis, the cost components considered are time, crash, emission, and money.

Focusing on auto travel, the total travel cost should cover the cost borne by the traveler, cost imposed on other motorized travelers, cost imposed on non-motorized travelers, and cost imposed on non-travelers. See Figure 5.1.
Driving From an Origin to a Destination

From the motorized transportation system’s perspective

\[
\text{Total Cost} = B + X + Y + Z
\]

From a traveler’s perspective

\[
T_I \quad \text{The Traveler’s Internal Cost} \quad S_I \quad \text{The System’s Internal Cost} \quad T_E \quad \text{The Traveler’s External Cost} \quad S_E \quad \text{The System’s External Cost}
\]

- **B** : Cost borne by the traveler;
- **X** : Cost imposed on other motorized travelers;
- **Y** : Cost imposed on non-motorized travelers;
- **Z** : Cost imposed on non-travelers;

Figure 5.1: Compositions of Total Cost

From a traveler’s perspective, B is the traveler’s internal cost \((T_I)\), while X, Y, and Z are the costs imposed on others, giving the traveler’s external cost \((T_E)\). From the motorized transport system’s perspective, however, B and X comprise the cost inside of the system \((S_I)\), while Y and Z give the out-of-system external cost \((S_E)\).

Those compositions of the total cost, however, cannot be added directly, as some parts of the external costs have been internalized based on the cost definitions. Adding the internal and external costs would cause the double-counting problem and overestimate the total cost of travel.

The following subsections introduce the factors that would generate the double-counting problems for each cost component of time, safety, and emission, respectively. Theoretical diagrams decompose each cost component.

### 5.1.1 Time Cost

Each auto traveler pays the cost of total travel duration time on roads and imposes traffic delay on other motorized travelers at the same time, which results in \(B_t\) and \(X_t\). Auto travelers do make the travel harder for non-motorized travelers, like pedestrians and bicyclists, for instance, at intersections or going across the street. However, cost from \(Y_t\)
would be lower if there were separated sidewalks or bicycle lanes. More importantly, in implementation, the cost from $Y_t$ is hard to quantify, as the count data for pedestrians and bicyclists are missing and their routes are too flexible to say when, where, and how the delay happens. Hence, we will not consider this cost composition in our FCA analysis but strongly encourage future research in this area.

There is no out-of-system time cost imposed on non-travelers.

Figure 5.2 shows the theoretical diagram for an illustration of the total cost of time, where $B_{t,k}$ stands for the total travel time for a trip borne by traveler $k$ and $X_{t,k,q}$ refers to the delay traveler $k$ imposed on traveler $q$. 
Figure 5.2: Time Cost Diagram: Internal vs. External

(a) Two Vehicles with No Delay
(b) Two Vehicles with Former Vehicle Imposing Delay on the Latter One
(c) Three Vehicles with Former Vehicles Imposing Delay on the Latter Ones
Three scenarios of vehicles’ interactions or effects on their travel times are displayed in the diagram,

- Scenario 1: Two Vehicles with No Delay (Figure 5.2a)
  
  Two vehicles driving through a lane from its upstream to downstream, where vehicle 2 is far behind vehicle 1 without interactions or effects on both of their travel times. In this scenario, the arrival rate of vehicles is lower than the service rate, so that no delays are imposed on either vehicle.

  Hence, there is no external time cost generated by vehicle 1 or vehicle 2, from a traveler’s perspective. The total time costs of both vehicles are determined by the travel time they spend on the lane, which is reflected by the area of the blue boxes shown on the diagram at the bottom of Figure 5.2a, assuming that the width of the boxes gives the unit time cost.

- Scenario 2: Two Vehicles with Former Vehicle Imposing Delay on the Latter One (Figure 5.2b)
  
  Two vehicles driving through a lane from its upstream to downstream, where vehicle 2 is right behind vehicle 1. In this scenario, the arrival rate is higher than the service rate temporarily, such that vehicle 1 imposes delays on vehicle 2, as it has to lower its speed to avoid any potential collisions. After widening the car-following distance, vehicle 2 can then drive at the free-flow speed, which ends the queue (it is assumed that free-flow speed is applied for vehicles with no delay). $\Delta_2$ shown in the middle diagram of Figure 5.2b represents the delay of vehicle 2, which equals the length of the $X_{t,1,2}$ area shown in the diagram at the bottom.

  The total time cost for vehicle 1 includes its internal time cost, $B_{t,1}$, and the external time cost vehicle 1 imposed on vehicle 2, $X_{t,1,2}$. The total time cost for vehicle 2 is equal to its internal time cost $B_{t,2}$ since it does not affect others’ travel time and generates 0 external time cost.

  From the system’s perspective, adding all internal and external parts would overestimate the total time cost, as $B_{t,2}$ has covered the cost of $X_{t,1,2}$. The total time cost is $B_{t,1} + B_{t,2}$ rather than $B_{t,1} + X_{t,1,2} + B_{t,2}$ in scenario 2.
• Scenario 3: Three Vehicles with Former Vehicles Imposing Delays on the Latter Ones (Figure 5.2c)

Three vehicles driving through a lane from its upstream to downstream, where vehicle 2 is right behind vehicle 1 and vehicle 3 is right behind vehicle 2. In this scenario, the arrival rate is higher than the service rate temporarily, such that vehicle 1 imposes delays on vehicle 2 and 3, and vehicle 2 imposes delays on vehicle 3. The queue ends at the time slot when vehicle 3 can drive at the free-flow speed. In the middle diagram of Figure 5.2c, \( \Delta_2 \) represents the delay of vehicle 2, which equals the length of the \( X_{t,1,2} \) area, while \( \Delta_3 \) represents that of vehicle 3, which equals the total length of \( X_{t,1,3} \) and \( X_{t,2,3} \) areas.

From a traveler’s perspective, the total time cost of vehicle 1 includes its internal time cost, \( B_{t,1} \), the external time cost vehicle 1 imposed on vehicle 2, \( X_{t,1,2} \), and the external time cost it imposed on vehicle 3, \( X_{t,1,3} \). The total time cost for vehicle 2 includes its own internal time cost, \( B_{t,2} \), and the delay it imposed on vehicle 3, \( X_{t,2,3} \). Vehicle 3 only pays for its internal time cost, \( B_{t,3} \), since it does not affect others’ travel time and generates 0 external time cost.

From a system’s perspective, adding all internal and external parts would overestimate the total time cost as \( B_{t,2} \) has covered the cost of \( X_{t,1,2} \) and \( B_{t,3} \) has covered the cost of \( X_{t,1,3} \) and \( X_{t,2,3} \). The total time cost is \( B_{t,1} + B_{t,2} + B_{t,3} \) rather than \( B_{t,1} + X_{t,1,2} + X_{t,1,3} + B_{t,2} + X_{t,2,3} + B_{t,3} \) in scenario 3.

In the time cost analysis for the Twin Cities road network, the speed we used is an annual average speed which contains all uncongested and congested records, as the average speed of vehicle 1, 2 and 3 in Figure 5.2c. The average internal time cost we measured is then an average of \( B_{t,1} \), \( B_{t,2} \) and \( B_{t,3} \), which already considered the external time cost imposed on other motorized travelers, i.e. \( X_{t,1,2} \), \( X_{t,1,3} \) and \( X_{t,2,3} \). Hence, to calculate the total time cost, the internal and external parts cannot be added to avoid the double-counting problem. Only the time cost borne by travelers themselves, \( B_t \), would be used to represent the total time cost in the full cost analysis.
5.1.2 Safety Cost

Each auto traveler pays the expected crash cost based on an average crash rate, which gives $B_s$. Meanwhile, the traveler increases the expected crash cost, including both motorized and non-motorized travelers, giving $X_s$, and $Y_s$. The cost imposed on non-travelers, $Z_s$, is independent of the others, which should be directly added to the total crash cost. $B_s$, $X_s$, and $Y_s$, however, overlap.

Figure 5.3 shows the theoretical diagram for an illustration of the total cost of crashes, where $B_{s,k}$ stands for the expected crash cost borne by traveler $k$, and $X_{s,k,q}$ refers to the increased crash cost due to vehicle $k$ imposed on vehicle $q$. 
Figure 5.3: Safety Cost Diagram: Internal vs. External
• Scenario 1: Single-vehicle Crashes (Figure 5.3a)

One vehicle drives through a lane from its upstream to downstream without other surrounded vehicles. In this scenario, vehicle 1 does not impose any external crash cost on others. Its internal crash cost is determined by the expected crash rate of single-vehicle crashes on the lane.

• Scenario 2: Multi-vehicle Crashes (Figure 5.3b)

Two vehicles drive through a lane from upstream to downstream with the same expected travel speed, where vehicle 2 is right behind vehicle 1. It is possible that vehicle 1 makes a sudden braking while vehicle 2 cannot or does not lower its speed enough to avoid a rear-end collision.

In this scenario, vehicle 1 pays for the expected crash cost, including the costs based on both single-vehicle crash rate and multi-vehicle crash rate. Comparing with Scenario 1, the increased crash cost borne by vehicle 1 is the external cost of vehicle 2 imposed on it, as \(X_{s,2,1}\) shown in the figure. Meanwhile, vehicle 2 pays for the expected crash cost including \(X_{s,1,2}\). Assuming that all the vehicles share the crash cost equally without considering the responsibility, \(X_{s,2,1}\) is equal to \(X_{s,1,2}\).

From the system’s perspective, adding all internal and external parts of the crash cost would overestimate the total safety cost as \(B_{s,1}\) has covered the cost of \(X_{s,2,1}\) and \(B_{s,2}\) has covered \(X_{s,1,2}\). The total safety cost should be \(B_{s,1} + B_{s,2}\) rather than \(B_{s,1} + X_{s,1,2} + B_{s,2} + X_{s,2,1}\).

Other types of multi-vehicle crashes, like side-impact collisions and cross-traffic collisions, follow the same theoretical diagram shown in Figure 5.3b.

For crashes involving non-motorized travelers, it is assumed that the involved vehicles take full responsibility of the crashes and the cost factors are all allocated to motor vehicles, which has been considered in the internal crash cost borne by travelers themselves.

5.1.3 Emission Cost

Travelers pay the health damage cost due to emission intake during traveling. At the same time, they emit pollution, which increases the health damage cost to other motorized
travelers, non-motorized travelers, and non-travelers. Hence, emission cost covers $B_g$, $X_g$, $Y_g$, and $Z_g$.

Figure 5.4 shows the theoretical diagram for an illustration of the total cost of emission, where $B_{g,k}$ stands for the total health damage cost due to emission intake for a trip borne by traveler $k$, $X_{g,k,q}$ refers to the health damage cost vehicle $k$ imposes on vehicle $q$, $Y_{g,k}$ shows the health damage cost vehicle $k$ imposed on non-motorized travelers, and $Z_{g,k}$ shows that imposed on non-travelers.

As shown in Figure 5.4, three vehicles drive on the road and emit pollution. Based on the air pollutant dispersion plume, vehicle 1 imposes health damage cost on vehicle 2 ($X_{g,1,2}$) and 3 ($X_{g,1,3}$), and vehicle 2 imposes health damage cost on vehicle 3 ($X_{g,2,3}$). All three vehicles impose health damage cost on the non-motorized travelers and non-travelers covered by the affected areas. Note that vehicles may impose health damage cost on themselves if the wind direction is the same as the traffic direction and travel speed is lower than the wind speed, which contributes to $B_{g,i}$ as well.

From the system’s perspective, adding all internal and external parts of the emission cost would overestimate the total emission cost as $B_{g,2}$ is fully covered by the cost of $X_{g,1,2}$ and $B_{g,3}$ is caused by $X_{g,1,3}$ and $X_{g,2,3}$. The total emission cost should be $X_{g,1,2} + X_{g,1,3} + Y_{g,1} + Z_{g,1} + X_{g,2,3} + Y_{g,2} + Z_{g,2} + Y_{g,3} + Z_{g,3}$ rather than considering the additional $B_{g,2} + B_{g,3}$.

In the emission cost analysis for the Twin Cities road network, each vehicle’s internal emission cost is affected by hundreds of vehicles’ pollution, and each vehicle affects hundreds
of travelers’ emission intake. Hence, to calculate the total emission cost, the $B_{g,k}$, and $X_{g,k,q}$ cannot be added to avoid the double-counting problem. $B_g$, $X_g$, and $Y_g$ would be used to represent the total emission cost in the full cost analysis, written as $B_g + N_g + P_g$.

5.2 Combining All Cost Components

The theory we propose to estimate the full cost of travel combines all cost components for auto travelers in the FCA analysis. Potential cost transfers among cost components are identified, which should be subtracted from one of the categories to avoid the double-counting problems. User monetary cost and infrastructure cost are separated into two categories for a better illustration.

Figure 5.5 shows the factors covered by each cost component for auto travelers, where the arrows represent the potential transfers among the cost components. As identified, there are four major transfers, including:

- Congestion-related cost due to crashes transfers to time cost, emission cost, and monetary cost;
- Vehicle insurance cost transfers to medical, insurance administration, and property damage cost;
- Fuel taxes transfer to emission cost and infrastructure cost;
- Tolls, vehicle sales tax, and vehicle registration tax transfer to infrastructure cost;

A discussion on these cost transfers is detailed in Section 5.2.1 - Section 5.2.4.
Full Cost of Travel for Automobiles

Time Cost + Safety Cost + Emission Cost + Monetary Cost + Infrastructure Cost

- Time
  - Medical;
  - Emergency services;
  - Market productivity loss;
  - Insurance administration;
  - Workplace cost;
  - Legal cost;
  - Congestion-related cost;
  - Property damage cost;
  - Quality of statistical life.

- Health damage cost;
- Climate change cost;
- Fuel cost (no tax);
- Fuel tax;
- Parking cost;
- Tolls;
- Vehicle sales tax;
- Vehicle maintenance and repair;
- Vehicle depreciation;
- Vehicle finance charges;
- Vehicle registration tax;
- Vehicle registration fees (no tax);
- Vehicle insurance.

Capital expenditure;
Maintenance and service;
Other costs.

Solid arrows refer to full transfers;
Dotted arrows refer to partial transfers.

Figure 5.5: Cost Factors of Auto Travelers
5.2.1 Congestion-related Cost Due to Crashes Transfers to Time, Emission Cost, and Monetary Cost

Congestion cost due to crashes is defined as the value of travel delay, added fuel consumption, and increased environmental impacts resulting from traffic crashes imposed on others who are not involved (Blincoe et al. 2015). These costs are transferred to time cost, fuel cost, and emission cost respectively, based on our cost definitions and measurements.

Congestion-related travel delay has been entirely transferred to time cost, as the speed data we used for time cost measurements are an annual average for specific time periods aggregated by millions of GPS navigation data for each link segment. This annual average speed data already include the speed records when traffic crashes happened, which reflects the travel delay due to those crashes. Additional fuel consumption due to the travel delay is transferred to fuel cost entirely as well since speed is the dominant factor for fuel consumption, for which, again, we used the annual average speed data that contain the crash-related speed records to estimate the fuel cost. The annual average speed data were also used as the speed input in MOVES simulations for pollution estimations in emission cost analysis.

Hence, for implementations, the travel delay, excess fuel consumption, and increased emission cost generated by crashes would not be added to safety cost to avoid the double-counting problem.

5.2.2 Vehicle Insurance Transfers to Safety Cost

Vehicle insurance cost paid by travelers covers approximately 54% of all crash costs (Blincoe et al. 2015). The insurance data developed by the Motorcycle Insurance Committee of the National Association of Independent Insurers classified 7 categories of insurance coverage, including (Blincoe et al. 2015, Miller & Lawrence 2003):

- Bodily injury liability: coverage if policyholder’s vehicle injures someone;
- Property damage liability: coverage if the policyholder’s vehicle damages or destroys someone else’s property;
- Own medical payments: coverage for the policyholder’s injury treatment costs;
• Personal injury protection: no-fault coverage for the policyholder’s losses;
• Collision: coverage for damage to the policyholder’s vehicle when the policyholder is at fault in the crash or no one is;
• Comprehensive: coverage for theft or non-crash damage to the policyholder’s vehicle
• Uninsured and underinsured motorist: coverage for injuries to the policyholder and other occupants of the policyholder’s vehicle, as well as the policyholder’s property damage when a driver without insurance is at fault or when the at-fault driver has too little insurance to fully compensate the policyholder’s losses.

Assuming that travelers purchase for all types of coverage (some types of coverage are not mandatory for some states), parts of the medical and property damage costs are transferred to the vehicle insurance cost that travelers have already paid for as well as the insurance administration cost.

Hence, to sum the safety cost and monetary cost up in the full cost analysis of travel, vehicle insurance cost should be excluded from the monetary cost to avoid the double-counting problem.

5.2.3 Fuel Tax Transfers to Emission and Infrastructure Cost

Travelers pay the fuel cost determined by fuel consumption, fuel cost exclusive of tax, and fuel tax (US Department of Transportation, Federal Highway Administration 2012). The fuel cost varies across fuel types, covering the cost of crude oil, refining, distribution, and marketing. Fuel tax includes the federal, state, and local taxes along with some other fees, such as sales tax, petroleum business tax, environmental fee, and clean-up fee in Minnesota. The revenue collected from state fuel tax is constitutionally dedicated only to highway purposes (Metropolitan Council, Transportation Committee 2015).

The federal motor fuel tax rate is $0.049/liter ($0.184/gallon) of gasoline, and $0.064/liter ($0.244/gallon) of diesel (US Energy Information Administration 2014), which is deposited into the Highway Trust Fund, the majority of which, 83% to 87%, is deposited into the Highway Account for road construction and maintenance. Approximately 11% to 15% of federal fuel tax goes to the Mass Transit Account, while $0.0003/liter ($0.001/gallon) goes
to the Leaking Underground Storage Tank Trust Fund (US Department of Transportation, Federal Highway Administration 2012).

For Minnesota, the total state tax rate is $0.075/liter ($0.285/gallon) of gasoline, diesel and some gasoline blends after 2013 (Burress 2018, Metropolitan Council, Transportation Committee 2015). Based on the 2017 Minnesota Highway Users Tax Distribution Fund (Minnesota Department of Transportation 2017a), the majority of motor fuel taxes is deposited into Trunk Highway Funds, Municipal State Aid Street Fund, and County State Aid Highway Fund; the others go into the Flexible Highway Account, Town Bridge Account, and Town Road Account.

The fuel tax is partially transferred to the emission cost, including both health damage cost and climate change cost if the environmental fee will be considered additionally in the fuel tax. However, this is not the case for Minnesota. Excepting the $0.0003/liter ($0.001/gallon) tax for the Leaking Underground Storage Tank Trust Fund, federal, state, and local fuel taxes are fully transferred to transport infrastructure cost of both highway and transit networks for capital expenditure, maintenance and service, and other costs like highway law, enforcement and safety, and bond retirement. But to measure the full cost for auto travelers, only the fuel tax transferred to highway infrastructure cost should be excluded from the monetary cost to avoid the double-counting problem.

### 5.2.4 Tolls, Vehicle Sales Tax, and Vehicle Registration Tax Transfer to Infrastructure Cost

**Tolls Transfer to Infrastructure Cost**

Tolls are imposed on vehicles for the use of specific roads based on time of day, location, type of vehicle, number of occupants, and other factors. The revenue from the tolls is reinvested in the capital expenditure, maintenance, and service of the toll roads (US Department of Transportation, Federal Highway Administration, Center for Innovative Finance Support 2018).

In Minnesota, MnPASS Express Lanes on I-394, I-35W, and I-35E are toll roads, operated by MnDOT, aiming to manage and reduce congestion on high-occupancy roads by charging an electronic fee on solo motorists (Minnesota Department of Transportation
2018). The revenue generated through MnPASS lanes is mainly used for their construction, operations, and maintenance. The remaining of the revenue from I-394 and I-35E is transferred to the Metropolitan Council for highway and transit improvements in the corridor while, for I-35W, a part of the revenue is used for transit capital expenses as well as highway and transit improvements.

Hence, monetary cost from tolls has been fully transferred to the infrastructure cost of transport systems, including both highway and transit networks. To measure the full cost of auto travelers, however, only the tolls transferred to highway infrastructure cost should be excluded to avoid the double-counting problem.

Note that tolls are imposed on toll road users. For auto travelers who only use free roads, there is no monetary cost from tolls.

**Motor Vehicle Sales Tax (MVST) Transfers to Infrastructure Cost**

The state imposes a Motor Vehicle Sales Tax on motor vehicles for most of the purchases or transfers except when an exemption applies (Minnesota Department of Revenue 2017). The tax rate is 6.5% of the vehicle purchase price. Based on the Highway Finance Overview (Burress 2018), 60% of MVST revenue is currently deposited into the Highway User Tax Distribution Fund for highways, while 40% goes to transit.

**Vehicle Registration Tax Transfers to Infrastructure Cost**

Minnesota imposes an annual registration tax on motor vehicles based on the base value and the age of the vehicle (Burress 2018, Minnesota Department of Public Safety 2018). The revenue from vehicle registration taxes is constitutionally dedicated to highway purposes. Similar to the fuel tax, it is deposited into Trunk Highway Funds, Municipal State Aid Street Fund, and County State Aid Highway Fund, as well as the Flexible Highway Account, Town Bridge Account, and Town Road Account (Minnesota Department of Transportation 2017). Therefore, vehicle registration tax should be excluded from the monetary cost to measure the full cost of travel since it has been fully transferred to the infrastructure cost.
Chapter 6

Shortest Time Path – Travel Time Cost and Routing

6.1 Introduction

The time cost is the key cost component affecting travelers’ route choice. Shortest travel time path, which optimizes the time cost, has been long used to simulate travelers’ actual route choice. For instance, Wardrop’s principle assumes that individuals aim to minimize their own travel time (Wardrop 1952). It has been shown that travelers’ actual route choices mostly overlap with the shortest travel time path, and are less than 5 minutes longer than the shortest time routes (Tang & Levinson 2015, Zhu & Levinson 2015).

The value of time depends on many factors, including time of day, mode of travel, purpose of trips, quality of trips, and personal characteristics of the travelers, such as income or age (Levinson & Gillen 1998, Hensher 1997). The recommended hourly values of travel time savings, proposed by US Department of Transportation, Office of the Secretary of Transportation (2016), is $13.60 for local personal travel and $25.40 for local business travel. Intercity travel has a higher unit time cost for personal trips, which is $19.00. The unit time cost for intercity business travel is $25.50. Adjusted for Minnesota earnings rate, Minnesota Department of Transportation (2015) recommends the standard value of travel time savings for auto travelers is $18.30/hr for benefit/cost analysis.

This chapter proposes a link-based time cost analysis for the Minneapolis - St.Paul
(Twin Cities) Metropolitan area, shown in Figure 6.1. The shortest travel time paths are found for all the work trip origin-destination (OD) pairs and aggregated into work trip flows to identify the shorter routes.

The data, methodology, results and summary are shown in sections 6.2 - 6.5 in turn.

Figure 6.1: Geographical Boundary of the Seven County Metro Area of the Twin Cities

### 6.2 Data Collection

#### 6.2.1 Speed and Road Network Data

The data source we used for time cost estimates is the GPS speed data for the year 2011. Comprehensive GPS data have high spatial and temporal coverage on the most widely
traveled links and reflect the actual driving patterns of drivers with GPS data. While this may not be perfectly representative of the population as a whole, it is the best available data. There is no reason to believe the speeds that are reported are systematically biased due to sampling (it is possible that flows on the links estimated from GPS traces are biased by sampling drivers with GPS devices, which may not be typical). This study employs TomTom data from 2011. The original data were collected by millions of GPS logging and navigation devices (across the US), while the speed data were aggregated and processed based on that (TomTom International BV 2013).

TomTom speed data were organized based on road classifications, time periods and speed percentiles specific to each link segment on the road network. At first, speed data were separated into 4 groups based on the Functional Roadway Classifications (FRCs), in which FRC0 to FRC4 were categorized into one dataset. For different time periods, considering the traffic properties, speed data for each link segment were aggregated based on the time of day, which was divided into seven parts, including Overnight, Morning Peak Hours (Two parts), Mid-Day, Evening Peak Hours (Two Parts) and Evening. Moreover, different percentiles of speed for each link segment, from the 5th percentile to the 95th percentile, in the different time periods of a day were measured. The 5th percentile speed shows the speed on links in the times which were the fastest 5 percent of those recorded, while the 95th percentile speed represents the slowest speed.

TomTom road network, which is displayed as a GIS shapefile, contains the geographic information of each link in the Twin Cities. TomTom speed data could be joined with the road network showing the travel time on each link.

6.2.2 LEHD Origin-Destination Employment Statistics dataset (LODES7.0)

The LEHD Origin-Destination Employment Statistics dataset (LODES 7.0), where LEHD itself stands for Longitudinal Employment Household Dynamics, was collected from US Census Bureau (2013b). It contains the tables of Workplace Area Characteristics (WAC), Residence Area Characteristics (RAC) and Origin and Destination Census blocks (OD table) for work trips.

In this study, the OD table was used to measure the work trip flow assigned to the shortest path to identify the shorter routes.
To join the OD table to the GIS map, the Census’s TIGER/Line shapefile at the block level of Minnesota in 2010 was used (US Census Bureau 2010). The features in the Seven County Twin Cities area were selected and the centroid of each block was extracted as the origin and destination for actual work trips.

### 6.3 Method

#### 6.3.1 Link-based Time Cost Analysis

Travel time is straightforward to be measured based on the TomTom speed data and TomTom road network, which is written as,

\[
t_i = \frac{L_i}{V_i}
\]

Where:
- \( t_i \): Travel time on link \( i \);
- \( L_i \): Length of link \( i \);
- \( V_i \): Speed on link \( i \).

50th (median) percentile speed in the morning peak hours (7AM-9AM) was used to measure the travel time. The standard value of travel time savings for auto travelers in Minnesota, $18.30/hour, was used to monetize the travel time.

#### 6.3.2 The Shortest Travel Time Path

The shortest travel time path is defined as the route with the lowest travel time cost. For a given origin-destination (OD) pair, the general mathematical expression of the shortest travel time path is written as,

\[
C_{OD,k,t} = \sum_{i \in P_{OD,k}} C_{t,i}
\]

\[
C_{OD,t} = \min(C_{OD,k,t})
\]

Where:
- \( C_{t,i} \): Time cost on link \( i \);
\( P_{OD,k} \): The \( k^{th} \) path between origin \( O \) and destination \( D \);
\( C_{OD,k,t} \): Time cost of the \( k^{th} \) path between origin \( O \) and destination \( D \);
\( C_{OD,t} \): Minimum time cost of the shortest travel time path between \( O \) and \( D \).

### 6.3.3 Work Trip Flow Estimates

Consistent with the concept of betweenness proposed by Freeman (1977), work trip flow is defined as the times of a link that is used as the shortest paths for work trips:

\[
q_i = \sum_{n=1}^{N_r} f(P_{OD,i}) \tag{6.4}
\]

\[
f(P_{OD,i}) = \begin{cases} 
1 & \text{if } P_{OD} \text{ pass through link } i \\
0 & \text{Others} 
\end{cases} \tag{6.5}
\]

Where:

- \( q_i \): Work trip flow on link \( i \);
- \( N_r \): Total number of work trips.

### 6.4 Results

The estimates show that the average time cost on the Twin Cities network is $0.382/veh-km, and 94% of links have a time cost lower than $0.60/veh-km. As expected, compared with road types, the average time cost of highways ($0.293/veh-km) is much lower than other surface roadways ($0.390/veh-km) since highways are designed to be faster than others. For different locations, driving in the core cities, like downtown Minneapolis or downtown St. Paul, results in more time cost ($0.464/veh-km) than other urban and rural areas due to more severe congestions. The average time costs in other urban and rural areas are $0.379/veh-km and $0.322/veh-km respectively.

Figure 6.2 gives the spatial distribution patterns of the time cost estimates. Consistent with discussions above, highways show a lower time cost than surface roadways, as the shape of the highway network is clearly visualized. Figure 6.3 shows the time cost of all vehicles generated on each link considering the traffic flow. Highways are highlighted since the highway network serves much more trips than other roads.
Figure 6.2: Time Cost Per Vehicle-Kilometer on Each Link of the Twin Cities Road Network ($/veh-km)
Figure 6.3: Time Cost of All Vehicles Generated on Each Link of the Twin Cities Road Network ($/km)

Figure 6.4 shows the baseline work trip flow estimates allocated to the shortest travel time path based on current traffic levels, i.e., assuming other traffic does not reroute. It reflects that highways serve more work trips than other roads, as travelers optimize travel times on routes with higher speeds. Its spatial distribution gives the shape of the highway network.
Figure 6.4: Work Trip Flow Assigned to the Shortest Travel Time Path

6.5 Summary

This chapter proposed a link-based time cost analysis for the road network in the Twin Cities metro area and found the shortest travel time paths for all the work trip OD pairs, which were aggregated to estimate work trip flows.

The time cost analysis shows that the average time cost of the Twin Cities network is around $0.382/veh-km. As expected, highways have a lower time cost than other surface roads. Driving in downtown roadways costs more than other urban and rural roads.

The work trip flows on the shortest travel time path indicates that work trips are more allocated to highways, as highways are shorter in terms of travel time.
Chapter 7

Safest Path–Crash Cost and Routing

7.1 Introduction

Traffic crashes were a very early byproduct of automobile travel, and remain a serious issue globally (De Blaeij et al. 2003, Shinar 2007). In the US, there were more than 5,000,000 police-reported motor vehicle crashes every year from 2005 to 2014 (National Highway Traffic Safety Administration (NHTSA) 2014), including over 30,000 traffic fatalities annually. The annual crash cost for all cities in the US is almost three times higher than the congestion cost (Cambridge Systematic Meyer, M 2011).

Individual travelers choose routes based on a number of factors, including trip-related factors, like travel time (and reliability) and trip distance, and person-related factors, like drivers’ urgency and experience (Ahn & Rakha 2008, Ben-Akiva et al. 1984, Zhu & Levinson 2015, Tang & Levinson 2015). Few travelers appear to consider avoiding more dangerous roads, or roads with other dangerous drivers; as, few, if any, travelers know these risks. Dijkstra & 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. As the optimal solution of route choices from the perspective of safety, the safest path could optimize on-road safety for individuals and minimize economic costs from crashes.

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. To give a more straightforward sense of crash risks for travelers, however, we define the safest path as the route with the lowest crash cost, subject to travelers engaging in the same set of activities at the same locations. We do this by monetizing crashes by severity.

Crash costs cover various components, including direct cost (such as property damage, medical, and legal costs), indirect cost (such as congestion, productivity loss for work and family, and tax losses), and intangible cost (such as the loss of life or degradation in quality of life and the pain and suffering for both victims and their families), which vary significantly across severities from fatal crashes to property damage only crashes (PDO) (Zhang et al. 2004, Goodchild et al. 2002, Blincoe et al. 2015).

Notably, the loss of life is the most economically expensive element of crash costs. Trottenberg & Rivkin (2014) indicates an economic Value of a Statistical Life (VSL) of $9.4 million in 2015, which has been widely used to monetize crash costs for different injury severities and express the unit value of crashes (US Department of Transportation 2014b).

On-road crash cost includes both internal and external elements. Internal crash cost is generated by the personal crash rate, which is borne by each traveler involved in a crash (it may be paid for in part via insurance policies, vehicle registration fees, and health insurance (Cui & Levinson 2018b, Levinson & Gillen 1998)). It references the number of crashes per vehicle kilometer traveled (Jakob et al. 2006, Edlin & Karaca-Mandic 2006). Each traveler also increases the crash risk for others (including pedestrians and bicyclists, as well as persons in other vehicles), this marginal increase of crash cost imposes an external crash cost (Vickrey 1968, Jansson 1994). The safest internal path, considering internal crash costs, and the safest external path, considering external crash costs, generate two new and distinct traffic routing patterns.

This chapter builds a framework of link-based crash cost analysis from the perspective of travelers based on selected crash frequency estimation models and measures the internal and external crash costs for each link segment in metropolitan road networks.

As a proof-of-concept, we apply this framework to the Twin Cities region and assess the crash costs for the region’s road network. The safest internal and external paths are found for all the work trip origin-destination (OD) pairs and aggregated into work trip
flows to identify the safer routes.

The data, methodology, results and summary of this study are shown in Section 7.2 - 7.5 in turn.

7.2 Data

Several sources of data are applied to this study.

7.2.1 Crash data from Minnesota

Crash records from 2003 to 2014 from Minnesota were acquired by the research team from the Minnesota Department of Transportation (MnDOT). These are police-reported crashes only, which are more accurate for more severe crashes, and likely under-report minor crashes. Throughout the remainder of the text, crash data refers only to reported crashes. For each year, the crash records contain GIS attributes, date of crash, type of crash, severity, and other related information, such as weather and light. All those crash records are displayed as a shapefile based on their GIS attributes, including route number, reference points, and coordinates. In this study, only crashes in the seven-county Twin Cities region were selected. Table 7.1 shows the number of crashes over the 12 years, cross-classified by crash severity and Functional Road Classification (FRC).

Table 7.1: Total Number of Crashes (12 years) by Severity and Functional Road Classification

<table>
<thead>
<tr>
<th>Severity</th>
<th>Primary Arterial</th>
<th>Minor Arterial</th>
<th>Collector</th>
<th>Local</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fatal</td>
<td>148</td>
<td>240</td>
<td>66</td>
<td>14</td>
<td>468</td>
</tr>
<tr>
<td>Incapacitating Injury</td>
<td>449</td>
<td>1,279</td>
<td>450</td>
<td>173</td>
<td>2,351</td>
</tr>
<tr>
<td>Non-incapacitating Injury</td>
<td>4,847</td>
<td>7,573</td>
<td>2,420</td>
<td>1,032</td>
<td>15,872</td>
</tr>
<tr>
<td>Complaint of Pain</td>
<td>17,717</td>
<td>20,939</td>
<td>6,415</td>
<td>2,654</td>
<td>47,725</td>
</tr>
<tr>
<td>Property Damage Only</td>
<td>64,576</td>
<td>64,861</td>
<td>19,838</td>
<td>8,849</td>
<td>158,124</td>
</tr>
</tbody>
</table>
7.2.2 Traffic Data

An estimate of average annual daily traffic (AADT) for Minnesota (from 2007 to 2014) was collected from the Traffic Volume Program of Minnesota Department of Transportation (2017b) (MnDOT). This traffic count program estimates AADT for around 33,000 count locations, including trunk highways, county state aid highways (CSAH), county roads (CR), and municipal state aid streets (MSAS). The majority of traffic data is collected by the total short duration count (48 hours) and adjusted by seasonal adjustment factors (and axle correction factors for trunk highways), based on which the final AADT estimates are determined by an AADT Decision Tree and Federal Rounding Conventions. In the Minneapolis - St. Paul Metro area, trunk highways are scheduled for traffic counting over a two-year period (published in the even years) and the municipalities provide MSAS counts every two or four years based on the municipal traffic counting schedule (Minnesota Department of Transportation 2016c). The seven counties in the Twin Cities update CSAH and CR counts in the odd years.

AADT is one of the conventional variables in the Safety Performance Functions (SPFs) that are developed to explain the expected crash rate. In this study, the features in the Twin Cities Metropolitan region were selected and joined to the TomTom road network.

7.2.3 Federal Urban/Rural GIS Shapefile

Federal Urban/Rural GIS Shapefile was acquired from Minnesota Department of Transportation, Transportation Data and Analysis (2016) and defined by Federal Adjusted Urban Area boundaries. The data cover roadways in Minnesota and are divided into Urban, Small Urban, and Rural Roads. The data were selected and joined with the Twin Cities’ road network as well, which were used as an independent variable in the selected SPFs.

TomTom speed data and TomTom road network, introduced in Section 6.2.1, were also required for crash risk estimations. The difference between 10th and 90th percentile speed in the morning peak hours (7AM-9AM) was used as a measure of speed variance, an independent variable in the crash frequency estimation models. Notably, this is an aggregate speed variance, measured across all vehicles across the year using the link, not the intra-day or intra-vehicle speed variance.
Origin and Destination Census blocks (OD table) for work trips in the LEHD Origin-Destination Employment Statistics dataset were used to measure the work trip flow based on the safest internal path and the safest external path to identify safer routes. The details are described in 6.2.2

7.3 Methodology

7.3.1 Link-Based Crash Cost Analysis

The link-based crash cost analysis contains three major steps: unit crash cost specification, crash frequency estimation, and internal vs. external crash cost assessment.

Unit Crash Cost Specification

Crash cost comprises both internal and external costs from the perspective of travelers. Internal crash cost refers to the cost borne by each traveler involved in a crash, including medical cost, property damage cost, and loss of quality of life. The external crash cost is defined as the marginal increase of crash cost borne by other travelers due to an additional vehicle driven on the roads, since each traveler increases the crash risk of others (Vickrey 1968)\(^1\).

Blincoe et al. (2015) measured the economic costs of motor vehicle crashes by severity specific to different cost components, which are shown in Table 7.2.

In determining crash costs, a single-vehicle crash is entirely attributable to the involved vehicle, which makes it relatively straightforward to assess the costs. However, for a multi-vehicle crash, an efficient allocation of crash costs is necessary among occupants considering the responsibility of each vehicle, like whose fault it is. In addition, researchers have considered vehicle type as a determinant for crash cost allocations in a multi-vehicle crash as well, as the harm to occupants varies with the weight and class of the involved vehicles (Miller et al. 1998).

\(^1\)Note that the external crash cost defined here is external from the perspective of travelers, but is at least in part internalized in the transport system. Legal, court, new employment (due to fatalities or serious injuries), and health costs are external to transport and paid by other social systems (Jakob et al. 2006).
Table 7.2: Descriptions of Crash Cost Factors

<table>
<thead>
<tr>
<th>Cost Components</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medical</td>
<td>The cost of all medical treatment associated with motor vehicle injuries</td>
</tr>
<tr>
<td>Property Damage</td>
<td>The value of vehicles or other items damaged in traffic crashes</td>
</tr>
<tr>
<td>Market</td>
<td>The discounted value of the lost wages and benefits over the victims remaining life span</td>
</tr>
<tr>
<td>EMS</td>
<td>Emergency service cost</td>
</tr>
<tr>
<td>Household Productivity</td>
<td>The value of lost productive household activity</td>
</tr>
<tr>
<td>Insurance Administration</td>
<td>The administrative costs of processing insurance claims due to motor vehicle crashes</td>
</tr>
<tr>
<td>Workplace Cost</td>
<td>The cost of workplace disruption due to the loss or absence of an employee</td>
</tr>
<tr>
<td>Legal Cost</td>
<td>The legal fees and court costs associated with civil litigation resulting from traffic crashes</td>
</tr>
<tr>
<td>Congestion Cost</td>
<td>The costs due to congestion results from motor vehicle crashes</td>
</tr>
<tr>
<td>Quality of Life</td>
<td>Lost quality of life</td>
</tr>
</tbody>
</table>

In our research, considering that the crash data do not provide accurate responsibility information, the costs of each vehicle are assigned to itself by assuming that vehicles share responsibility equally. Hence, the value of each cost component by severity are shown in Table 7.3 (Blincoe et al. 2015).
Table 7.3: Unit Values of Crash Cost Factors

<table>
<thead>
<tr>
<th>Cost per Injured Person</th>
<th>Fatal Injury</th>
<th>Incapacitating Injury</th>
<th>Non-incapacitating Injury</th>
<th>Complaint of Pain</th>
<th>Property-damage Only</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medical</td>
<td>$11,317</td>
<td>$21,189</td>
<td>$4,981</td>
<td>$4,393</td>
<td>$2,571</td>
</tr>
<tr>
<td>Market</td>
<td>$933,262</td>
<td>$24,403</td>
<td>$6,465</td>
<td>$5,096</td>
<td>$2,184</td>
</tr>
<tr>
<td>EMS</td>
<td>$902</td>
<td>$122</td>
<td>$56</td>
<td>$45</td>
<td>$20</td>
</tr>
<tr>
<td>Household Productivity</td>
<td>$289,910</td>
<td>$7,182</td>
<td>$1,966</td>
<td>$1,562</td>
<td>$710</td>
</tr>
<tr>
<td>Insurance Administration</td>
<td>$28,322</td>
<td>$11,751</td>
<td>$3,670</td>
<td>$3,648</td>
<td>$2,240</td>
</tr>
<tr>
<td>Workplace Cost</td>
<td>$11,783</td>
<td>$3,941</td>
<td>$1,459</td>
<td>$208</td>
<td>$7</td>
</tr>
<tr>
<td>Legal Cost</td>
<td>$106,488</td>
<td>$8,557</td>
<td>$1,684</td>
<td>$1,125</td>
<td>$56</td>
</tr>
<tr>
<td>Congestion Cost</td>
<td>$5,720</td>
<td>$1,385</td>
<td>$995</td>
<td>$1,009</td>
<td>$1,026</td>
</tr>
<tr>
<td>Quality of Life</td>
<td>$7,747,082</td>
<td>$919,158</td>
<td>$252,268</td>
<td>$108,274</td>
<td>$31,859</td>
</tr>
<tr>
<td>Total</td>
<td>$9,134,786</td>
<td>$997,688</td>
<td>$273,544</td>
<td>$125,360</td>
<td>$40,673</td>
</tr>
</tbody>
</table>

Cost per Crashing Vehicle  Property Damage Cost | $10,712 | $3,518 | $2,465 | $2,407 | $1,624
As Table 7.3 shows, the cost components were categorized into a per-person based cost \((u_{s,p})\) and a per-vehicle based cost \((u_{s,v})\). For a crash with \(N_{s,p}\) injuries and \(N_{s,v}\) involved vehicles, the crash cost could be measured as

\[
u_s = u_{s,p} \times N_{s,p} + u_{s,v} \times N_{s,v}
\]  

(7.1)

Crash Frequency Estimation

The crash frequency may be estimated for micro (a segment or intersection) or macro (a transportation analysis zone or county) levels (Cai et al. 2016). This study conducts a micro-level of estimation considering specific link segments as observations but applies the resulting model regionally to the Twin Cities road network.

The Minnesota crash data were classified as fatal, incapacitating injury, non-incapacitating injury, complaint of pain and PDO crashes by severity. The most commonly used method to measure the severity-based crash frequency is to estimate the expected crash frequency considering all types of crashes, and then identify the crash severities separately (Lord & Mannering 2010, Lee & Mannering 2002, Carson & Mannering 2001).

Safety Performance Functions (SPFs) are defined by the Highway Safety Manual (HSM) (American Association of State Highway and Transportation Officials (AASHTO) 2010) as statistical base models to measure the average crash frequency with specified base conditions. SPFs not only can estimate the crash frequency with the existing roadway conditions but can predict it by applying the future conditions with a projected AADT (Brimley et al. 2012).

The conventional variables for SPFs in the HSM are AADT and segment length in the case of roadway segments. We add additional variables to better estimate crash frequencies.

The HSM suggests using the Negative Binomial Distribution to estimate SPFs, this extends the Poisson distribution, but better models the crash data due to overdispersion, data with a higher variance than the mean. The Negative Binomial model of SPFs could be expressed as (Brimley et al. 2012):

\[
\ln(y) = \beta_0 + \sum_{k=1}^{n} \beta_k x_k
\]  

(7.2)
Where:

\( y \): Dependent variable measuring the number of crashes in SPFs;

\( x_k \): Independent variables;

\( n \): Number of independent variables;

\( \beta_k \): Coefficients.

The ordered probit model is suitable for modeling with a categorical dependent variable, which has been widely applied to crash severity analysis (Quddus et al. 2002, Duncan et al. 1998, Kockelman & Kweon 2002). The general specification for ordered probit is:

\[
y_k^* = X_k \beta + \varepsilon_k
\]  

(7.3)

Where:

\( y_k^* \): Latent variable measuring the crash severity of the \( k \)th crash;

\( X_k \): Vector of independent variables;

\( \beta \): Vector of coefficients;

\( \varepsilon_k \): Random error term.

The observed and coded discrete crash severity variable \( y_k \) is determined by the following model,

\[
y_k = \begin{cases} 
  1 & \text{if } -\infty \leq y_k^* \leq \mu_1 \\
  2 & \text{if } \mu_1 \leq y_k^* \leq \mu_2 \\
  3 & \text{if } \mu_2 \leq y_k^* \leq \mu_3 \\
  4 & \text{if } \mu_3 \leq y_k^* \leq \mu_4 \\
  5 & \text{if } \mu_4 \leq y_k^* \leq \infty 
\end{cases}
\]  

(7.4)

Where:

\( y_k = (1, 2, 3, 4, 5) \): Property damage only, complaint of pain, non-incapacitating injury, incapacitating injury, and fatal crashes, respectively;

\( \mu_1, \mu_2, \mu_3 \) and \( \mu_4 \): The threshold values to be estimated.

**Internal vs. External Crash Cost**

Link-based internal crash cost refers to the expected crash cost per vehicle kilometer traveled specific to link segments. It is determined by expected crash frequency, unit crash
cost, and vehicle-kilometer traveled (vkt) on each link, expressed as:

\[ C_{s,\text{int},i_f} = \sum_z \frac{N_{s,i_f} * R_{i_f,z} * u_{s_z}}{N_Y * N_D * Q} \]  

(7.5)

Where:
- \( C_{s,\text{int},i_f} \): Internal crash cost on link \( i_f \), in which \( f \) is specific to FRCs;
- \( N_{s,i_f} \): Expected crash frequency on link \( i_f \);
- \( R_{i_f,z} \): Probability of type \( z \) crashes happened on link \( i_f \);
- \( u_{s_z} \): Unit crash cost per vehicle in a type \( z \) crash;
- \( N_Y \): Number of years, \( N_Y = 12 \);
- \( N_D \): Number of days per year, \( N_D = 365 \);
- \( Q \): AADT.

We measured the unit crash cost per vehicle as:

\[ u_{s_z} = u_{s_p,z} \frac{N_{p,f}}{N_{v,f}} + u_{s_v,z} \]  

(7.6)

Where:
- \( u_{s_p,z} \): Per injured person based crash cost in a type \( z \) crash;
- \( u_{s_v,z} \): Per crashing vehicle based crash cost in a type \( z \) crash;
- \( N_{p,f} \): Average number of injured or killed persons per crash for all the links with FRC of \( f \);
- \( N_{v,f} \): Average number of crashing vehicles per crash for all the links with FRC of \( f \).

Both \( N_{p,f} \) and \( N_{v,f} \) for the road links in the Twin Cities Metro area are shown in Table 7.4.

Link-based external crash cost refers to the marginal crash cost for a specific link, written as:

\[ C_{s,\text{ext},i_f} = \sum_z \frac{u_{s_z} * R_{i_f,z} * \partial N_{s,i_f}}{N_Y * N_D * \partial Q} \]  

(7.7)

Where:
- \( C_{s,\text{ext},i_f} \): External crash cost on link \( i_f \).
Table 7.4: Average Number of Injured Persons and Crashing Vehicles Per Crash

<table>
<thead>
<tr>
<th>Severity</th>
<th>Primary Arterial</th>
<th>Minor Arterial</th>
<th>Collector Arterial</th>
<th>Local Arterial</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( N_p )</td>
<td>( N_v )</td>
<td>( N_p )</td>
<td>( N_v )</td>
</tr>
<tr>
<td>Fatal</td>
<td>2.507</td>
<td>2.223</td>
<td>1.938</td>
<td>1.804</td>
</tr>
<tr>
<td>Incapacitating Injury</td>
<td>1.804</td>
<td>1.980</td>
<td>1.660</td>
<td>1.805</td>
</tr>
<tr>
<td>Non-incapacitating Injury</td>
<td>1.483</td>
<td>2.056</td>
<td>1.506</td>
<td>1.896</td>
</tr>
<tr>
<td>Complaint of Pain</td>
<td>1.306</td>
<td>2.184</td>
<td>1.320</td>
<td>2.006</td>
</tr>
<tr>
<td>Property Damage Only</td>
<td>0.000</td>
<td>2.029</td>
<td>0.000</td>
<td>1.982</td>
</tr>
</tbody>
</table>

**Crash Cost Adjustment in Full Cost Estimates**

Based on Figure 5.5, the unit crash cost considers the congestion-related cost due to crashes, which, however, has been transferred to the time cost, monetary cost and emission cost, explained in Section 5.2.1. Hence, in the full cost analysis, adjustments are needed to exclude the congested-related cost due to crashes to avoid the double-counting problem.

Table 7.5 shows the original and adjusted unit crash cost. The latter one was used to measure the on-road safety cost contributed to the full cost.
<table>
<thead>
<tr>
<th></th>
<th>Fatal Injury</th>
<th>Incapacitating Injury</th>
<th>Non-incapacitating Injury</th>
<th>Complaint of Pain</th>
<th>Property-damage Only</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Original</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost per Injured Person</td>
<td>$9,134,786</td>
<td>$997,688</td>
<td>$273,544</td>
<td>$125,360</td>
<td>$40,673</td>
</tr>
<tr>
<td>Cost per Crashing Vehicle</td>
<td>$10,712</td>
<td>$3,518</td>
<td>$2,465</td>
<td>$2,407</td>
<td>$1,624</td>
</tr>
<tr>
<td><strong>Adjusted</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost per Injured Person</td>
<td>$9,129,066</td>
<td>$996,303</td>
<td>$272,549</td>
<td>$124,351</td>
<td>$39,647</td>
</tr>
<tr>
<td>Cost per Crashing Vehicle</td>
<td>$10,712</td>
<td>$3,518</td>
<td>$2,465</td>
<td>$2,407</td>
<td>$1,624</td>
</tr>
</tbody>
</table>
7.3.2 The Safest Path

The safest internal path is defined as the route with the lowest internal crash cost. The safest external path is the route with the lowest external crash cost considering the marginal increases of crash costs imposed on others. Both the safest internal and external paths provide new rules of traffic assignment to minimize the crash cost from the perspective of travelers.

For a given origin-destination (OD) pair, the general mathematical expression of the safest path is written as:

\[ C_{OD,k,s} = \sum_{i \in P_{OD,k}} C_{s,i} \]  
\[ C_{OD,s} = \min(C_{OD,k,s}) \]

(7.8) \( (7.9) \)

Where:
- \( C_{s,i} \): Crash cost on link \( i \);
- \( C_{OD,k,s} \): Crash cost of the \( k \)th path between origin \( O \) and destination \( D \);
- \( C_{OD,s} \): Minimum cumulative crash cost between \( O \) and \( D \).

7.4 Results

7.4.1 Crash Frequency Estimates

Negative Binominal Estimates

As described in Section 7.3.1, Negative Binominal Models of SPF's were applied to estimate the crash frequencies. Four separate models were established for different functional roadway classifications considering their unique attributes. The use of separate models was statistically validated (Carson 1998, Carson & Mannering 2001).
Table 7.6: Descriptive Statistics in Negative Binomial Model

<table>
<thead>
<tr>
<th>Variables</th>
<th>Description</th>
<th>Primary Arterial</th>
<th>Minor Arterial</th>
<th>Collector</th>
<th>Local</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean  S.D.</td>
<td>Mean  S.D.</td>
<td>Mean  S.D.</td>
<td>Mean  S.D.</td>
</tr>
<tr>
<td>$N_s$</td>
<td>Dependent Variables, number of crashes on a link</td>
<td>22.11  56.74</td>
<td>7.20  15.03</td>
<td>3.01  8.10</td>
<td>2.00  6.30</td>
</tr>
<tr>
<td>$L$</td>
<td>Length of link segment (km)</td>
<td>0.64  0.70</td>
<td>0.63  0.71</td>
<td>0.41  0.43</td>
<td>0.38  0.41</td>
</tr>
<tr>
<td>$V$</td>
<td>Median speed, 50th percentile TomTom speed</td>
<td>78.38  24.51</td>
<td>57.13  21.05</td>
<td>49.16  18.07</td>
<td>44.70  16.09</td>
</tr>
<tr>
<td>$V_{Var}$</td>
<td>Speed variance, differences between 10th and 90th percentile TomTom speed</td>
<td>31.90  16.90</td>
<td>26.08  12.91</td>
<td>21.30  13.76</td>
<td>19.81  14.99</td>
</tr>
<tr>
<td>$U$</td>
<td>Dummy variable, urban road=1, others=0</td>
<td>0.88  0.33</td>
<td>0.83  0.38</td>
<td>0.87  0.34</td>
<td>0.92  0.27</td>
</tr>
</tbody>
</table>
The selected independent variables for the Negative Binomial Models are described in Table 7.6. Note that $V_{Var}$ is not the typical measure of speed variance which measures the dispersion of space mean speeds among drivers within or across lanes at the same time (Wang et al. 2015, Kockelman & Ma 2010). $V_{Var}$ is more likely to show the dispersion of time mean speed that describes the differences of the fastest 5% and the slowest 5% speeds over a specific time period, like the morning peak hours across a year.

The regression results of the SPF's are shown in Table 7.7, in which $Q$ and $L$ have been transformed into natural log format in the models. Both original and natural log formats of $Q$ and $L$ were tested for different functional roadway classifications. Using natural log format is a better fit, as it produces a much lower AIC and higher pseudo $R^2$.

From Table 7.7, the conventional variables ($Q$ and $L$) show significant positive effects on crash counts for all roadway classifications. It recognizes that links with higher AADT or longer length tend to have more crashes, consistent with expectations. Travel speed was found to affect crash frequencies negatively and significantly, so that driving with a lower speed would result in more crashes. It is reasonable since, as TomTom speed data describes, for a given roadway functional class, lower travel speeds reflect more congested driving conditions and congested roads are typically associated with more crashes (note that speed is not statistically significant for crash counts on primary arterials). Speed variances, which implies on-road shockwaves, are positively correlated with crash counts. More serious stop-and-go driving conditions tend to be associated with more collisions. In addition, it was found that urban roadways are more likely to have higher crash counts than rural.
Table 7.7: Safety Performance Function Results for Crashes by Roadway Class

<table>
<thead>
<tr>
<th>Variables</th>
<th>Primary Arterial</th>
<th>Minor Arterial</th>
<th>Collector</th>
<th>Local Roads</th>
</tr>
</thead>
<tbody>
<tr>
<td>Const.</td>
<td>-2.654</td>
<td>0.323</td>
<td>***</td>
<td>-1.445</td>
</tr>
<tr>
<td>ln(Q)</td>
<td>0.486</td>
<td>0.035</td>
<td>***</td>
<td>0.475</td>
</tr>
<tr>
<td>ln(L)</td>
<td>0.326</td>
<td>0.045</td>
<td>***</td>
<td>0.593</td>
</tr>
<tr>
<td>V</td>
<td>-0.001</td>
<td>0.002</td>
<td></td>
<td>-0.019</td>
</tr>
<tr>
<td>V_var</td>
<td>0.008</td>
<td>0.002</td>
<td>***</td>
<td>0.002</td>
</tr>
<tr>
<td>U</td>
<td>0.624</td>
<td>0.112</td>
<td>***</td>
<td>0.634</td>
</tr>
</tbody>
</table>

AIC: 23,681  60,687  26,686  14,642
Pseudo $R^2$: 0.018  0.029  0.067  0.060

*** p-value < 0.001, ** p-value < 0.01, * p-value < 0.05, . p-value < 0.1
Ordered Probit Models

To identify crash severity, ordered probit models were used to estimate the probability of each type of crashes on specific links by functional roadway classifications.

The same link property attributes were used as the independent variables in the severity identification models, in addition to which dummy variables, $W_{Wet}$, $W_{Snow}$, and $W_{Ice}$, describing road surface features were added (the baseline is dry road surface). Moreover, for each functional roadway classification, we used the natural log format of $Q$ and $L$ (Again, the natural log format of $Q$ and $L$ has a lower AIC and higher pseudo $R^2$ than the untransformed variables). The descriptive statistics of selected independent variables are shown in Table 7.8.

Note that the dependent variable in the ordered probit models is crash severity. The number of observations shown in Table 7.8 refers to the number of crash records, which differs from Table 7.6, where each link is an observation. The mean and standard deviation, thus, differ for the same link property attributes in the negative binomial and ordered probit models.

Table 7.8: Descriptive Statistics in Ordered Probit Model

<table>
<thead>
<tr>
<th>Independent Variables</th>
<th>Primary Arterial (n=82,328)</th>
<th>Minor Arterial (n=81,178)</th>
<th>Collector (n=21,879)</th>
<th>Local (n=9,917)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean S.D.</td>
<td>Mean S.D.</td>
<td>Mean S.D.</td>
<td>Mean S.D.</td>
</tr>
<tr>
<td>Q</td>
<td>84,439 46,516</td>
<td>14,509 14,543</td>
<td>10,225 23,412</td>
<td>10,711 18,637</td>
</tr>
<tr>
<td>L</td>
<td>0.86 0.97</td>
<td>0.71 0.74</td>
<td>0.55 0.46</td>
<td>0.62 0.52</td>
</tr>
<tr>
<td>V</td>
<td>85.38 20.39</td>
<td>53.16 19.94</td>
<td>45.05 17.24</td>
<td>44.21 17.57</td>
</tr>
<tr>
<td>V_{Var}</td>
<td>36.23 18.65</td>
<td>27.10 12.37</td>
<td>23.89 14.26</td>
<td>23.63 17.36</td>
</tr>
<tr>
<td>U</td>
<td>0.95 0.22</td>
<td>0.93 0.26</td>
<td>0.96 0.20</td>
<td>0.97 0.18</td>
</tr>
<tr>
<td>$W_{Wet}$</td>
<td>0.15 0.36</td>
<td>0.15 0.36</td>
<td>0.15 0.36</td>
<td>0.15 0.36</td>
</tr>
<tr>
<td>$W_{Snow}$</td>
<td>0.05 0.23</td>
<td>0.06 0.23</td>
<td>0.07 0.25</td>
<td>0.07 0.25</td>
</tr>
<tr>
<td>$W_{Ice}$</td>
<td>0.07 0.26</td>
<td>0.07 0.26</td>
<td>0.09 0.28</td>
<td>0.09 0.29</td>
</tr>
</tbody>
</table>

1 The dependent variable in ordered probit models is crash severity.
Table 7.9 shows the regression results of the ordered probit models. Considering the link property attributes, traffic flow was found to be negatively correlated with the crash severity that a higher AADT is associated with less severe crashes. This is understandable since drivers tend to be more careful on busy roadways. Segment length affects crash severity positively that longer links are associated with more severe crashes. Travel speeds are positively associated with crash severity, except for the category of local roads (which is insignificant), so a higher speed is more likely to be associated with injury crashes. Speed variance has no significant effect on crash severity for all different classifications of roadways. The dummy variable, urban, is correlated with less crash severity but tends to be less statistically significant.
Table 7.9: Ordered Probit Regression to Identify Crash Severity

<table>
<thead>
<tr>
<th>Coefficients</th>
<th>Primary Arterial</th>
<th></th>
<th>Minor Arterial</th>
<th></th>
<th>Collector</th>
<th></th>
<th>Local</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>ln(Q)</td>
<td>-0.1031</td>
<td>0.0098</td>
<td>***</td>
<td>-0.0958</td>
<td>0.0100</td>
<td>***</td>
<td>-0.0495</td>
<td>0.0189</td>
</tr>
<tr>
<td>ln(L)</td>
<td>0.0454</td>
<td>0.0099</td>
<td>***</td>
<td>0.0561</td>
<td>0.0107</td>
<td>***</td>
<td>0.0329</td>
<td>0.0199</td>
</tr>
<tr>
<td>V</td>
<td>0.0009</td>
<td>0.0005</td>
<td>0.0020</td>
<td>0.0005</td>
<td>***</td>
<td>0.0041</td>
<td>0.0010</td>
<td>***</td>
</tr>
<tr>
<td>V&lt;sub&gt;Var&lt;/sub&gt;</td>
<td>-0.0001</td>
<td>0.0005</td>
<td>0.0011</td>
<td>0.0006</td>
<td>*</td>
<td>-0.0020</td>
<td>0.0011</td>
<td>0.0007</td>
</tr>
<tr>
<td>U</td>
<td>-0.0267</td>
<td>0.0372</td>
<td>0.0009</td>
<td>0.0005</td>
<td>0.0020</td>
<td>0.0006</td>
<td>0.0041</td>
<td>0.0010</td>
</tr>
<tr>
<td>W&lt;sub&gt;Wet&lt;/sub&gt;</td>
<td>-0.0792</td>
<td>0.0221</td>
<td>***</td>
<td>-0.1292</td>
<td>0.0210</td>
<td>***</td>
<td>-0.1976</td>
<td>0.0409</td>
</tr>
<tr>
<td>W&lt;sub&gt;Snow&lt;/sub&gt;</td>
<td>-0.4997</td>
<td>0.0394</td>
<td>***</td>
<td>-0.5470</td>
<td>0.0357</td>
<td>***</td>
<td>-0.6980</td>
<td>0.0656</td>
</tr>
<tr>
<td>W&lt;sub&gt;Ice&lt;/sub&gt;</td>
<td>-0.1755</td>
<td>0.0318</td>
<td>***</td>
<td>-0.6162</td>
<td>0.0330</td>
<td>***</td>
<td>-0.7058</td>
<td>0.0577</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>-0.1325</td>
<td>0.0957</td>
<td>-0.1794</td>
<td>0.0897</td>
<td>*</td>
<td>0.1361</td>
<td>0.1645</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>1.5681</td>
<td>0.0963</td>
<td>***</td>
<td>1.3015</td>
<td>0.0900</td>
<td>***</td>
<td>1.5946</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>3.8570</td>
<td>0.1044</td>
<td>***</td>
<td>3.1973</td>
<td>0.0935</td>
<td>***</td>
<td>3.4422</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td>5.2561</td>
<td>0.1285</td>
<td>***</td>
<td>5.0587</td>
<td>0.1138</td>
<td>***</td>
<td>5.4640</td>
</tr>
<tr>
<td>AIC</td>
<td>121,801</td>
<td>139,568</td>
<td>38,476</td>
<td>16,661</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pseudo R&lt;sup&gt;2&lt;/sup&gt;</td>
<td>0.0028</td>
<td>0.0053</td>
<td>0.0082</td>
<td>0.0084</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1 *** p-value<0.001, ** p-value<0.01, * p-value<0.05, . p-value<0.1
2 Order Definition: Fatal=5; Incapacitating Injury=4; Non-Incapacitating Injury=3; Complaint of Pain=2; Property Damage Only=1.
The coefficients of selected road surface features show that driving on wet, snow and icy roadways tends to lower the injury crashes compared with driving on dry roadways. The estimates are consistent with some previous reports that snow or icy condition reduces injury severity for crashes due to lower average speed and more careful driving. Property damage crashes, however, are more frequent during winter (Brown & Baass 1997, Brorsson et al. 1988, Maze et al. 2006).

In the crash severity identification, scenarios of roads with dry, wet, snow, and icy surface features have been all estimated. The proportions of crash records on different road surfaces specific to functional roadway classifications were used as the weights to determine the probability of each type of crashes.

7.4.2 Link-Based Crash Cost Estimates

The link-based internal and external crash costs were estimated for the road network in the Minneapolis - St. Paul Metropolitan area.

The estimates show that the average internal crash cost of all link segments is approximately $0.040/veh-km, and 95.7% of links have an internal crash cost less than $0.10/veh-km. The external crash cost borne by other travelers is much lower than the internal cost, in that the mean value is $0.023/veh-km. Around 99.2% of links in the Twin Cities network have an external crash cost lower than $0.10/veh-km.

Highways are much safer than other surface roadways based on the estimates. It is shown that the mean value of internal crash costs for highways (shown as grey lines in Figure 6.1) is $0.020/veh-km, while for other surface roadways is $0.042/veh-km, and that of external crash costs for highways is $0.010/veh-km, while for other surface roadways is $0.024/veh-km.

In addition, driving in the downtown area is more expensive from a crash perspective than in other areas. Based on our estimates, the average crash costs for the roadways in the core cities (Internal: $0.048/veh-km, External: $0.028/veh-km) is much higher than the roadways in other urban (Internal: $0.037/veh-km, External: $0.021/veh-km) or rural areas (Internal: $0.039/veh-km, External $0.021/veh-km).

Figure 7.1 gives the spatial distribution patterns of the link-based crash cost estimates for both internal and external versions. Consistent with discussions above, the crash costs
borne by travelers themselves (Internal, Figure 7.1a) are higher than that borne by other travelers (External, Figure 7.1b), and highways are safer than surface roadways.

Figure 7.2 displays the crash cost of all vehicles generated on each link. Considering the traffic flow, total crash costs are higher generated on the highway network.
Figure 7.1: Crash Cost Per Vehicle-Kilometer on Each Link of the Twin Cities Road Network ($/veh-km)
Figure 7.2: Crash Cost of All Vehicles Generated on Each Link of the Twin Cities Road Network ($/km)
7.4.3 Work Trip Flow

Based on the crash cost analysis, both the safest internal path \( (P_{s,int}) \) and the safest external path \( (P_{s,ext}) \) have been considered as the shortest paths in the estimation of work trip flow from the aspects of crash cost. A comparison with the shortest travel time path (Figure 6.4) indicates the differences in spatial distributions between the safest and the shortest travel time paths.

Figure 7.3 shows the spatial distributions of work trip flow estimates for the safest internal and safest external paths based on current traffic levels, assuming other traffic does not reroute in response to this posited change in traffic flow and concomitant changes in speeds and crash risks.

The work trip flow on the hypothetical safest path (Figure 7.3a and Figure 7.3b) shows largely the same distribution patterns as the baseline estimates that work trips are more allocated to highways to minimize the safety costs for both internal and external versions. The colors on the maps shift so that several major safer routes are identified from the crash costs perspective, I-35W, I-35E, I-94, I-394, and I-94, shown clearly in Figure 7.4. However, some state (non-interstate) routes designed to lower standards, MN-100 and US-169, become less important for the optimization of safety costs.

For the safest internal path and the safest external path, their work trip flow estimates do not have significant differences.
Figure 7.3: Work Trip Flow Assigned to the Safest Internal/External Path
Figure 7.4: Differences of Work Trip Flow Assigned to the Safest Internal/External Path Minus That Assigned to the Shortest Travel Time Path

(a) Safest Internal Path

(b) Safest External Path
7.5 Summary

This chapter built a framework of link-based crash cost analysis, analyzed the internal and external crash cost for the road network in the Minneapolis - St. Paul metropolitan area, and found the safest paths for all OD pairs. The travel on these paths was aggregated to evaluate the potential work trip flow.

This analysis estimated both internal and external on-road crash costs. Internal cost is defined as the crash cost borne by each traveler involved in a crash and external cost considers the marginal increases of crash costs imposed on others due to an additional vehicle on roads.

The safest (internal/external) path was proposed to estimate the minimum crash cost during travel. The link costs associated with the safest path are valuable data inputs for a full cost analysis of travel, which could be used in planning and economic analyses.

The crash cost analysis shows that the average internal crash cost of the link segments in the Twin Cities area is approximately $0.040/veh-km, while the average external cost is around $0.023/veh-km. It indicates that the crash costs travelers borne by themselves are much higher than that they impose on others. More importantly, highways are safer than other surface roadways for both internal and external crash costs, which is expected since highways are designed to provide safe and effective travel. In addition, downtown roads have higher crash costs, for which both internal and external crash costs are much higher than roads elsewhere.

The work trip flows on the hypothetical safest path for both internal and external versions show largely the same distribution as that on the shortest travel time path that work trips are more allocated to highways. Interstate highways, I-35W, I-35E, I-94, I-394, and I-494, are identified to be the major safer routes in the Minneapolis - St. Paul Metropolitan area. It implies that, generally, travelers could pursue a safer and shorter route simultaneously considering their crash costs.

Compared with the values of time ($18.30/h), it is unlikely travelers will shift their route significantly to account for safety. However, external costs should still be internalized.
Chapter 8

Greenest/Healthiest Path – Pollution Exposure/Emission Cost and Routing

8.1 Introduction

Outdoor urban air pollution is a major risk to health. According to the World Health Organization, urban air pollution is one of the top 15 causes of death globally, and one of the top 10 causes in medium- and high-income countries. Health effects of urban air pollution include respiratory and cardiovascular disease, and adverse birth outcomes. Exposure to high concentration of airborne particle matter (PM) correlates with many adverse respiratory and cardiovascular health problems, as revealed through epidemiological and toxicological studies (e.g. Dockery (2001), Pope III et al. (2002)).

Motor vehicles are a dominant source of urban air pollution. As a result of incomplete combustion of fossil fuels, a number of contaminants are released into the environment, including carbon monoxide, hydrocarbons, smog-forming constituents, and particulate matter (PM).

The switch to hybrid, and ultimately electric vehicles, improves the situation, particularly tailpipe emissions, but does not eliminate the pollution problem. With full electrification of the fleet decades away, the need to mitigate the effects of automobile tailpipe
pollution remains especially salient. Further, all vehicles also generate particulates where the rubber meets the road, from abrasion processes like tires and brake wear, and road dust resuspension (Gillies et al. 2001, Charron & Harrison 2005, Lee et al. 2003). Thus, even with electrification, automobile pollution will not disappear, and depending on the types of electric power generation, some pollution may be relocated.

Once emitted into the atmosphere, air pollutants undergo mixing, diffusion, or chemical reactions, the degree of which depends on background concentration, meteorological and geographical conditions, and other local characteristics. Since exposure to significant levels of contaminants harms human health, regulations on air quality and vehicle emissions are employed in many countries. In the United States, metropolitan areas must certify that transport plans conform to air quality standards which set maximum allowable levels of criteria pollutants (failure to do so results in suspension of federal highway funds).

On-road emissions are economically costly to human health (Mayeres et al. 1996) including both internal costs due to air pollution intake and external costs, that is, the health damage costs from emitted pollutants imposed on others. These costs depend on the economic value (due to morbidity and mortality) of pollution emissions. The full costs combine the internal and external costs.

There remains uncertainty about the operating characteristics of vehicles which minimize emissions, as this depends on the nature of the vehicle and the driving conditions. There is less uncertainty about exposure, where pollution intake occurs, as traffic counts and individual travel routes are readily employed.

The economic measure of environmental externalities of travel would be lower if travelers took alternative routes with reduced pollution generation and the exposure of others, or personal intake or exposure (Ahn & Rakha 2007, Lena et al. 2002). In this dissertation, the healthiest path minimizes personal exposure, while the greenest path minimizes external pollution costs (due to emissions and general population exposure). We find traffic routing patterns which minimize the costs of air pollution exposure and emissions for individual trips. This kind of analysis could subsequently be iterated with an equilibrium or other traffic assignment procedure to discover routing for all trips, subject to others also using such a routing logic (Wardrop 1952, Daganzo & Sheffi 1977).

As a proof-of-concept, this chapter proposes a framework of link-based emission cost
analysis, based on the EPA MOVES and RLINE models for on-road and off-road concentration estimates, and measures the internal and external emission costs for each link segment for the Twin Cities metropolitan road network. Pollution produced by travelers and travelers’ pollution intake along various routes could then be estimated as a function of endogenous traffic levels.

Applying the framework in the Twin Cities Metro Area, the healthiest and the greenest paths are found for all work trip origin-destination (OD) pairs and then aggregated into work trip flows to identify healthier or greener routes.

8.2 Data Collection

Several sources of data are applied in this analysis.

8.2.1 Surface Meteorology Data

Minnesota Pollution Control Agency (2013) describes the hourly surface meteorology for the five-year period between 2009 and 2013 for Minnesota. It was generated from AER-MET and AERMIN models, the meteorological preprocessor for AERMOD (AMS/EPA Regulatory Model) (US Environmental Protection Agency 2004b). As the main input of the RLINE model, the meteorology data covers 21 surface stations with attributes of surface friction velocity, the convective velocity scale, the heights of both the convectively-generated and mechanically-generated boundary layer, the Monin-Obhukov length, the surface roughness length, the wind speed and direction at reference height, and so on (Snyder & Heist 2013). In this study, the concentration estimates were based on the 2013 meteorology data at the Minneapolis - St. Paul International Airport station.

8.2.2 Road Condition Data

Minnesota Department of Transportation (MnDOT) roadway condition data includes the pavement quality indicator (PQI), ride quality index (RQI), surface rating (SR), and, the most relevant for our analysis, truck percentage ($R_t$) for highway links in Minnesota from 2000 to 2015. A corresponding shapefile was also provided by MnDOT to locate the data
point on the network. Link type source, an essential input of MOVES, was established from this data.

TomTom speed data and TomTom road network are important inputs for the estimations of pollution concentration as well. Details are introduced in Section 6.2.1. TomTom road network, joined with TomTom speed records, was used as an input to the project-level of MOVES simulations to estimate the on-road emissions, which was then used for concentration estimates based on the RLINE dispersion model. In addition, the estimated emission cost was, again, joined with the road network to find the healthiest (internal emission cost) path and the greenest (external emission cost) path.

An estimate of average annual daily traffic (AADT), expressed in Section 7.2.2, joined to the TomTom road network, was used as an input of MOVES as well.

Origin and Destination (OD) table in LEHD dataset was used to estimate the work trip flows on each link segment with the assumption that each worker in the dataset would select the healthiest path or the greenest path, as determined based on current flows. See Section 6.2.2.

8.3 Methodology

To overview the methodology detailed below, we apply a project-level of MOVES simulation (Section 8.3.1) to model the on-road emissions for all the link segments on the road network of the Twin Cities. We then use the RLINE model (Section 8.3.2) to estimate the on-road and off-road concentrations for each pollutant generated from vehicles. We analyze the internal and external emission costs by measuring the health damage cost of travelers and general population due to exposure (Section 8.3.3). These three parts give the framework of link-based emission cost analysis. Section 8.3.4 defines the healthiest and greenest paths mathematically.

8.3.1 MOVES: Pollution Estimation

In contrast with other vehicle emission models such as CMEM (Barth et al. 2000) and VT-Micro (Rakha et al. 2004), MOVES performs quantitative project-level of simulation to estimate the localized emission for different types of pollutants in addition to national and regional level of emission estimations (Lin et al. 2011, US Environmental Protection Agency 2015c, US Environmental Protection Agency 2015b).

To identify the healthiest or the greenest paths, we require air pollution estimates for each link segment on the metropolitan road network. We conducted project-level of MOVES simulations to estimate the quantity of emitted pollutants and greenhouse gases, including nitrogen oxides (NO\textsubscript{X}), particulate matter (PM), sulfur dioxide (SO\textsubscript{2}), and carbon dioxide (CO\textsubscript{2}).

The inputs to project-level simulations, such as meteorology and fuel type, vary across counties. We estimated each county separately and combined their results subsequently for the whole road network. Most of the inputs were set as the defaults specific to time and location, except for the tables of links and link source types, which are described as follows:

- **Links**
  
The link table defines the individual roadway link properties: segment length, traffic flow, average speed, and road grade. TomTom data provide segments length, and 50th percentile speed during the morning peak hours (7AM - 9AM), directly. Traffic flow, vehicles per hour, was extracted from the AADT data by dividing by the AADT to peak period ratio of 6.09, which was computed from the MnDOT’s IRIS traffic database for the Twin Cities region (Minnesota Department of Transportation 2014). The road grade for all the links were set as 0; future research could improve this with Digital Elevation Model data.

- **Link Source Type**
  
Link source type describes the composition of link traffic flow by vehicle type (source type). Observed (i.e., measured) link source type data for each link segment on the Twin Cities road network do not exist.

The MnDOT roadway condition database provides the truck percentage ($R_{vt}$) on
highway link segments in the Twin Cities, for buses, single-unit trucks, and combination trucks. Based on the average statewide vehicle classification in Minnesota, the fractions of buses, single-unit trucks, and combination trucks are 0.207, 0.505 and 0.288 respectively (Wilde & Stahl 2010). Combining the vehicle source type defined in MOVES, Table 8.1 shows the setting of vehicle type fractions for different types of trucks on highway links by assuming each sub-category shares the same fraction. While among passenger vehicles, the fractions of cars, trucks, and motorcycles are 0.698, 0.292 and 0.001 respectively (Traffic Forecasts and Analysis Section 2012).

Table 8.1: Vehicle Type Fraction Setting for Highway Link Segments

<table>
<thead>
<tr>
<th>MnDOT Use Type</th>
<th>Avg Percentage</th>
<th>MOVES Use Type</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Autos, Pickups</td>
<td>1-$R_{vt}$</td>
<td>21. Passenger Cars</td>
<td>0.698*(1-$R_{vt}$)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>31. Passenger Truck</td>
<td>0.292*(1-$R_{vt}$)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>11. Motorcycle</td>
<td>0.010*(1-$R_{vt}$)</td>
</tr>
<tr>
<td>Buses, Trucks w/ Trailers</td>
<td>0.207*$R_{vt}$</td>
<td>41. Intercity Bus</td>
<td>0.207*$R_{vt}$/3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>42. Transit Bus</td>
<td>0.207*$R_{vt}$/3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>43. School Bus</td>
<td>0.207*$R_{vt}$/3</td>
</tr>
<tr>
<td>Single-unit Truck (SU)</td>
<td>0.505*$R_{vt}$</td>
<td>51. Refuse Truck</td>
<td>0.505*$R_{vt}$/3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>52. Single-unit Short-haul Truck</td>
<td>0.505*$R_{vt}$/3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>53. Single-unit Long-haul Truck</td>
<td>0.505*$R_{vt}$/3</td>
</tr>
<tr>
<td>Combination Truck (TST)</td>
<td>0.288*$R_{vt}$</td>
<td>61. Combination Short-haul Truck</td>
<td>0.288*$R_{vt}$/2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>62. Combination Long-haul Truck</td>
<td>0.288*$R_{vt}$/2</td>
</tr>
</tbody>
</table>

Truck percentage data on other link segments are not available in the Twin Cities. Wilde and Stahl (2010) proposed to categorize vehicle classifications by average daily traffic ranges (Wilde & Stahl 2010). Hence, we estimated a linear regression of truck percentage on the same AADT ranges using the samples of highway links. The results
are shown in Table 8.2. The fraction setting of the MOVES-used type then follows the rules shown in Table 8.1 based on the estimated $R_t$.

Table 8.2: Truck Percentage Estimation Based on AADT Range

<table>
<thead>
<tr>
<th>Variables</th>
<th>Est.</th>
<th>S.E.</th>
<th>Signif.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>10.417</td>
<td>0.251</td>
<td>***</td>
</tr>
<tr>
<td>AADT Range</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>400-1499</td>
<td>0.928</td>
<td>0.268</td>
<td>***</td>
</tr>
<tr>
<td>1500–7000</td>
<td>-1.197</td>
<td>0.261</td>
<td>***</td>
</tr>
<tr>
<td>&gt;7000</td>
<td>-2.443</td>
<td>0.262</td>
<td>***</td>
</tr>
<tr>
<td>$R^2$</td>
<td></td>
<td></td>
<td>0.049</td>
</tr>
</tbody>
</table>

Note: *** $p < 0.01$

8.3.2 RLINE Dispersion Model

For city-wide estimates, with sufficient information on source emissions and meteorology, dispersion models are well suited to modeling short-term concentrations (Gulliver & Briggs 2011).

Many dispersion models have been proposed in previous studies. The Environmental Protection Agency’s (EPA) Regulatory Model (AERMOD) is a steady-state plume model for multiple sources including point, area, and volume sources (US Environmental Protection Agency 2004a, Cimorelli et al. 2005). It has the ability to characterize the planetary boundary layer through both surface and mixed layer scaling in air dispersion modeling. AERMOD is more frequently used for stationary sources including industries (Zhai et al. 2016). To simulate line-type source, such as on-road vehicles, AERMOD represents the line source as an elongated area source or a series of volume sources (Heist et al. 2013).

RLINE is a research dispersion modeling tool developed by the EPA based on a steady-state Gaussian dispersion model with new formulations for horizontal and vertical plume spread (Snyder et al. 2013, Snyder & Heist 2013, Venkatram et al. 2013). It simulates line source emissions specifically by integrating emissions of point sources numerically and
applies the surface meteorology data provided by AERMET and AERMIN models, the meteorological preprocessor for AERMOD. RLINE is suitable for flat roadways without surrounding complexities. In this study, we elected to use RLINE to estimate the concentrations both on-road and off-road.

- **Emission Source Input**
  
The emission source input identifies the line-type emission sources, including the coordinates of each link (starting and ending points), initial vertical dispersion, number of lanes, emission rate, and roadway configurations, in which project-level of MOVES simulation provides the emission rate for road links.

  In RLINE, each of the 48,000 links on the road network represents a line-type emission source, which generates a certain amount of pollution.

- **Receptor Input**
  
The receptor input specifies the locations of concentration receptors.

  For internal emission cost analysis, on-road concentrations determine emission exposure for on-road drivers. Hence, we selected the center point of each of the 48,000 links on the Twin Cities network as a receptor.

  For external emission cost analysis, vehicle emissions affect the health of general population. The centroid of each of the 54,000 census blocks in the Twin Cities was selected as a receptor to represent the off-road concentrations.

### 8.3.3 Emission Cost Analysis

As a key cost component of travel, the on-road emission is typically considered as an external cost of transport, due to damages to human health, vegetation, materials, aquatic ecosystems, visibility, climate change, and the like (Mayeres et al. 1996, Maibach et al. 2008). The estimates of external costs depend on different pollutants (Matthews et al. 2001, Koomey 1990). Small & Kazimi (1995) measures the health damage costs of VOC, NO\(_X\), SO\(_X\), and PM10 emissions from motor vehicles based on the raised mortality and morbidity. National Highway Traffic Safety Administration estimated the unit emission cost referring to the values of reductions in health damage costs per ton of emission of each
pollutant that is avoided (McGarity 2012). These values represent the savings due to lower concentrations when emissions of each pollutant that contributes to PM2.5 concentrations are reduced.

In this study, we are concerned more about the unit intake-emission cost which describes the health damage cost per unit of emission intake specific to pollutants. Intake fraction, the fraction of emissions that are inhaled by exposed people, relates emission to inhalation (Bennett et al. 2002, Evans et al. 2002). Assuming exposure efficiency is constant across exposed individuals, the unit intake-emission cost is represented as:

$$u_{g,int,p} = \frac{u_{g,p}}{R_g}$$

Where:
- $u_{g,int,p}$: Unit intake-emission cost of pollutant $p$;
- $u_{g,p}$: Unit emission cost of pollutant $p$;
- $R_g$: Intake fraction.

Marshall et al. (2005) estimated the intake fraction for nonreactive gaseous vehicle emissions in US urban areas, and gave the range of intake fraction of between 7 and 21 per million. Evans et al. (2002) measured the intake fraction for primary vehicle PM2.5, which is between 3 and 18 per million for urban locations and between 1 and 18 per million for rural locations based on a stratified random sample of 40 highway segments. Hence, a 10 per million intake fraction was set in this study, based on which Table 8.3 shows the unit intake damage cost with reference to the unit emission cost estimated by National Highway Traffic Safety Administration (McGarity 2012).
Table 8.3: Unit Intake-Emission Costs

<table>
<thead>
<tr>
<th>Unit Intake-Emission</th>
<th>Cost ($/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM</td>
<td>30,650</td>
</tr>
<tr>
<td>SO₂</td>
<td>3,960</td>
</tr>
<tr>
<td>NOₓ</td>
<td>670</td>
</tr>
</tbody>
</table>

Note: PM refers to PM2.5 and PM10.

**Internal Emission Cost**

The internal emission cost of auto travelers was defined as the health damage cost due to air pollution intake during commute (home to work) travel, which highly depends on the on-road concentrations of pollutants, travelers’ breathing rate, exposure time, and unit damage cost of pollutants (Hassanien et al. 2009). Considering the continuous changes of pollution concentration due to dispersion, the internal emission cost is written as:

\[
C_{g\text{-int},i} = \sum_p u_{g\text{-int},p} \int_0^{T_i} R_b \cdot \rho_{p,i}(t) \, dt
\]  

(8.2)

Where:

- \(C_{g\text{-int},i}\): Internal emission cost of link \(i\);
- \(u_{g\text{-int},p}\): Unit intake-emission cost of pollutant \(p\);
- \(\rho_{p,i}(t)\): Concentrations of pollutant \(p\) of link \(i\), which varies with time;
- \(T_i\): Exposure time on link \(i\);
- \(R_b\): Breathing rate.

For a specific link segment, the on-road concentrations estimated by RLINE dispersion model provide \(\rho_{p,i}(t)\), and travel speed and segment length determine the exposure time \(T_i\).
External Emission Cost

The external emission cost of auto travelers is the health damage cost from emitted pollutants imposed on others (non-drivers) (We also considered the costs of greenhouse gas (CO₂) in the external emission cost). The off-road concentrations and affected population are the determinants for the external cost. The external emission cost is written as:

\[
C_{g,\text{ext},i} = \left( \sum_p \sum_j u_{g,\text{int},p} * H_{D,j} * \int_0^T B_r * \rho_{g,i,j}(t) \, dt \right) + (N_{i,\text{CO}_2} * u_{\text{CO}_2}) * Q_i^{-1}
\]  

(8.3)

Where:
- \(C_{g,\text{ext},i}\): External emission cost of link \(i\);
- \(H_{D,j}\): Daytime population of block \(j\);
- \(\rho_{p,i,j}(t)\): Off-road concentration of block \(j\) contributed by emissions \(p\) from link \(i\);
- \(N_{i,\text{CO}_2}\): Quantity of CO₂ generated on link \(i\);
- \(u_{\text{CO}_2}\): Unit emission cost of CO₂, $22/ton (2010 US dollar);
- \(Q_i\): Traffic flow on link \(i\).

Daytime population was defined as “the number of people who are present in an area during normal business hours, including workers” (US Census Bureau 2015). US Census Bureau (2013a) estimated the commuter-adjusted daytime population based on the 2006-2010 five-year American Community Survey (ACS) at the level of county subdivisions for Minnesota. The percentage daytime population change for each county subdivision was applied for all the contained blocks. Future research could improve this estimate.

8.3.4 Healthiest Path vs. Greenest Path

The route with the lowest on-road pollution intake defines the healthiest path. A complement to this, the route with the lowest external emission cost considering the health damage costs borne by others due to pollutants from motor vehicles defines the greenest path. Both the healthiest path and the greenest path give new rules of traffic route assignment to minimize the costs of either pollution-intake or emissions from the perspective of travelers.

For a given origin-destination (OD) pair, the general mathematical expression of the healthiest path is written as:
\[ C_{OD,k,g,int} = \sum_{i \in P_{OD,k}} C_{g,int,i} \] (8.4)

\[ C_{OD,g,int} = \min(C_{OD,k,g,int}) \] (8.5)

Where:
- \( C_{OD,k,g,int} \): Internal emission cost of the \( k^{th} \) path traveling between \( O \) and \( D \);
- \( C_{OD,g,int} \): Internal emission cost along with the greenest path between \( O \) and \( D \).

Similarly, the greenest path, which aims to minimize the external emission cost is given as:

\[ C_{OD,k,g,ext} = \sum_{i \in P_{OD,k}} C_{g,ext,i} \] (8.6)

\[ C_{OD,g,ext} = \min(C_{OD,k,g,ext}) \] (8.7)

Where:
- \( C_{OD,k,g,ext} \): External emission cost of the \( k^{th} \) path traveling between \( O \) and \( D \);
- \( C_{OD,g,ext} \): External emission cost along with the greenest path between \( O \) and \( D \).

8.4 Results

8.4.1 RLINE Dispersion Model Estimates

On-road and off-road concentrations of PM, \( \text{SO}_2 \), and \( \text{NO}_X \) estimated by RLINE model for the Minneapolis - St. Paul Metropolitan area are shown in Figures 8.1 and 8.2. The on-road concentrations determine the emission intake of travelers along their commute trips, while the off-road ones affect the health of general population.

The average on-road concentrations in the Twin Cities area are PM: 1.916\( \mu g/m^3 \), \( \text{SO}_2 \): 0.743\( \mu g/m^3 \), \( \text{NO}_X \): 27.197\( \mu g/m^3 \).

Specifically, Figure 8.1 shows that all pollutants have higher on-road concentrations in urban areas (PM: 2.216\( \mu g/m^3 \), \( \text{SO}_2 \): 0.845\( \mu g/m^3 \), \( \text{NO}_X \): 33.471\( \mu g/m^3 \) ) than rural areas (PM: 0.955\( \mu g/m^3 \), \( \text{SO}_2 \): 0.416\( \mu g/m^3 \), \( \text{NO}_X \): 7.143\( \mu g/m^3 \)). Downtown Minneapolis and downtown St. Paul have the highest on-road concentrations overall (PM: 3.099\( \mu g/m^3 \),
SO\textsubscript{2}: 1.656\(\mu g/m^3\), NO\textsubscript{X}: 48.755\(\mu g/m^3\)) because downtown roads serve more traffic in the morning peak hours.

In addition, the on-road concentration maps clearly reflect the shape of the highway network in the Twin Cities. The concentrations on urban highways, e.g., I-35W, I-35E, I-394, are relatively higher as well due to higher traffic flows. The average concentrations of urban highways for different pollutants are PM: 3.064\(\mu g/m^3\), SO\textsubscript{2}: 1.059\(\mu g/m^3\), NO\textsubscript{X}: 67.500\(\mu g/m^3\).

The average off-road concentrations in the Twin Cities area are PM: 1.178\(\mu g/m^3\), SO\textsubscript{2}: 0.455\(\mu g/m^3\), NO\textsubscript{X}: 17.231\(\mu g/m^3\), which are lower than the on-road ones since the off-road receptors are farther from the emission sources. However, Figure 8.2 shows the similar patterns as Figure 8.1 that urban areas, especially in the core cities, have higher concentrations than rural areas and near-road blocks are affected by on-road emissions the most in which the concentrations are relatively higher, especially for those near the highways. Such a consistency is expected since both on-road and off-road concentrations we are concerned with here are determined by vehicle emissions, and decrease with distance increases from the emission sources to the receptors.

Figure 8.3 also shows the emission rate of other pollutants generated from MOVES simulation.
Figure 8.1: On-road Pollution Concentration from Motor Vehicle Emissions
Figure 8.2: Off-road Pollution Concentration from Motor Vehicle Emissions

(a) PM

(b) SO₂

(c) NOₓ
Figure 8.3: Greenest/Healthiest Path: Estimates of Emission Rate (µg/m s) from MOVES Simulation

8.4.2 Internal vs. External Emission Cost Analysis

The link-based internal and external emission costs were estimated for the road network based on the on-road and off-road concentrations.

The estimates show that the mean value of internal emission costs for all link segments is approximate $0.0009/veh-km, and most links (92%) have an internal emission cost less than $0.002/veh-km. As expected, comparing locations, driving in the core cities ($0.0017/veh-km) results in an intake of more internal emission cost than other urban ($0.0008/veh-km)
and rural areas ($0.0003/veh-km) due to higher concentrations. However, the average internal emission cost of highways ($0.00085/veh-km) is slightly lower than other roads ($0.00090/veh-km), which is explained by faster highways decreasing drivers’ exposure time.

The link-based external emission cost is much higher than the internal one that the average is around $0.0192/veh-km which indicates that the emission costs travelers impose on others are greater than those borne by themselves. It is expected as the external unit costs include damage to non-travelers, while the internal costs here exclude pollution costs from non-transport sources. Similarly, for different locations, using downtown roadways generates more external emission costs ($0.0298/veh-km) than other urban ($0.0184/veh-km) and rural areas ($0.0114/veh-km).

Daytime population density is much higher in the core cities, as Figure 8.4 shows which indicates that more people are affected by on-road emissions the core cities. In addition, downtown roadways serve more traffic during morning peak hours which results in more severe congestion. Stop-and-go traffic conditions lower vehicle fuel efficiency (US Environmental Protecting Agency 2017) which generate more on-road emissions per vehicle. Driving on highways generates less external emission cost ($0.0110/veh-km) than other roads ($0.0198/veh-km) which is mainly because of the stop-and-go traffic on other roads.
Figure 8.4: Daytime Population Density of the Twin Cities

Figure 8.5 gives the distribution patterns of the link-based internal and external emission cost estimates on the Twin Cities road network, which is consistent with our discussions above. Figure 8.6 shows the emission costs of all vehicles generated on each link considering the traffic flow.
Figure 8.5: Emission Cost Per Vehicle-Kilometer on Each Link of the Twin Cities Road Network ($/veh-km)
Figure 8.6: Emission Cost of All Vehicles Generated on Each Link of the Twin Cities Road Network ($/km)
8.4.3 Work Trip Flow

Figure 8.7 shows the work trip flow estimates for the healthiest path and the greenest path, based on current traffic levels, i.e., assuming other traffic does not reroute. It is indicated that, to minimize the intake emission cost, the hypothetical personally healthiest travel path detours to exurban areas where the on-road concentrations are lower. As Figure 8.7a shows, a complete circle on the exurban area of the Twin Cities is generated which identifies the less polluted roads (trading off lower pollution levels for longer exposure times). In addition, several major healthier paths are identified which connect downtown Minneapolis with the exurban area.

For Figure 8.7b, it is shown that, basically, the work trip flow on the hypothetical greenest path has largely the same distribution patterns as baseline shortest path estimates. Slight differences exist, as shown in Figure 8.8, for instance, more work trips reassign from I-94 and I-35W to MN-100 if travelers are assigned to the greenest path rather than the shortest one.
Figure 8.7: Work Trip Flow Assigned to the Healthiest/Greenest Path
Figure 8.8: Differences of Work Trip Flow Assigned to the Healthiest/Greenest Path Minus That Assigned to the Shortest Travel Time Path
8.5 Summary

This chapter analyzed the internal and external emission costs from on-road vehicles in the Minneapolis - St. Paul metropolitan area based on the EPA MOVES and RLINE dispersion model and evaluated the work trip flows based on the healthiest and greenest paths.

Generally, on-road emissions are categorized as an external cost expressing the health damage from emitted pollutants imposed on others. However, as active agents in transport systems, travelers also bear health damage costs due to pollution intake, which logically should be considered as an internal cost of travel.

The healthiest and greenest paths were proposed to estimate the minimum pollution exposure and emission costs during traveling. The link costs associated with the healthiest and greenest paths are valuable data as inputs to a full cost accounting of the cost of travel, and could subsequently be used in planning and economic analyses.

Urban highways have higher on-road concentrations due to higher traffic flows, which means the blocks closer to highways have higher off-road concentrations, as expected. However, pollution intake on highways is slightly lower than other roads on average since using highways decreases the exposure time for travelers. In addition, the model implies driving on highways generates less external emission costs. This is mainly because of the stop-and-go traffic on other roads. More importantly, comparing with the internal and external versions of costs, the emission cost travelers impose on others (external) is much greater than that borne by themselves (internal).

The work trip flows on the greenest path have similar patterns to the shortest path. In contrast, using the healthiest path generates more detours onto exurban roadways.

Given actual values of time ($18.30/hr), it is highly unlikely many travelers would be persuaded to shift routes based on such small pollution or health savings suggested by the healthiest and greenest paths compared with the shortest path. However, external costs should still be internalized.

From a policy perspective, road pricing presents a family of potential mechanisms to encourage the use of socially optimal routes. Present implementations of road pricing are quite crude compared to what is technically feasible. Currently, prices are fixed by area (there is a fixed charge to drive into central London, Singapore, or Stockholm for the day),
or by link (e.g. most highway or bridge tolls) or for a given on ramp - off ramp pair (e.g. the New Jersey Turnpike). There are off-peak discounts on many priced roads. Further, a few facilities vary by time-of-day (e.g. SR 91 in southern California) or dynamically (e.g. the High Occupancy/Toll lanes on I-394 in Minneapolis). However, the technology exists to geolocate individual vehicles and charge tolls varying by time of day, and by the specific route chosen to connect the origin and destination, and thus by the level of pollution produced or inadvertently consumed.
Chapter 9

Lowest Monetary/Infrastructure Path—Monetary/Infrastructure Cost and Routing

This chapter describes and measures the link-based monetary and infrastructure costs of auto travelers of the Twin Cities road network. The lowest monetary cost path and the lowest infrastructure cost path are found for all work trips, and aggregated into work trip flows to identify the cheaper routes for both internal and external versions.

9.1 Monetary Cost Factors

User monetary cost refers to vehicle operation costs borne by travelers themselves. It depends upon numerous factors which are determined by vehicle, user, and market price (Levinson & Gillen 1998). Generally, costs of owning vehicles are more concentrated regardless of how much they are driven (Barnes & Langworthy 2004). Instead, in this analysis, both the variable cost, which is a distance-based operation cost, and fixed cost, which is an annualized operating cost, are considered. The specific cost factors considered include:

- Variable Cost ($/veh-km)
  - Fuel Cost;
- Vehicle Maintenance and Repair Cost;
- Kilometer-based Vehicle Depreciation Cost.

- Fixed Cost ($/veh-year)
  - Time-based Vehicle Depreciation Cost;
  - Vehicle Finance Charges;
  - Vehicle Registration Fee;
  - Vehicle Insurance;
  - Vehicle Sales Tax;

For the Twin Cities Metropolitan region, the parking cost and MnPASS toll are critical monetary cost components, which are more complicated to be categorized into either variable costs or fixed costs.

- Parking Cost
  The parking cost could be classified as a fixed cost factor for travelers with contract parking. It is a trip-based cost for travelers paid by hours ($/veh-trip).

- MnPASS Toll
  Only MnPASS users pay the MnPASS toll, which is a trip-based cost ($/veh-trip) varying with traffic density.

The following section provides details on each monetary cost factor.

9.1.1 Variable Cost

Fuel Cost

Two factors effect a vehicle’s fuel cost: fuel consumption and fuel price.

- Fuel consumption Cost
  Fuel consumption is determined by vehicle model, driving behavior, (i.e., speed, acceleration, and braking), and driving condition. US Department of Energy, Environmental Protection Agency (2015) provides fuel economy data showing the standard
fuel efficiency (kilometers-per-liter) by vehicle model for both city and highway driving conditions. The Minnesota state market share of auto brands in 2014 (Minnesota Automobile Dealers Association 2015) and the new vehicle sales by car model in the US (Good Car Bad Car 2017) were applied to estimate the number of vehicles by car model. It was used as the weight to measure the average fuel efficiency, shown in Table 9.1.

Table 9.1: Average Fuel Efficiency (Kilometers-per-liter) for Different Driving Conditions

<table>
<thead>
<tr>
<th></th>
<th>City</th>
<th>Highway</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>8.999</td>
<td>12.229</td>
<td>10.453</td>
</tr>
</tbody>
</table>

1 US Department of Energy, Environmental Protection Agency (2015) assumes a combination of 55% city driving and 45% highway driving.

California Department of Transportation (2012) measured the fuel efficiency varying with speed from 8 to 128 km/h (5 to 80 mph), which gave the pattern of how driving speed affects fuel consumption. A polynomial regression model was proposed to estimate the pattern, and the regression results of speed on fuel efficiency are shown in Table 9.2.

Table 9.2: Regression Results of Speed (km/h) on Fuel Efficiency (Kilometers-per-liter)

<table>
<thead>
<tr>
<th></th>
<th>Est.</th>
<th>S.E.</th>
<th>Signif.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>0.2796</td>
<td>0.1992</td>
<td></td>
</tr>
<tr>
<td>V</td>
<td>0.2502</td>
<td>0.0067</td>
<td>***</td>
</tr>
<tr>
<td>V^2</td>
<td>-0.0015</td>
<td>0.0000</td>
<td>***</td>
</tr>
<tr>
<td>R^2</td>
<td></td>
<td>0.9602</td>
<td></td>
</tr>
</tbody>
</table>

1 *** p-value < 0.001, ** p-value < 0.01, * p-value < 0.05;
2 V refers to driving speed.
The results illustrate that fuel efficiency is significantly affected by travel speed. It predicts that 80km/h (50mph) is the most efficient driving speed and the corresponding fuel efficiency is 10.419 kilometers-per-liter (24.508 MPG).

According to the TomTom speed data, the fuel efficiency of each link in the Twin Cities road network can be estimated based on the results shown in Table 9.2. Assuming these estimated results reflect the combined fuel efficiency, we can give an adjustment factor of 0.861 for city driving and 1.170 for highway driving.

- **Fuel Price**

  Fuel price varies significantly, and there is no clear trend or pattern (Barnes & Langworthy 2004). Table 9.3 shows the annual average gasoline retail price in Minnesota.

  Table 9.3: Minnesota Gasoline Retail Prices ($/Liter), Source: US Energy Information Administration (2018)

<table>
<thead>
<tr>
<th>Year</th>
<th>Fuel Type</th>
<th>Regular</th>
<th>Midgrade</th>
<th>Premium</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011</td>
<td></td>
<td>0.928</td>
<td>0.949</td>
<td>0.987</td>
</tr>
<tr>
<td>2012</td>
<td></td>
<td>0.930</td>
<td>0.952</td>
<td>0.999</td>
</tr>
<tr>
<td>2013</td>
<td></td>
<td>0.910</td>
<td>0.937</td>
<td>0.994</td>
</tr>
<tr>
<td>2014</td>
<td></td>
<td>0.856</td>
<td>0.888</td>
<td>0.948</td>
</tr>
<tr>
<td>2015</td>
<td></td>
<td>0.617</td>
<td>0.653</td>
<td>0.719</td>
</tr>
</tbody>
</table>

  Based on the fuel consumption analysis and the historical fuel price, the standard fuel consumption cost (80km/h, Midgrade fuel) in 2014 is $0.0789/veh-km.

- **Maintenance and Repair Costs**

  Barnes & Langworthy (2004) gave a full estimation of vehicle maintenance and repair costs for Minnesota. In their studies, the cost of maintenance was estimated for each car model based on the recommended vehicle maintenance schedule varying with industry-standard
service time, labor-rate average, and price of parts. The number of vehicle registrations by car model in Minnesota was estimated as a weight to give the average marginal maintenance cost per mile. The cost of repair was measured based on the expected repair costs of a five-year, zero-deductible repair-service contract by car model generated by InteliChoice, Inc (2002a) and IntelliChoice, Inc (2002b). The vehicle age distribution and the number of vehicle registrations by car model in Minnesota were used as the weights to give the average marginal repair cost per mile.

The estimation conducted by Barnes & Langworthy (2004) is based on the price in 2003. Comparing the Consumer Price Index in motor vehicle maintenance and repair in 2003 (195.6) and 2014 (266.025), the maintenance and repair cost in 2014 is shown in Table 9.4.

<table>
<thead>
<tr>
<th>City</th>
<th>Highway</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Automobile</td>
<td>Pickup</td>
</tr>
<tr>
<td>2.92</td>
<td>3.29</td>
</tr>
</tbody>
</table>

1 The combined maintenance and repair costs were calculated based on a 48% of automobile and a 52% of pickup/van/SUV, which was measured according to the new vehicle sale volume by car model in US (Good Car Bad Car 2017).

**Depreciation Cost (Distance-Based)**

Barnes & Langworthy (2004) also gave a full estimation of vehicle depreciation cost due to additional mileage being driven by car model. Again, the vehicle age distribution and the number of vehicle registrations by car model in Minnesota were used as the weights to give the average marginal depreciation cost per mile in their estimations.

Comparing the Consumer Price Index in new and used motor vehicles in both 2003 (96.5) and 2014 (100.796), the depreciation cost in 2014 is shown in Table 9.5.
Table 9.5: Kilometer-based Vehicle Depreciation Cost (2014 cents per veh-km)

<table>
<thead>
<tr>
<th>City</th>
<th>Highway</th>
</tr>
</thead>
<tbody>
<tr>
<td>Automobile</td>
<td>Highway</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>4.60</td>
<td>3.85</td>
</tr>
<tr>
<td>5.03</td>
<td>4.35</td>
</tr>
<tr>
<td>4.83</td>
<td>4.11</td>
</tr>
</tbody>
</table>

1 The combined maintenance and repair costs were calculated based on a 48% of automobile and a 52% of pickup/van/SUV.

9.1.2 Fixed Cost

Among fixed cost categories, time-based depreciation costs, finance charges, registration fees, vehicle sales tax, and insurance were measured as a unit of $/veh-year. Based on the Travel Behavior Inventory Survey data, the average number of daily trips per person by auto is 4, including all types of activities. The average number of trips annually by auto (4 × 165=1,460) would be used to assign those fixed costs to each trip.

US Department of Labor, Bureau of Labor Statistics (2015) provides the average annual expenditures of vehicle expenses based on a consumer expenditure survey in the Midwest region:

- Vehicle finance charges: $204;
- Vehicle insurance: $1,162.

For the case of Minnesota, it had 259,483 new car sales and $379 million new vehicle sales tax in 2013. Considering that the average age of vehicles in Minnesota is 11.6 years, the annual vehicle sales tax is $127.66/veh-year in 2014 dollar (Auto Alliance, Driving Innovation 2015, Kim Hill 2015).
Time-Based Vehicle Depreciation Cost

American Automobile Association (2015) measured vehicle depreciation costs as the differences between new vehicle purchase price and estimated trade-in value at the end of five years. Assuming the annual driving distance is 24,140km (15,000 miles), depreciation costs were estimated shown in Table 9.6, where the values in (brackets) show the fraction of each size of vehicles 1.

Table 9.6: Average Vehicle Depreciation Cost per Year, Source: American Automobile Association (2015)

<table>
<thead>
<tr>
<th></th>
<th>Sedan</th>
<th>4WD SUV</th>
<th>Minivan</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small</td>
<td></td>
<td></td>
<td>(16.0%)</td>
</tr>
<tr>
<td>Median</td>
<td></td>
<td></td>
<td>(8.8%)</td>
</tr>
<tr>
<td>Large</td>
<td>(31.9%)</td>
<td>(36.7%)</td>
<td>(6.6%)</td>
</tr>
<tr>
<td></td>
<td>2,515</td>
<td>3,687</td>
<td>4,759</td>
</tr>
<tr>
<td></td>
<td>4,646</td>
<td>4,039</td>
<td></td>
</tr>
</tbody>
</table>

Hence, the average total vehicle depreciation cost \( (C_{VD}) \) is $3,568/year, which covers both time-based \( (C_{VD,t}) \) and distance-based \( (C_{VD,d}) \) costs:

\[
C_{VD} = C_{VD,t} + C_{VD,d}
\] (9.1)

According to the estimation of the kilometer-based vehicle depreciation cost (4.83 cents

1Depreciation costs are based on average costs for five top-selling 2014 models selected by AAA. By size category They are

- Small sedan: Chevrolet Cruze, Ford Focus, Honda Civic, Hyundai Elantra and Toyota Corolla;
- Medium sedan: Chevrolet Malibu, Ford Fusion, Honda Accord, Nissan Altima and Toyota Camry;
- Large sedan: Buick LaCrosse, Chrysler 300, Ford Taurus, Nissan Maxima and Toyota Avalon;
- SUV: Chevrolet Traverse, Ford Explorer, Jeep Grand Cherokee, Nissan Pathfinder and Toyota 4Runner;
- Minivans: Dodge Grand Caravan, Kia Sedona, Honda Odyssey, Nissan Quest and Toyota Sienna.
for city driving and 4.11 cents for highway driving), described in Section 9.1.1, the time-based cost is $2,481/veh-year with the assumptions that the annual driving distance is 24,140km (15,000 miles) and trips combine 55% of city driving and 45% of highway driving.

**Vehicle Registration Fee**

Minnesota registration renewal fees include the following categories (IHS Automotive 2014):

- Filing fee: $6.00;
- Technology surcharge: $1.00;
- Online renewal fee (if applicable): $1.50;
- Wheelage tax (if applicable): $10.00;
- License plates, if required: $6.00 for double plates or $4.50 for single plate;
- Registration tax: Varies based on the year and type of your vehicle (Passenger vehicles 10 years old and older: $35.00);
- Motorcycles: $10.00;
- Mopeds: $6.00.

Minnesota Department of Public Safety (2016) provides passenger vehicle tax tables giving the value of registration taxes based on vehicles’ base value brackets and the model year. However, the average age of vehicles in Minnesota is 11.6 years, which refers to a registration tax of $35 for all types of vehicles. This value is applied, so the average annual vehicle registration fee is $46.50 assuming no online renewal fee and wheelage tax.

**9.1.3 Other Cost Components**

**Parking Cost**

Parking data covering the areas of downtown Minneapolis, downtown St. Paul and University of Minnesota have been collected (Data Source: BestParking (2017), OpenStreetMap
(2017), University of Minnesota, Parking and Transportation Services (2017)). It is assumed that parking is free for other places in this analysis.

The collected data include,

- GIS locations of parking ramps or lots;

- Daily parking rate (or 8 hours parking rate) and monthly parking rate (Note that not all of the collected parking ramps provide monthly parking service.).

- Number of parking spaces.

GIS information was used to identify the parking locations considering the boundary of Transportation Analysis Zone (TAZ). As Figure 9.1 shows, the polygons in red are the destinations with collected parking cost. The number of parking spaces was used as the weight to measure the average daily or monthly parking rate for work trips in each TAZ. The results show that the average monthly parking rate is $4.54/veh-trip for travelers with contract parking and the average daily parking rate of $9.88/veh-trip for travelers paid by hours in specific destinations.
MnPASS Toll

MnPASS Express Lanes, which are operated by Minnesota Department of Transportation (2016a), help to “maintain traffic flow, reduce congestion and give drivers a safe, reliable commute when they pay an electronic fee”. The current MnPASS Express Lanes are on I-394, I-35W, and I-35E, shown in Figure 9.2.

MnPASS Lanes charge fees from Monday through Friday during peak hour travel times for solo motorists,

- I-394: 6AM-10AM and 2PM-7PM
- I-35W: 6AM-10AM and 3PM-7PM
• I-35E: 6AM-10AM and 3PM-7PM

while they are open to all motorists on weekends and during non-peak hours. The fee for solo motorists varies between $0.25 and $8.00 depending on current traffic volume in the MnPASS Lanes. It ensures that traffic in the MnPASS Lanes continues to flow at about 80 to 88km/h (50 to 55 mph).

![MnPASS Express Lanes map](source: Metropolitan Council 2040 Transportation Policy Plan)

**Figure 9.2: MnPASS Express Lanes**

As described above, the travel speed on MnPASS lanes has critical differences from the general-purpose lanes, which causes concomitant changes in crash risk, emission-intake, fuel consumption, and so on. The unit cost for MnPASS users, like unit time values, should differ from the general-purpose users as well. Hence, full cost analysis of MnPASS lanes
should be a separate topic for future research. Scenarios of only general-purpose lanes are considered in this dissertation.

### 9.1.4 Monetary Cost Adjustment in Full Cost Estimates

Based on Figure 5.5, fuel cost, including taxes, vehicle insurance cost, vehicle registration fee, including taxes, and tolls are fully or partially transferred to the emission, safety and infrastructure costs. Adjustments are needed to avoid the double-counting problem for the full cost analysis.

- **Fuel Tax Adjustment**
  
  As described in Section 5.2.3, around 83% to 87% of federal fuel tax is deposited into the Highway Trust Fund. In 2014, 83.91% of the federal fuel tax is transferred to Highway Account for infrastructure expenditures (US Department of Transportation, Federal Highway Administration 2017). For the case of Minnesota, most of the state fuel tax, 97.50%, is deposited into Highway User Tax Distribution Fund for road infrastructure, either highways or state aid streets, the rest of which is used for non-highway activities, such as operating ATVs, motorboats, snowmobiles and off-road vehicles (Burress 2018).

  Hence, the unit fuel cost, including un-transferred fuel taxes, in 2014 is $0.742/liter ($2.807/gallon), which gives an adjustment factor of 0.867 comparing with Minnesota gasoline retail price, $0.856/liter ($3.240/gallon).

  In the internal cost measurement, this adjustment factor does not need to be applied.

- **Fixed Monetary Cost Adjustment**
  
  We considered the time-based vehicle depreciation cost, vehicle finance charges, vehicle registration fee, vehicle sales tax, and vehicle insurance as the fixed monetary cost, which, in total, is $4,021.16/veh-year. Based on Figure 5.5, vehicle insurance and registration tax are fully transferred to the safety cost and infrastructure cost respectively, and 60% of vehicle sales tax is transferred to the infrastructure cost, which should be subtracted from the fixed monetary cost for the full cost analysis.
Hence, the adjusted fixed cost is 2,747.56/veh-year in total, which gives an adjustment factor of 0.68 for the fixed monetary cost.

9.2 Monetary Cost Estimates

Average and variable monetary costs were measured, where the latter one considers variable cost factors only and gives a link-based monetary cost, shown in Section 9.2.1. The average monetary cost, however, covers the fixed cost and parking cost in addition, in which the average fixed cost per veh-year is $4021.16, equivalent to $2.75/veh-trip, and the average contract parking rate is $4.54/veh-trip and the average daily parking rate is $9.88/veh-trip.

Note that both fixed and parking costs cannot be allocated to each link, which, however, are critical for monetary cost analysis and do affect the accessibility measurements regarding monetary cost.

9.2.1 Link-based Monetary Cost

Based on the cost analysis, the mean value of the monetary cost among all links on the Twin Cities road network is $0.219/veh-km, and 95% of the links have a monetary cost less than $0.300/veh-km.

As expected, highways are much cheaper than other surface roadways from the monetary cost perspective. The estimates show that the mean value of monetary cost for highways is $0.142/veh-km, while for others is $0.227/veh-km. Comparing locations, driving in the core cities ($0.239/veh-km) causes a slightly higher monetary cost than other urban ($0.217/veh-km) and rural areas ($0.210/veh-km).

Figure 9.3 displays the spatial distribution patterns of the link-based monetary cost estimates. Considering traffic, the monetary costs of all vehicles generated on each link are shown in Figure 9.4. It indicates that more monetary costs are coming from the highway network since it serves more traffic each day, but its unit monetary cost per vehicle is lower.
Figure 9.3: Monetary Cost Per Vehicle-Kilometer on Each Link of the Twin Cities Road Network ($/veh-km)
Figure 9.4: Monetary Cost of All Vehicles Generated on Each Link of the Twin Cities Road Network ($/km)

9.2.2 Work Trip Flow

Figure 9.5 assigns the work trip flow estimates to the lowest monetary cost path. The shape of the highway network in the Twin Cities is clearly visualized, which implies that more work trips are assigned to highways. This is largely the same as the baseline estimates, work trip flow allocated to the shortest travel time path, shown in Figure 6.4. Slight differences exist.
Figure 9.6 shows their differences more clearly. It indicates that work trips on some interstate highways have been reassigned to the parallel state highways using the lowest monetary cost path rather than the shortest travel time path, like the shifts from I-394 to MN-55 and MN-7 and from I-94 to MN-100. However, they still serve as major cheaper routes, from the aspect of the monetary cost.
9.3 Infrastructure Cost Factors

Infrastructure cost mainly includes capital expenditure, maintenance and service, administration and miscellaneous, highway law enforcement and safety, interest, and bond retirement. Table 9.7 summarizes the average annual expenditures for highways across the United States. For other classifications of roads, capital expenditures and maintenance costs are available, summarized in Table 9.8.

Figure 9.6: Differences of Work Trip Flow Assigned to the Lowest Monetary Cost Path Minus That Assigned to the Shortest Travel Time Path
Table 9.7: Average Annual Expenditures for Highways across United States (2012 US $ thousands), Source: Table HF-2, Total Disbursements for Highways, Highway Statistics 2013 (US Department of Transportation, Office of Highway Policy Information, Policy and Governmental Affairs 2016)

<table>
<thead>
<tr>
<th>Capital Expenditure</th>
<th>Maintenance and Service</th>
<th>Administration and Miscellaneous</th>
<th>Highway Law Enforcement and Safety</th>
<th>Interest</th>
<th>Bond Retirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>2,048,090</td>
<td>935,423</td>
<td>279,667</td>
<td>349,938</td>
<td>227,660</td>
</tr>
</tbody>
</table>

Table 9.8: Average Annual Expenditures for Minor Arterials, Collectors and Local Roadways across United States (2012 US $ thousands), Source: Table SF-12, State Capital Outlay and Maintenance, Classified by Functional System and Area, Highway Statistics 2013 (US Department of Transportation, Office of Highway Policy Information, Policy and Governmental Affairs 2016)

<table>
<thead>
<tr>
<th>Capital Expenditure</th>
<th>Maintenance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minor Arterial</td>
<td>184,713</td>
</tr>
<tr>
<td>Collector</td>
<td>141,706</td>
</tr>
<tr>
<td>Local</td>
<td>229,350</td>
</tr>
</tbody>
</table>

9.4 Infrastructure Cost Estimates

Levinson & Gillen (1998) proposed models predicting total expenditures on infrastructure as a function of price inputs, travel-related inputs, and network variables specific to road classifications. Applying the same models, average and marginal infrastructure costs per vehicle-kilometer were measured for both short run and long run scenarios, where the short run scenario considers the maintenance, administration, and operation costs, while the long run scenario considers the annualized capital cost in addition.
9.4.1 Data Collection

For building the models, we collected highway infrastructures and travel data from US Department of Transportation, Office of Highway Policy Information, Policy and Governmental Affairs (2016) showing the corresponding annual statistics broken down by state and functional system. Prices of labor and construction materials were also collected as price inputs in the prediction models. Details of the data are shown as follows,

Travel-related Inputs

Vehicle-kilometer of travel was selected as the travel-related inputs. Table 9.9 summarizes the mean value of vehicle-kilometer traveled by functional system.

Table 9.9: Average Vehicle Kilometers of Travel by Functional System (millions), Source: Table VM-2, Vehicle-miles of Travel by Functional System, Highway Statistics 2013 (US Department of Transportation, Office of Highway Policy Information, Policy and Governmental Affairs 2016)

<table>
<thead>
<tr>
<th></th>
<th>Interstate</th>
<th>Other Principal Arterial</th>
<th>Other Arterial</th>
<th>Minor Arterial</th>
<th>Major Collector</th>
<th>Minor Collector</th>
<th>Local</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rural</td>
<td>7,856</td>
<td>1,357</td>
<td>6,214</td>
<td>4,601</td>
<td>5,428</td>
<td>1,693</td>
<td>4,027</td>
<td>18,469</td>
</tr>
<tr>
<td>Urban</td>
<td>15,945</td>
<td>7,984</td>
<td>14,659</td>
<td>12,028</td>
<td>5,775</td>
<td>307</td>
<td>8,950</td>
<td>40,126</td>
</tr>
</tbody>
</table>

Considering the distribution of annual vehicle distance traveled by vehicle type, summarized in Table 9.10, it is straightforward to measure the vehicle-kilometer traveled for each vehicle type. Table 9.11 shows the average vehicle-kilometer traveled by vehicle type.

Note that the vehicle type distribution of the category ‘Other Roads’, shown in the last row of Table 9.10, was used for the measurements of ‘Collectors’ and ‘Local Roads’, shown in the last two rows of Table 9.11.
Table 9.10: Average Distribution Annual Vehicle Distance Traveled by Vehicle Types (%),
Source: Table VM-4, Distribution of Annual Vehicle Distance Traveled, Highway Statistics 2013 (US Department of Transportation, Office of Highway Policy Information, Policy and Governmental Affairs 2016)

<table>
<thead>
<tr>
<th></th>
<th>Motorcycle</th>
<th>Passenger Cars</th>
<th>Light Trucks</th>
<th>Buses</th>
<th>Single-unit Trucks</th>
<th>Combination Trucks</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interstate</td>
<td>0.52</td>
<td>58.12</td>
<td>18.58</td>
<td>0.63</td>
<td>3.94</td>
<td>18.21</td>
<td>100</td>
</tr>
<tr>
<td>Other Arterials</td>
<td>0.77</td>
<td>62.54</td>
<td>23.95</td>
<td>0.60</td>
<td>4.79</td>
<td>7.34</td>
<td>100</td>
</tr>
<tr>
<td>Other Roads</td>
<td>0.87</td>
<td>63.01</td>
<td>26.91</td>
<td>0.56</td>
<td>4.93</td>
<td>3.72</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 9.11: Average Vehicle-kilometers Traveled by Vehicle Types (millions)

<table>
<thead>
<tr>
<th></th>
<th>Motorcycle</th>
<th>Passenger Cars</th>
<th>Light Trucks</th>
<th>Buses</th>
<th>Single-unit Trucks</th>
<th>Combination Trucks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interstate</td>
<td>123</td>
<td>14,131</td>
<td>4,212</td>
<td>143</td>
<td>948</td>
<td>4,679</td>
</tr>
<tr>
<td>Other Arterial</td>
<td>348</td>
<td>29,225</td>
<td>10,455</td>
<td>255</td>
<td>2,129</td>
<td>3,476</td>
</tr>
<tr>
<td>Collectors</td>
<td>117</td>
<td>8,449</td>
<td>3,383</td>
<td>78</td>
<td>648</td>
<td>510</td>
</tr>
<tr>
<td>Local Roads</td>
<td>117</td>
<td>8,604</td>
<td>3,310</td>
<td>77</td>
<td>621</td>
<td>488</td>
</tr>
</tbody>
</table>

Price Input

The prices of labor and construction materials were selected as the price inputs.

- Price of Labor

The average annual wage of state government employees was used to reflect the price of labor. Table 9.12 shows the average employment and wages of state government employees across all the states.

<table>
<thead>
<tr>
<th>Annual Average Employment</th>
<th>Annual Average Weekly Wage</th>
<th>Annual Wages per Employee</th>
</tr>
</thead>
<tbody>
<tr>
<td>35,014</td>
<td>960</td>
<td>49,897</td>
</tr>
</tbody>
</table>

- Price of Materials

The National Highway Construction Cost Index (NHCCI) was used as a price index to track the price changes associated with highway construction costs (US Department of Transportation, Federal Highway Administration 2006). Data from 2005 were used, as this is the most recent year construction material cost information is available for the state of Minnesota.

Table 9.13 shows the average contract price for construction materials. The bituminous concrete price was selected to reflect the price of materials in the regression models.


<table>
<thead>
<tr>
<th>Common excavation</th>
<th>Portland Cement Concrete</th>
<th>Bituminous Concrete</th>
<th>Reinforcing Steel</th>
<th>Structural Steel</th>
<th>Structural Concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.99</td>
<td>33.42</td>
<td>45.56</td>
<td>0.94</td>
<td>1.57</td>
<td>394.88</td>
</tr>
</tbody>
</table>

Network Input

Road length and width were selected as network inputs for infrastructure expenditure estimations.

- Length of Roads
Length of roads (centerline length) was summarized by functional roadway classification in the series of Highway Statistics (US Department of Transportation, Office of Highway Policy Information, Policy and Governmental Affairs 2016). Table 9.14 shows the average across all the states.


<table>
<thead>
<tr>
<th></th>
<th>Interstate</th>
<th>Other Freeways</th>
<th>Other Principal Arterial</th>
<th>Minor Arterial</th>
<th>Major Collector</th>
<th>Minor Collector</th>
<th>Local</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rural</td>
<td>995</td>
<td>325</td>
<td>2,910</td>
<td>4,276</td>
<td>13,352</td>
<td>8,621</td>
<td>64,451</td>
</tr>
<tr>
<td>Urban</td>
<td>565</td>
<td>415</td>
<td>2,099</td>
<td>3,504</td>
<td>3,831</td>
<td>305</td>
<td>26,647</td>
</tr>
<tr>
<td>Total</td>
<td>1,560</td>
<td>740</td>
<td>5,009</td>
<td>7,779</td>
<td>17,182</td>
<td>8,926</td>
<td>91,098</td>
</tr>
</tbody>
</table>

• Width of Roads

Lane-kilometers by functional roadway classifications were measured based on the number of through traffic lanes and centerline length. Note that lane-kilometers data for rural minor collectors and rural/urban local functional system were estimated by Federal Highway Administration assuming the number of lanes is 2. Table 9.15 shows the average lane-kilometer across all the states. The width of roads could be derived by the roads length and lane-kilometer depending on the width of a lane.

<table>
<thead>
<tr>
<th></th>
<th>Interstate</th>
<th>Other Freeways</th>
<th>Other Principal Arterial</th>
<th>Minor Arterial</th>
<th>Major Collector</th>
<th>Minor Collector</th>
<th>Local</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rural</td>
<td>4,052</td>
<td>1,184</td>
<td>7,602</td>
<td>8,884</td>
<td>26,844</td>
<td>17,242</td>
<td>128,902</td>
</tr>
<tr>
<td>Urban</td>
<td>3,122</td>
<td>1,953</td>
<td>7,537</td>
<td>9,102</td>
<td>8,371</td>
<td>659</td>
<td>53,294</td>
</tr>
<tr>
<td>Total</td>
<td>7,174</td>
<td>3,137</td>
<td>15,138</td>
<td>17,986</td>
<td>35,215</td>
<td>17,901</td>
<td>182,196</td>
</tr>
</tbody>
</table>

9.4.2 Regression of Expenditure on Selected Variables

For all the states in the US,

- Delaware and District of Columbia are excluded from the samples for regressions since they do not have specific vehicle-kilometer traveled data for each type of vehicles, which are the most significant input for the infrastructure cost analysis.

- There are 8 states that do not have bituminous concrete price records, including Arkansas, Delaware, Florida, Mississippi, Rhode Island, Tennessee, Vermont, and Virginia. Values of neighboring states were used for those 8 states in the regression models, as follows,

  - Arkansas → Missouri
  - Delaware → New Jersey
  - Florida → Georgia
  - Mississippi → Alabama
  - Rhode Island → Connecticut
  - Tennessee → Kentucky
  - Vermont → New Hampshire
For each road classification, highways, minor arterials, collectors, and local roads, we proposed to use linear regression models to estimate the infrastructure expenditures considering both long run and short run scenarios.

In all the models, we dropped the intercept term to force the fitted line go through the \((0,0)\) origin, as infrastructure cost will be 0 if there is no traffic generated. To avoid the multicollinearity problems, network inputs were dropped from all the models as well. Besides, since the infrastructure cost generated by automobiles is the primary concern in this study, all other types of vehicles, including light trucks, buses, single-unit trucks, and combination trucks, are summed up as an independent variable named Trucks. Hence, the selected independent variables are shown in Table 9.16.

Table 9.16: Selected Independent Variables for Regressions of Infrastructure Expenditures

<table>
<thead>
<tr>
<th>Independent Variables</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Q_a )</td>
<td>Vehicle-kilometer traveled by autos</td>
</tr>
<tr>
<td>( Q_t )</td>
<td>Vehicle-kilometer traveled by trucks</td>
</tr>
<tr>
<td>( u_L )</td>
<td>Price of labor</td>
</tr>
<tr>
<td>( u_B )</td>
<td>Price of construction materials</td>
</tr>
</tbody>
</table>

Note that we tested both original and natural log formats of independent variables in the regression models, the results displayed here are the ones with the best fit (Adjusted \( R^2 \)).

**Highways**

Table 9.17 shows the regression results for highways. It is shown that, for both short run and long run scenarios, the selected independent variables explain highway infrastructure expenditures well, and are all statistically significant for highway infrastructure expenditures. As expected, highway infrastructure expenditures are positively affected by
vehicle-kilometer traveled by autos and trucks that more traffic on highways would cause more infrastructure costs. For the price inputs, the labor cost is positively related to the highway infrastructure cost as well. However, the price of construction materials shows negative effects.

Table 9.17: Regression Models of Highway Infrastructure Expenditures

<table>
<thead>
<tr>
<th></th>
<th>Short Run</th>
<th></th>
<th></th>
<th>Long Run</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$log(Q_a)$</td>
<td>0.494</td>
<td>0.130</td>
<td>***</td>
<td>0.406</td>
<td>0.089</td>
<td>***</td>
</tr>
<tr>
<td>$log(Q_t)$</td>
<td>0.270</td>
<td>0.124</td>
<td>*</td>
<td>0.365</td>
<td>0.085</td>
<td>***</td>
</tr>
<tr>
<td>$log(u_L)$</td>
<td>0.283</td>
<td>0.126</td>
<td>**</td>
<td>0.431</td>
<td>0.097</td>
<td>***</td>
</tr>
<tr>
<td>$log(u_B)$</td>
<td>-0.345</td>
<td>0.182</td>
<td>.</td>
<td>-0.293</td>
<td>0.126</td>
<td>*</td>
</tr>
<tr>
<td>$R^2$</td>
<td></td>
<td>0.832</td>
<td></td>
<td></td>
<td>0.888</td>
<td></td>
</tr>
</tbody>
</table>

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

Based on Table 9.17, Table 9.18 shows the estimates of the average and marginal highway infrastructure costs per vehicle-kilometer in a short run and long run perspectives for Minnesota (MN) and the US.

The estimates are expected that, at first, trucks cause more infrastructure costs than autos, as the trucks are heavier and result in more wear and tear on the roadways. Long run cost estimates are significantly higher than the short run due to counting the capital cost. US highway infrastructure cost is basically approximate to Minnesota.
Table 9.18: Long and Short Run Average and Marginal Infrastructure Costs for Highways ($/veh-km)

<table>
<thead>
<tr>
<th></th>
<th>Auto</th>
<th>Trucks</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average</td>
<td>Marginal</td>
</tr>
<tr>
<td><strong>Short Run</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MN</td>
<td>0.064 (0.028-0.147)</td>
<td>0.032</td>
</tr>
<tr>
<td>US</td>
<td>0.046 (0.025-0.129)</td>
<td>0.028</td>
</tr>
<tr>
<td><strong>Long Run</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MN</td>
<td>0.145 (0.081-0.258)</td>
<td>0.059</td>
</tr>
<tr>
<td>US</td>
<td>0.135 (0.077-0.237)</td>
<td>0.055</td>
</tr>
</tbody>
</table>

1 Parentheses refer to the cost ranges estimated based on 95% confidence interval; 2 Using the upper and lower bound of confidence interval does not affect the marginal cost.

Minor Arterials

For minor arterials, there are 7 states that do not have expenditure records (Dist. of Columbia, Louisiana, Maine, Maryland, Oregon, South Carolina, and Wisconsin), which have been removed from the regression samples. Vehicle-kilometer traveled by trucks, price of labor, and price of materials are not significant for both short run and long run estimations, and removing them gives the best adjusted $R^2$. The selected regression results are shown in Table 9.19.

Table 9.19: Regression Models of Minor Arterial Infrastructure Expenditures

<table>
<thead>
<tr>
<th></th>
<th>Short Run</th>
<th>Long Run</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\log(Q_a)$</td>
<td>0.748</td>
<td>0.009</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.330</td>
<td>0.366</td>
</tr>
</tbody>
</table>

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

Similar to highways, the results show that the infrastructure expenditures of minor
arterials are positively and significantly affected by vehicle-kilometer traveled by autos.

Applying the regression results, Table 9.20 shows the average and marginal estimates of minor arterial infrastructure costs per vehicle-kilometer for Minnesota and the US for both short run and long run scenarios.

Table 9.20: Long and Short Run Average and Marginal Infrastructure Costs for Minor Arterials by Auto ($/veh-km)

<table>
<thead>
<tr>
<th></th>
<th>Average</th>
<th>Marginal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short Run</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MN</td>
<td>0.0025 (0.0002-0.0336)</td>
<td>0.0019</td>
</tr>
<tr>
<td>US</td>
<td>0.0060 (0.0004-0.0803)</td>
<td>0.0045</td>
</tr>
<tr>
<td>Long Run</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MN</td>
<td>0.0210 (0.0052-0.8580)</td>
<td>0.0176</td>
</tr>
<tr>
<td>US</td>
<td>0.0371 (0.0091-0.1505)</td>
<td>0.0311</td>
</tr>
</tbody>
</table>

1 Parentheses refer to the cost ranges estimated based on 95% confidence interval.

Collectors

For collectors, there are 8 states that do not have expenditure records (Louisiana, Maine, Maryland, New Jersey, Oregon, South Carolina, Tennessee, and Wisconsin), which have been removed from the regression samples. Similar to the models for minor arterials, vehicle-kilometer traveled by trucks, price of labor, and price of materials are not significant for both short run and long run estimations, and removing them gives the best adjusted $R^2$. Hence, the regression results of the selected models for collectors are shown in Table 9.21.
Table 9.21: Regression Models of Collector Infrastructure Expenditures

<table>
<thead>
<tr>
<th></th>
<th>Short Run</th>
<th>Long Run</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\log(Q_a)$</td>
<td>0.764</td>
<td>0.011</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.203</td>
<td>0.510</td>
</tr>
</tbody>
</table>

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

Again, the results show that collector infrastructure expenditures are positively and significantly affected by vehicle-kilometer traveled by auto.

We estimated the average and marginal collector infrastructure costs per vehicle-kilometer for Minnesota and the US for both short run and long run scenarios. Based on the regression results, which are shown in Table 9.22.

Table 9.22: Long and Short Run Average and Marginal Infrastructure Costs for Collectors by Auto ($/veh-km)

<table>
<thead>
<tr>
<th></th>
<th>Average</th>
<th>Marginal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short Run</td>
<td>MN 0.0051 (0.0002-0.1036)</td>
<td>0.0039</td>
</tr>
<tr>
<td></td>
<td>US 0.0058 (0.0003-0.1179)</td>
<td>0.0044</td>
</tr>
<tr>
<td>Long Run</td>
<td>MN 0.0320 (0.0046-0.2227)</td>
<td>0.0271</td>
</tr>
<tr>
<td></td>
<td>US 0.0345 (0.0050-0.2397)</td>
<td>0.0292</td>
</tr>
</tbody>
</table>

1 Parentheses refer to the cost ranges estimated based on 95% confidence interval.

Local Roads

There are 7 states, which do not have expenditure records for local roads (Alaska, Colorado, Hawaii, Missouri, Oregon, Tennessee, and Wisconsin), have been removed from the regression samples. Using vehicle-kilometer traveled by auto as the only independent variable in the regression models, again, has the best fit. The results are shown in Table 9.23.
Table 9.23: Regression Models of Local Road Infrastructure Expenditures

<table>
<thead>
<tr>
<th></th>
<th>Short Run</th>
<th></th>
<th>Long Run</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$\log(Q_a)$</td>
<td>0.725</td>
<td>0.021</td>
<td>***</td>
<td>0.850</td>
</tr>
<tr>
<td>$R^2$</td>
<td></td>
<td></td>
<td></td>
<td>0.103</td>
</tr>
</tbody>
</table>

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

The table indicates that vehicle-kilometer traveled by autos are positively and significantly related to local road infrastructure expenditures.

Table 9.24 shows the short run and long run estimates of the average and marginal local road infrastructure costs per vehicle-kilometer for Minnesota and the US.

Table 9.24: Long and Short Run Average and Marginal Infrastructure Costs for Local Roads by Auto ($/veh-km$)

<table>
<thead>
<tr>
<th></th>
<th>Average</th>
<th>Marginal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short Run</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MN</td>
<td>0.0022 (0.0000-0.6570)</td>
<td>0.0016</td>
</tr>
<tr>
<td>US</td>
<td>0.0025 (0.0000-0.7580)</td>
<td>0.0018</td>
</tr>
<tr>
<td>Long Run</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MN</td>
<td>0.0352 (0.0018-0.7055)</td>
<td>0.0299</td>
</tr>
<tr>
<td>US</td>
<td>0.0377 (0.0019-0.7546)</td>
<td>0.0321</td>
</tr>
</tbody>
</table>

1 Parentheses refer to the cost ranges estimated based on 95% confidence interval.

**Link-based Infrastructure Cost**

To summarize the results discussed above, the link-based infrastructure cost on the Twin Cities road network is shown in Table 9.25. As expected, the infrastructure cost is much higher on highways than other types of roads as the highway infrastructure expenditures are much higher.
Table 9.25: Link-based Infrastructure Cost on Each Link of the Twin Cities Road Network ($/veh-km)

<table>
<thead>
<tr>
<th>Road Types</th>
<th>Long run</th>
<th></th>
<th>Short run</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average</td>
<td>Marginal</td>
<td>Average</td>
<td>Marginal</td>
</tr>
<tr>
<td>Highways</td>
<td>0.145</td>
<td>0.059</td>
<td>0.064</td>
<td>0.032</td>
</tr>
<tr>
<td>Minor Arterials</td>
<td>0.021</td>
<td>0.018</td>
<td>0.003</td>
<td>0.002</td>
</tr>
<tr>
<td>Collectors</td>
<td>0.032</td>
<td>0.027</td>
<td>0.005</td>
<td>0.004</td>
</tr>
<tr>
<td>Local Roads</td>
<td>0.035</td>
<td>0.030</td>
<td>0.002</td>
<td>0.002</td>
</tr>
</tbody>
</table>

Figure 9.7 gives the spatial distribution patterns of the long term average infrastructure cost, and Figure 9.8 shows that of all vehicles generated on each link considering the traffic flow. Other scenarios of infrastructure cost estimates have the same distribution patterns.
Figure 9.7: Infrastructure Cost Per Vehicle-Kilometer on Each Link of the Twin Cities Road Network ($/veh-km)
Figure 9.8: Infrastructure Cost of All Vehicles Generated on Each Link of the Twin Cities Road Network ($/km)

9.4.3 Work Trip Flow

Figure 9.9 shows the work trip flow estimates allocated to the lowest infrastructure cost path based on current traffic levels.

The lowest infrastructure cost path avoids using the highway network and detours to local surface roadways where the infrastructure costs are lower. Several major cheaper routes, from the infrastructure cost point of view, have been identified, which are, generally, parallel to major highways, such as the University Avenue.
Comparing with the baseline estimates, work trip flow allocated to the shortest travel time path, they have critical differences, shown in Figure 9.10, since the highways are shorter but more expensive concerning the infrastructure cost.

Figure 9.9: Work Trip Flow Assigned to the Lowest Infrastructure Cost Path
9.5 Summary

This chapter analyzed monetary and infrastructure costs of roads in the Minneapolis - St. Paul metropolitan area and evaluated the work trip flows based on the lowest monetary cost path and the lowest infrastructure cost path.

The user monetary cost borne by travelers includes fuel cost, maintenance, and repair cost, tolls and taxes, and the like. While the infrastructure cost considers the road wear and tear damage costs.

The lowest monetary cost path and the lowest infrastructure cost path were proposed to
estimate the minimum monetary and infrastructure costs during travel, which are valuable data as inputs to a full cost accounting of the cost of travel, and could subsequently be used in planning and economic analyses.

The monetary cost (mean: $0.219/veh-km) imposed on travelers themselves is much greater than the infrastructure cost (mean: $0.036/veh-km). Note that part of the infrastructure cost has been internalized via the user monetary cost such as the fuel tax. Hence, this infrastructure cost overestimates the un-internalized external monetary cost. Besides, driving on highways generates less user monetary cost than other roads. However, the infrastructure cost on highways is way much higher than surface roadways.

The work trip flows on the lowest monetary cost path have similar patterns to the shortest path. In contrast, using the lowest infrastructure cost path generates more detours onto surface roads.

Given actual values of time ($18.30/h, equivalent to $0.28/veh-km with a travel speed of 65km/h), it is likely many travelers would be persuaded to shift routes to account for the monetary cost.
Chapter 10

Internal and Full Cost Estimates for Automobiles

This chapter describes the results of link-based internal and full cost of travel for the Minneapolis - St. Paul Metropolitan area. Work trip flows are assigned to the lowest internal cost and full cost paths, and compared, indicating the magnitude of the social loss from ignoring externalities in vehicle routing.

10.1 Internal Cost Estimates

Table 10.1 summarizes the average internal cost by road type and percentage of cost allocations for different cost components of the internal cost. The estimates show that the average internal cost of travel is $0.64/veh-km. 94% of links have an internal cost less than $1.00/veh-km. Driving on the highways is much cheaper than other roads from the perspective of internal cost. The mean value of the internal cost for highways is $0.46/veh-km, while for other surface roadways is $0.66/veh-km.

For all types of roads, however, time cost is the dominant cost component for the internal cost, which accounts for more than 50% of the total. Monetary cost shares a large percent of the internal cost as well, around 30% or more. Comparatively, emission cost and safety cost share lower proportions.

From the aspect of area types, the estimates show that driving on roads in the core
cities is more expensive from an internal cost perspective than other areas, as shown in Table 10.2. The mean value of internal cost for roadways in the core cities ($0.75/veh-km) is much higher than in other urban ($0.63/veh-km) or rural areas ($0.57/veh-km). For all type of areas, similarly, time and monetary costs are the determinant factors of the internal cost.

Table 10.1: Link-based Internal Cost Estimates By Road Types ($/veh-km)

<table>
<thead>
<tr>
<th>Road Types</th>
<th>Internal Cost</th>
<th>Time</th>
<th>Emission</th>
<th>Safety</th>
<th>Money</th>
</tr>
</thead>
<tbody>
<tr>
<td>Highway (n=3,066)</td>
<td>0.46</td>
<td>52.49%</td>
<td>0.19%</td>
<td>2.54%</td>
<td>31.05%</td>
</tr>
<tr>
<td>Other Surface Road (n=44,927)</td>
<td>0.66</td>
<td>59.37%</td>
<td>0.14%</td>
<td>6.34%</td>
<td>34.37%</td>
</tr>
<tr>
<td>All Links (n=47,993)</td>
<td>0.64</td>
<td>59.48%</td>
<td>0.14%</td>
<td>6.22%</td>
<td>34.17%</td>
</tr>
</tbody>
</table>

Table 10.2: Link-based Internal Cost Estimates By Area Types ($/veh-km)

<table>
<thead>
<tr>
<th>Road Types</th>
<th>Internal Cost</th>
<th>Time</th>
<th>Emission</th>
<th>Safety</th>
<th>Money</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core Cities</td>
<td>0.75</td>
<td>61.68%</td>
<td>0.23%</td>
<td>6.39%</td>
<td>31.69%</td>
</tr>
<tr>
<td>Other Urban Area</td>
<td>0.63</td>
<td>59.92%</td>
<td>0.13%</td>
<td>5.80%</td>
<td>34.14%</td>
</tr>
<tr>
<td>Rural Area</td>
<td>0.57</td>
<td>56.38%</td>
<td>0.06%</td>
<td>6.90%</td>
<td>36.66%</td>
</tr>
<tr>
<td>All Links</td>
<td>0.64</td>
<td>59.48%</td>
<td>0.14%</td>
<td>6.22%</td>
<td>34.17%</td>
</tr>
</tbody>
</table>

Figure 10.1 gives the spatial distribution patterns of the link-based internal cost estimates. Highways are cheaper than other surface roadways in terms of internal cost. However, more internal cost of travel is generated from the highway network since it serves more traffic, shown in Figure 10.2.
Figure 10.1: Internal Cost Per Vehicle-Kilometer on Each Link of the Twin Cities Road Network ($/veh-km)
Figure 10.2: Internal Cost of All Vehicles Generated on Each Link of the Twin Cities Road Network ($/km)

Figure 10.3 shows the spatial distribution of the work trip flow assigned to the lowest internal cost path.

The work trip flow assigned to the lowest internal cost path shows largely the same distribution patterns as the baseline estimates of the work trip flow assigned to the shortest travel time path (Figure 6.4). This is expected since, as Table 10.1 and Table 10.2 show, time cost dominates the internal cost. The shape of the highway network is clearly given by Figure 10.3. Consistent with Figure 10.1, it indicates that work trips tend to be assigned to highways to minimize the internal cost of travel.
Slight differences exist, as the colors shifted on the maps. For a better illustration, Figure 10.4 displays their differences, which is the work trip flow assigned to the lowest internal cost path minus that assigned to the shortest travel time path. It is shown that some work trips reassign from major interstate highways, e.g. I-35W and I-394, to some state routes, e.g. MN-47 and MN-51, and local roads, e.g. Hennepin Avenue and New Brighton Blvd.

Figure 10.3: Work Trip Flow Assigned to the Lowest Internal Cost Path
Figure 10.4: Differences of Work Trip Flow Assigned to the Lowest Internal Cost Path Minus That Assigned to the Shortest Travel Time Path

10.2 Full Cost Estimates

The estimates of the link-based full cost of travel show that the mean value of full travel cost for all link segments in the Twin Cities is approximate $0.68/veh-km, and most links (93.6%) have a full cost less than $1.00/veh-km. Comparing among road types, driving on the highways ($0.54/veh-km) is much cheaper than on other surface roadways ($0.69/veh-km) from the full cost perspective. Comparing locations, the average full cost for the roadways in the core cities ($0.80/veh-km) is much higher than in other urban ($0.67/veh-km) or rural ($0.60/veh-km) areas.
Table 10.3 illustrates the percentage of cost allocations among different cost components in the full cost. It indicates that, for all types of roads, similar to the internal cost estimates, the time cost and monetary cost are the dominant components of the full cost. In addition, the infrastructure cost of highway links shares a large proportion, as well as the time and monetary costs. Note that part of the infrastructure cost has already been internalized through fuel taxes, vehicle sales taxes, or vehicle registration taxes.

Table 10.4 summarizes the full cost allocations by area among different cost components. Similar to Table 10.3, time and monetary costs are the determinants of the full cost.

Table 10.3: Link-based Full Cost Estimates By Road Types ($/veh-km)

<table>
<thead>
<tr>
<th>Road Types</th>
<th>Full Cost</th>
<th>Percentage of Cost Allocation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Time</td>
<td>Emission</td>
</tr>
<tr>
<td>Highway (n=3,066)</td>
<td>0.54</td>
<td>43.91%</td>
</tr>
<tr>
<td>Other Surface Road(n=44,927)</td>
<td>0.69</td>
<td>56.67%</td>
</tr>
<tr>
<td>All Links (n=47,993)</td>
<td>0.68</td>
<td>56.29%</td>
</tr>
</tbody>
</table>

Table 10.4: Link-based Full Cost Estimates By Area Types ($/veh-km)

<table>
<thead>
<tr>
<th>Area Types</th>
<th>Full Cost</th>
<th>Percentage of Cost Allocation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Time</td>
<td>Emission</td>
</tr>
<tr>
<td>Core Cities</td>
<td>0.80</td>
<td>58.40%</td>
</tr>
<tr>
<td>Other Urban Area</td>
<td>0.67</td>
<td>56.48%</td>
</tr>
<tr>
<td>Rural Area</td>
<td>0.60</td>
<td>53.77%</td>
</tr>
<tr>
<td>All Links</td>
<td>0.68</td>
<td>56.29%</td>
</tr>
</tbody>
</table>

Figure 10.1 gives the spatial distribution patterns of the link-based full cost estimates. Consistent with tables shown above, it clearly accentuates the shape of the highway network in the Twin Cities, which implies that highways are cheaper than other surface roadways in terms of full cost. Figure 10.2 shows the total full cost of all vehicles generated on each
link of the Twin Cities road network.

In addition, Figure 10.7 to Figure 10.11 show the contribution of the link-based total cost of each cost component to the full cost of travel.

Figure 10.5: Full Cost Per Vehicle-Kilometer on Each Link of the Twin Cities Road Network ($/veh-km)
Figure 10.6: Full Cost of All Vehicles Generated on Each Link of the Twin Cities Road Network ($/km)
Figure 10.7: Total Time Cost Per Vehicle-Kilometer Contributed to the Full Cost of Travel on Each Link of the Twin Cities Road Network ($/veh-km)
Figure 10.8: Total Crash Cost Per Vehicle-Kilometer Contributed to the Full Cost of Travel on Each Link of the Twin Cities Road Network ($/veh-km)
Figure 10.9: Total Emission Cost Per Vehicle-Kilometer Contributed to the Full Cost of Travel on Each Link of the Twin Cities Road Network ($/veh-km)
Figure 10.10: Total Monetary Cost Per Vehicle-Kilometer Contributed to the Full Cost of Travel on Each Link of the Twin Cities Road Network ($/veh-km)
Figure 10.11: Total Infrastructure Cost Per Vehicle-Kilometer Contributed to the Full Cost of Travel on Each Link of the Twin Cities Road Network ($/veh-km)

Figure 10.12 shows the spatial distribution of the work trip flow assigned to the lowest full cost path, which shows similar distribution patterns to the baseline estimates, work trip flow assigned to the shortest travel time path, shown in Figure 6.4. Interstate highways, e.g. I-94 and I-494, serve more work trips whether the shortest travel time or the lowest full cost path is selected. However, many trips will reassign from major interstate highways to state routes, like MN-169, MN-100, and MN-55, if all work trips were assigned to paths to minimize the full cost. Figure 10.13 shows the changes more clearly.

Figure 10.14 describes the work trip flow differences assigned to the lowest full cost
path vs. the lowest internal cost path.

Figure 10.12: Work Trip Flow Assigned to the Lowest Full Cost Path
Figure 10.13: Differences of Work Trip Flow Assigned to the Lowest Full Cost Path Minus That Assigned to the Shortest Travel Time Path
Figure 10.14: Differences of Work Trip Flow Assigned to the Lowest Full Cost Path Minus That Assigned to the Lowest Internal Cost Path
Chapter 11

Full Cost Analysis of Accessibility for Automobiles

This chapter shows the accessibility measurements and accessibility difference analysis for automobiles considering each cost component, and the total internal and full cost.

11.1 Accessibility Measurements

11.1.1 Time Cost

Figure 11.1 shows the traditional job accessibility measurement based on the shortest travel time path with time thresholds from 10 min - 60 min. Table 11.1 shows the population-weighted results.

For a specific time threshold, e.g. in 20 min (Figure 11.1b), the zones with higher job accessibility are centered on downtown Minneapolis, which is visible in more intense red. 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. In the surrounding exurban areas, census blocks have the lowest job accessibility. This condition comports with our understanding of the region since the number of jobs in and around the downtown area is relatively higher than in the far reaches.

With different time thresholds, the results of job accessibility change significantly. From Figures 11.1a and 11.1f, we see that an expansion of the red area, which indicates higher
accessibility, centering on the downtown correlates with the increase of time threshold. It is obvious that most of the Twin Cities region can reach most jobs when the time threshold is equal to 60 minutes. Since the time threshold for job accessibility measurement represents travelers’ willingness to pay for the travel time of home-to-work trips, with the same speed percentiles on all links, such a condition is reasonable to expect that residents can reach more jobs if they are willing to spend more time traveling.

Figure 11.2 displays the time-weighted job accessibility based on the shortest travel time path, which combines different time thresholds with an impedance factor indicating that the accessibility to opportunities is expected to decrease with a higher time cost from the origins (Anderson et al. 2013, Levinson & Kumar 1995, Hansen 1959). Based on the definition of time-weighted accessibility, it can be expressed as:

\[
A_{O,w_t} = \sum_{T_t=10}^{60} (A_{i,T_t} - A_{i,T_{t-10}})e^{\beta T_t} 
\]

(11.1)

Where:
- \(T_t\): Time threshold;
- \(\beta\): Impedance parameter, for work trips by auto, \(\beta\) was set as -0.08.

Table 11.1: Population-weighted Job Accessibility Based on the Shortest Travel Time Path in Different Time Thresholds from 10min to 60min by Auto

<table>
<thead>
<tr>
<th>Time Threshold</th>
<th>10 min</th>
<th>20 min</th>
<th>30 min</th>
<th>40 min</th>
<th>50 min</th>
<th>60 min</th>
<th>Time-weighted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accessibility</td>
<td>120,515</td>
<td>560,612</td>
<td>1,035,843</td>
<td>1,296,005</td>
<td>1,389,399</td>
<td>1,415,453</td>
<td>198,647</td>
</tr>
</tbody>
</table>
Figure 11.1: Job Accessibility Based on the Shortest Travel Time Path in Different Time Cost Thresholds from 10 min to 60 min by Auto
Figure 11.2: Time-weighted Job Accessibility Based on the Shortest Travel Time Path
11.1.2 Safety Cost

Figure 11.3 and Figure 11.4 show the job accessibility based on the safest internal path and safest external path, respectively, with the crash cost threshold changing from $0.10 to $0.60. Table 11.2 gives the population-weighted results.

Similar to the traditional time-based accessibility (Figure 11.1), it is shown that job accessibility based on the safest path (both internal and external) is higher in or around downtown Minneapolis, and the accessibility decreases gradually from downtown to exurban areas as the mapped colors change from red to light blue. It is reasonable to have such a pattern in the Twin Cities region since job opportunities are centered on downtown Minneapolis, which means residents living in or around the downtown area need less time to reach the same number of job opportunities and have a lower crash rate along the home-to-work trips. Moreover, job accessibility increases significantly overall with a higher level of crash cost threshold as well. Within the $0.60 of crash cost, most residents in the Twin Cities region can reach most job opportunities by using the safest (both internal and external) path.

Table 11.2: Population-weighted Job Accessibility Based on the Safest Internal/External Path in Different Crash Cost Thresholds from $0.10 to $0.60 by Auto

<table>
<thead>
<tr>
<th>Crash Cost Threshold</th>
<th>$0.10</th>
<th>$0.20</th>
<th>$0.30</th>
<th>$0.40</th>
<th>$0.50</th>
<th>$0.60</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accessibility</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Internal</td>
<td>22,133</td>
<td>271,992</td>
<td>774,643</td>
<td>1,151,829</td>
<td>1,321,037</td>
<td>1,386,708</td>
</tr>
<tr>
<td>External</td>
<td>106,770</td>
<td>611,061</td>
<td>1,154,583</td>
<td>1,381,074</td>
<td>1,417,683</td>
<td>1,421,075</td>
</tr>
</tbody>
</table>
Figure 11.3: Job Accessibility Based on the Safest Internal Path in Different Internal Crash Cost Thresholds from $0.10 to $0.60 by Auto
Figure 11.4: Job Accessibility Based on the Safest External Path in Different External Crash Cost Thresholds from $0.10 to $0.60 by Auto
11.1.3 Emission Cost

Figure 11.5 shows the job accessibility based on the healthiest path in different emission intake cost thresholds from $0.009 to $0.024. Figure 11.6 shows the job accessibility based on the greenest path in different emission cost thresholds from $0.10 to $0.60. Table 11.3 and Table 11.4 show their population-weighted results.

The basic distribution pattern of job accessibility based on the healthiest path is slightly different from the traditional time-based job accessibility (Figure 11.1), on that accessibility is more evenly distributed in the Twin Cities metro region; the downtown area does not have apparent advantages in reaching job opportunities considering the emission intake. This is mainly resulted from a higher on-road concentration of pollutants in the downtown area. For different cost thresholds, job accessibility increases significantly, such that most of the Twin Cities region can reach most job opportunities in $0.024 of emission intake cost.

Figure 11.6 displays a more general job accessibility distribution which shows the downtown area has a higher job accessibility, and accessibility declines with the increase of the distance to the downtown area. Also, emission cost thresholds significantly affect the job accessibility based on the greenest path overall. Allowing $0.60 of emission cost, most job opportunities can be reached for most of the Twin Cities area.

Table 11.3: Population-weighted Job Accessibility Based on the Healthiest Path in Different Internal Emission Cost Thresholds from $0.009 to $0.024 by Auto

<table>
<thead>
<tr>
<th>Internal Emission Cost Threshold</th>
<th>$0.009</th>
<th>$0.012</th>
<th>$0.015</th>
<th>$0.018</th>
<th>$0.021</th>
<th>$0.024</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accessibility</td>
<td>212,667</td>
<td>389,297</td>
<td>604,664</td>
<td>832,606</td>
<td>1,058,801</td>
<td>1,253,862</td>
</tr>
</tbody>
</table>

Table 11.4: Population-weighted Job Accessibility Based on the Greenest Path in Different External Emission Cost Thresholds from $0.10 to $0.60 by Auto

<table>
<thead>
<tr>
<th>External Emission Cost Threshold</th>
<th>$0.10</th>
<th>$0.20</th>
<th>$0.30</th>
<th>$0.40</th>
<th>$0.50</th>
<th>$0.60</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accessibility</td>
<td>69,887</td>
<td>397,225</td>
<td>876,460</td>
<td>1,234,177</td>
<td>1,376,709</td>
<td>1,413,135</td>
</tr>
</tbody>
</table>
Figure 11.5: Job Accessibility Based on the Healthiest Path in Internal Emission Cost Thresholds from $0.009 to $0.024 by Auto
Figure 11.6: Job Accessibility Based on the Greenest Path in External Emission Cost Thresholds from $0.10 to $0.60 by Auto
11.1.4 Monetary/Infrastructure Cost

Based on the monetary/infrastructure cost analysis in Chapter 9, four scenarios of accessibility based on the lowest monetary cost path could be measured:

- marginal monetary cost with daily parking rate;
- average monetary cost with daily parking rate;
- marginal monetary cost with contract parking rate;
- average monetary cost with contract parking rate.

Four scenarios of accessibility based on the lowest infrastructure cost path could be measured as well:

- short-term marginal infrastructure cost;
- short-term average infrastructure cost;
- long-term marginal infrastructure cost;
- long-term average infrastructure cost.

Figure 11.7 shows the job accessibility based on the lowest monetary cost path considering the marginal monetary cost, with daily parking rate, in different monetary cost thresholds from $2 to $12. Figure 11.8 shows the job accessibility based on the lowest infrastructure cost path considering the long term average infrastructure cost in different infrastructure cost thresholds from $0.20 to $1.20. Other scenarios of accessibility measurements have similar spatial distributions.

Similar to the time-based accessibility, Figure 11.7 shows that job accessibility based on the lowest monetary cost path is higher in or around downtown Minneapolis, and it decreases gradually from downtown to exurban areas. As job opportunities are centered on downtown Minneapolis, it is expected that living in or near the downtown areas lowers the monetary cost needed to reach the same number of job opportunities compared with living in suburban and exurban areas.
Accessibility based on the lowest infrastructure cost path (Figure 11.8) shows similar spatial distribution patterns to the time-based measurements as well.

Table 11.5: Population-weighted Job Accessibility Based on the Lowest Monetary Cost Path in Different Monetary Cost Thresholds from $2.00 to $12.00

<table>
<thead>
<tr>
<th>Monetary Cost Threshold</th>
<th>$2</th>
<th>$4</th>
<th>$6</th>
<th>$8</th>
<th>$10</th>
<th>$12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accessibility</td>
<td>105,422</td>
<td>475,623</td>
<td>877,493</td>
<td>1,127,768</td>
<td>1,239,165</td>
<td>1,286,210</td>
</tr>
</tbody>
</table>

Table 11.6: Population-weighted Job Accessibility Based on the Lowest Infrastructure Cost Path in Different Infrastructure Cost Thresholds from $0.20 to $1.20 by Auto

<table>
<thead>
<tr>
<th>Infrastructure Cost Threshold</th>
<th>$0.20</th>
<th>$0.40</th>
<th>$0.60</th>
<th>$0.80</th>
<th>$1.00</th>
<th>$1.20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accessibility</td>
<td>69,725</td>
<td>269,964</td>
<td>537,160</td>
<td>816,802</td>
<td>1,052,570</td>
<td>1,217,788</td>
</tr>
</tbody>
</table>
Figure 11.7: Job Accessibility Based on the Lowest Monetary Cost Path for Travelers with Daily Parkings in Different Monetary Cost Thresholds from $2.00 to $12.00 by Auto
Figure 11.8: Job Accessibility Based on the Lowest Infrastructure Cost Path in Different Infrastructure Cost Thresholds from $0.20 to $1.20 by Auto
11.1.5 Total Internal Cost

Figure 11.9 shows the job accessibility based on the lowest internal cost path in internal cost thresholds of $5.00 to $30.00. Table 11.7 gives its population-weighted average.

Job accessibility based on the lowest internal cost path shows a general monocentric distribution pattern; as with the traditional time-based accessibility (Figure 11.1), the zones with higher job accessibility are centered on downtown areas. With the increase of distance to the downtown area, accessibility declines gradually. In addition, job accessibility increases significantly overall with a higher internal cost threshold. Most residents in the Twin Cities region can reach most job opportunities in $30.00 of internal cost based on the lowest internal cost path.

Table 11.7: Population-weighted Job Accessibility Based on the Lowest Internal Cost Path in Different Internal Cost Thresholds from $5.00 to $30.00 by Auto

<table>
<thead>
<tr>
<th>Internal Cost Threshold</th>
<th>$5</th>
<th>$10</th>
<th>$15</th>
<th>$20</th>
<th>$25</th>
<th>$30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accessibility</td>
<td>107,289</td>
<td>503,755</td>
<td>960,944</td>
<td>1,246,057</td>
<td>1,366,775</td>
<td>1,407,535</td>
</tr>
</tbody>
</table>

Figure 11.9: Job Accessibility Based on the Lowest Internal Cost Path in Different Internal Cost Thresholds from $5.00 to $30.00 by Auto
11.1.6 Full Cost

Figure 11.10 displays the job accessibility in full cost thresholds of $5.00 to $30.00 based on the lowest full cost path, and Table 11.8 shows the population-weighted results.

As with the traditional time-based accessibility (Figure 11.1), it is indicated that job accessibility based on the lowest full cost path is higher in the downtown area than the suburban and exurban areas. Accessibility decreases gradually with the increase of distance to the downtown areas. Also, full cost thresholds affect the job accessibility significantly based on the lowest full cost path overall. In $30.00 of full cost, most job opportunities can be reached for most of the Twin Cities area.

Table 11.8: Population-weighted Job Accessibility Based on the Lowest Full Cost Path in Different Full Cost Thresholds from $5.00 to $30.00 by Auto

<table>
<thead>
<tr>
<th>Full Cost Threshold</th>
<th>$5</th>
<th>$10</th>
<th>$15</th>
<th>$20</th>
<th>$25</th>
<th>$30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accessibility</td>
<td>82,139</td>
<td>367,513</td>
<td>746,864</td>
<td>1,071,557</td>
<td>1,268,418</td>
<td>1,363,970</td>
</tr>
</tbody>
</table>
Figure 11.10: Job Accessibility Based on the Lowest Full Cost Path in Different Full Cost Thresholds from $5.00 to $30.00 by Auto
11.2 Accessibility Differences Analysis

11.2.1 Accessibility Differences Comparing with the Traditional Time-based Accessibility

Safety Cost

Figure 11.11 and Figure 11.12 show the accessibility differences of using the safest internal and external paths compared with the shortest path in different time thresholds from 10 min to 60 min. Figure 11.13 displays the time-weighted differences.

The changes in job accessibility considering the safety costs for both internal and external versions are negative with any given time thresholds in comparison with using the shortest path. It is expected since the shortest path is the optimal solution with the restriction of the time cost. Using other types of paths makes the trips longer, which results in an accessibility loss. The accessibility changes exemplify the time-safety trade-off that travelers either spend more time to pursue a safer trip or pay more safety cost to pursue a shorter one. Figure 11.14 illustrates the job-weighted crash cost savings of using the safest path rather than using the shortest travel time path for both internal and external versions.
Figure 11.11: Difference of Job Accessibility in Different Time Cost Thresholds from 10 min to 60 min by Auto: Safest Internal Path - Shortest Travel Time Path
Differences of Job Accessibility:
Safest External Path - Shortest Path
in 10min Time Cost Thresholds

(a) In 10 min

Differences of Job Accessibility:
Safest External Path - Shortest Path
in 20min Time Cost Thresholds

(b) In 20 min

Differences of Job Accessibility:
Safest External Path - Shortest Path
in 30min Time Cost Thresholds

(c) In 30 min

Differences of Job Accessibility:
Safest External Path - Shortest Path
in 40min Time Cost Thresholds

(d) In 40 min

Differences of Job Accessibility:
Safest External Path - Shortest Path
in 50min Time Cost Thresholds

(e) In 50 min

Differences of Job Accessibility:
Safest External Path - Shortest Path
in 60min Time Cost Thresholds

(f) In 60 min

Figure 11.12: Difference of Job Accessibility in Different Time Cost Thresholds from 10 min to 60 min by Auto: Safest External Path - Shortest Travel Time Path
Figure 11.13: Differences of Time-weighted Job Accessibility: Safest Internal/External Path - Shortest Travel Time Path
Figure 11.14: Job-weighted Internal/External Crash Cost Savings: Safest Internal/External Path - Shortest Travel Time Path
Emission Cost

Figure 11.15 and Figure 11.16 show the accessibility differences of using the healthiest path and the greenest path compared with the shortest path in time thresholds from 10 min to 60 min. Figure 11.17 displays the time-weighted differences.

For both figures, the changes in job accessibility accounting for the environmental costs (both internal and external) are negative in any given time threshold. Same as the accessibility changes analysis on crash costs, this is also expected since the shortest path is the optimal solution with the restriction of time cost, and using other types of paths makes the trips longer, which results in an accessibility loss. The internal/external emission costs, however, are lower based on the healthiest/greenest path, which shows the trade-off between the time cost and the environmental cost that travelers make to either pay more time to pursue a healthier/greener trip or pay more environmental costs to pursue a travel time optimization. The job-weighted environmental cost savings for both internal and external versions are shown in Figure 11.18.
Figure 11.15: Difference of Job Accessibility in Different Time Cost Thresholds from 10 min to 60 min by Auto: Healthiest Path - Shortest Travel Time Path
Figure 11.16: Difference of Job Accessibility in Different Time Cost Thresholds from 10 min to 60 min by Auto: Greenest Path - Shortest Travel Time Path
Figure 11.17: Differences of Time-weighted Job Accessibility: Healthiest/Greenest Path - Shortest Travel Time Path
Figure 11.18: Job-weighted Internal/External Emission Cost Savings: Healthiest/Greenest Path - Shortest Travel Time Path
Monetary/Infrastructure Cost

Figure 11.19 and Figure 11.20 show the changes in job accessibility of using the lowest monetary cost path and the lowest infrastructure cost path, respectively, compared with the shortest path in time thresholds from 10 min to 60 min. Figure 11.21 displays their time-weighted differences.

The changes are all negative in any given time threshold. This is expected since the shortest path is the optimal solution when the time threshold is considered. Using the lowest monetary/infrastructure cost path makes the trips longer compared with the shortest path, which results in an accessibility loss with the restriction of time thresholds. Meanwhile, the lowest monetary/infrastructure cost path optimizes the monetary/infrastructure cost, which brings a monetary/infrastructure cost saving, shown in Figure 11.22. This reflects the trade-off between the time cost and the monetary/infrastructure cost that travelers make between having to spend more time during traveling to pursue a monetary optimization and choosing a higher-cost shorter path.
Figure 11.19: Difference of Job Accessibility in Different Time Cost Thresholds from 10 min to 60 min by Auto: Lowest Monetary Cost Path - Shortest Travel Time Path
Figure 11.20: Difference of Job Accessibility in Different Time Cost Thresholds from 10 min to 60 min by Auto: Lowest Infrastructure Cost Path - Shortest Travel Time Path
Figure 11.21: Differences of Time-weighted Job Accessibility: Lowest Monetary/Infrastructure Cost Path - Shortest Travel Time Path
Figure 11.22: Job-weighted Monetary/Infrastructure Cost Savings: Lowest Monetary/Infrastructure Cost Path - Shortest Travel Time Path
Total Internal Cost

Figure 11.23 shows the accessibility differences of using the lowest internal cost path compared with the shortest path in different time threshold from 10 min to 60 min. Figure 11.24 displays the time-weighted differences.

The changes in job accessibility considering the total internal costs are negative in any given time threshold. As with the accessibility difference analysis of any single cost component, this is expected, as the shortest path optimizes the time cost, and using other types of paths involves more detours, which increases the travel time and generates an accessibility loss. Using the lowest internal cost path, however, lowers the internal cost of travel compared with using the shortest travel time path. Figure 11.25 displays the job-weighted average internal cost savings. It represents the trade-off between the time cost and the total internal cost that travelers make between spending more time to pursue an internal cost optimization or paying more internal costs to pursue a shorter trip.
Figure 11.23: Difference of Job Accessibility in Different Time Cost Thresholds from 10 min to 60 min by Auto: Lowest Internal Cost Path - Shortest Travel Time Path
Figure 11.24: Differences of Time-weighted Job Accessibility: Lowest Internal Cost Path - Shortest Travel Time Path
Figure 11.25: Job-weighted Internal Cost Savings: Lowest Internal Cost Path - Shortest Travel Time Path
**Full Cost**

Figure 11.26 shows the accessibility differences of using the lowest full cost path compared with the shortest travel time path in different time thresholds from 10 min to 60 min. Figure 11.27 displays the time-weighted differences.

The changes in job accessibility accounting for the full costs are negative with any given time thresholds in comparison with using the shortest path. The job-weighted average full cost savings using the lowest full cost path compared with the full cost along the shortest travel time path is shown in Figure 11.28.
Differences of Job Accessibility:
Lowest Full Cost Path - Shortest Path
in 10 min Time Cost Threshold

Figure 11.26: Difference of Job Accessibility in Different Time Cost Thresholds from 10 min to 60 min by Auto: Lowest Full Cost Path - Shortest Travel Time Path
Figure 11.27: Differences of Time-weighted Job Accessibility: Lowest Full Cost Path - Shortest Travel Time Path
Figure 11.28: Job-weighted Full Cost Savings: Lowest Full Cost Path - Shortest Travel Time Path
Population Weighted Differences

Table 11.9 summarizes the population-weighted accessibility differences using different path types compared with using the shortest time path. Table 11.10 indicates the population-weighted cost savings of each cost component using the corresponding optimal path types compared with using the shortest travel time paths.

Based on the time-weighted accessibility differences, it is indicated that using the lowest infrastructure cost path results in the highest accessibility loss considering the time restrictions. The main reason is that driving on the highways yields higher infrastructure costs, but lower time costs than surface roads. The work trip flow assigned to the lowest infrastructure cost path, shown in Figure 9.9, gives the consistent result that fewer trips would be assigned to highways if the lowest infrastructure cost path is selected; this maximizes associated infrastructure cost savings. It, again, exemplifies the time-infrastructure cost trade-off that travelers either save $1.95 infrastructure cost or lose access to 97,359 jobs on average.

Using the healthiest path also shows a higher accessibility loss; as Figure 8.7a shows, the healthiest travel path detours to exurban areas where the on-road concentrations of pollution are lower to minimize the emission intake cost. But the internal emission cost savings of using the healthiest path are small, which is $0.01 per trip on average. Hence, as expressed in the emission cost analysis, it is highly unlikely many travelers would be persuaded to shift routes based on such small internal emission cost savings afforded by the healthiest paths compared with the shortest paths.

Using the lowest internal cost path affects the job accessibility the least, as the internal cost contains the time cost, which is the dominant cost component. The work trip flow assigned to the lowest internal cost path has a similar distribution to the distribution associated with the shortest travel time path, shown in Figure 10.3, which demonstrates that the lowest internal cost path is largely consistent with the shortest travel time path. Hence, the internal cost savings are small as well.

To illustrate the trade-off between time cost and other cost components more clearly, Table 11.11 shows the accessibility differences per cent of cost savings for each cost component using the corresponding optimal path type compared with using the shortest travel time path. The results show that the lowest internal cost path is the most cost-efficient.
choice that it only costs 187 job accessibility to save 1 cent of internal cost of travel. Similarly, the lowest full cost path pays 191 job opportunities to save 1 cent of full cost. Choosing the healthiest path results in the greatest accessibility loss among individual cost components, compared to the optimal condition of the shortest paths.
### Table 11.9: Population-weighted Accessibility Differences: New Path Types - Shortest Travel Time Path

<table>
<thead>
<tr>
<th>Path Type</th>
<th>10 min</th>
<th>20 min</th>
<th>30 min</th>
<th>40 min</th>
<th>50 min</th>
<th>60 min</th>
<th>Time-weighted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Healthiest Path</td>
<td>-34,816</td>
<td>-214,838</td>
<td>-373,063</td>
<td>-397,721</td>
<td>-367,429</td>
<td>-319,809</td>
<td>-66,402</td>
</tr>
<tr>
<td>Greenest Path</td>
<td>-23,308</td>
<td>-95,520</td>
<td>-126,667</td>
<td>-83,576</td>
<td>-37,755</td>
<td>-13,214</td>
<td>-25,080</td>
</tr>
<tr>
<td>Lowest Monetary Cost Path</td>
<td>-8,468</td>
<td>-46,445</td>
<td>-65,420</td>
<td>-43,284</td>
<td>-19,132</td>
<td>-6,519</td>
<td>-11,746</td>
</tr>
<tr>
<td>Lowest Internal Cost Path</td>
<td>-1,185</td>
<td>-3,778</td>
<td>-4,876</td>
<td>-3,587</td>
<td>-1,667</td>
<td>-533</td>
<td>-1,509</td>
</tr>
<tr>
<td>Lowest Full Cost Path</td>
<td>-3,643</td>
<td>-19,172</td>
<td>-23,413</td>
<td>-13,823</td>
<td>-5,733</td>
<td>-1,896</td>
<td>-4,587</td>
</tr>
</tbody>
</table>

### Table 11.10: Population-weighted Cost Savings: Corresponding Optimal Path Types - Shortest Travel Time Path

<table>
<thead>
<tr>
<th>Cost Type</th>
<th>Crash Cost</th>
<th>Emission Cost</th>
<th>Monetary Cost</th>
<th>Infrastructure Cost</th>
<th>Internal Cost</th>
<th>Full Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Internal</td>
<td>External</td>
<td>Internal</td>
<td>External</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost Savings</td>
<td>0.0816</td>
<td>0.1095</td>
<td>0.0106</td>
<td>0.0769</td>
<td>0.1788</td>
<td>1.9538</td>
</tr>
</tbody>
</table>
Table 11.11: Population-weighted Accessibility Differences Per Cent of Cost Savings: Corresponding Optimal Path Types - Shortest Travel Time Path

<table>
<thead>
<tr>
<th>Path</th>
<th>10 min</th>
<th>20 min</th>
<th>30 min</th>
<th>40 min</th>
<th>50 min</th>
<th>60 min</th>
<th>Time-weighted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Safest Internal Path</td>
<td>-4,024</td>
<td>-13,992</td>
<td>-16,099</td>
<td>-9,729</td>
<td>-4,338</td>
<td>-1,489</td>
<td>-3,630</td>
</tr>
<tr>
<td>Safest External Path</td>
<td>-3,747</td>
<td>-18,156</td>
<td>-26,866</td>
<td>-20,690</td>
<td>-11,100</td>
<td>-5,037</td>
<td>-4,906</td>
</tr>
<tr>
<td>Greenest Path</td>
<td>-3,031</td>
<td>-12,421</td>
<td>-16,471</td>
<td>-10,867</td>
<td>-4,909</td>
<td>-1,718</td>
<td>-3,261</td>
</tr>
<tr>
<td>Lowest Monetary Cost Path</td>
<td>-474</td>
<td>-2,597</td>
<td>-3,659</td>
<td>-2,421</td>
<td>-1,070</td>
<td>-365</td>
<td>-657</td>
</tr>
<tr>
<td>Lowest Infrastructure Cost Path</td>
<td>-321</td>
<td>-1,677</td>
<td>-2,826</td>
<td>-2,749</td>
<td>-1,983</td>
<td>-1,159</td>
<td>-498</td>
</tr>
<tr>
<td>Lowest Full Cost Path</td>
<td>-152</td>
<td>-799</td>
<td>-976</td>
<td>-576</td>
<td>-239</td>
<td>-79</td>
<td>-191</td>
</tr>
</tbody>
</table>
11.2.2 Accessibility Differences: Internal Cost vs. Full Cost

Figure 11.29 shows the accessibility differences using the lowest full cost path compared with the lowest internal cost path in different internal cost thresholds from $5.00 to $30.00.

The changes in job accessibility accounting for the full costs are negative with any given internal cost threshold in comparison with using the lowest internal cost path. The job-weighted average full cost savings using the lowest full cost path is shown in Figure 11.30 compared with the full cost along the lowest internal cost path. The population-weighted full cost savings is $0.25.
Figure 11.29: Difference of Job Accessibility in Different Internal Cost Thresholds from $5.00 to $30.00 by Auto: Lowest Full Cost Path - Lowest Internal Cost Path
Figure 11.30: Job-weighted Full Cost Savings: Lowest Full Cost Path - Lowest Internal Cost Path
Chapter 12

Conclusion

12.1 Summary of Research

Full Cost Accessibility Framework

This dissertation 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 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 in the United States, and likely in many countries. 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.

**Implementation of the FCA Framework**

A toy network was built in this study to illustrate the implementation of the framework, which demonstrates the potential and practicality of applications in real networks. The Minneapolis - St. Paul Metropolitan area was then selected as the study area for a real-world application of the FCA framework.

The cost analysis shows that, in Minneapolis - St. Paul, the mean value of full travel cost is approximately $0.68/veh-km, and 93.6% of links have a full cost less than $1.00/veh-km. Time cost and monetary cost are the determinants for travelers’ full cost, which account for approximately 85% of the total. Crash cost and emission cost share lower proportions, which makes it unlikely that travelers will shift their route significantly to account for safety or emission. However, external costs should still be internalized.

Comparing road types, highways are cheaper than other surface roadways in terms of time cost, internal cost and full cost from the perspective of travelers. However, it is worth noting that the infrastructure costs for highways are much higher than surface roads. It reveals a cost-benefit trade-off of highway construction. Comparing with locations, link segments in the core cities have a higher travel cost for all different cost components than other urban and rural areas.
Work trip flow allocated to different path types, except for the healthiest path and the lowest infrastructure cost path, show largely the same distribution as the baseline estimates assigned to the shortest travel time path. Based on current traffic levels, i.e. assuming other traffic does not reroute, highways serve more work trips than other surface roads due to a comparatively lower cost. The healthiest path, concerning the emission intake cost, however, detours to exurban areas where the on-road concentrations of pollution are lower. The lowest infrastructure cost path, concerning the external monetary cost, detours from highways to local surface roadways where the infrastructure expenses are lower.

Job accessibility based on different cost components show similar spatial distribution patterns; areas with higher job accessibility are centered on downtown Minneapolis and accessibility decreases along with the increase of the distance to the downtown area. Slight differences, however, exist depending on the properties of the included cost components. For instance, accessibility in the realm of internal emission cost does not have apparent advantages in the downtown area since pollution concentrations are much higher in downtown Minneapolis, which cause a higher internal emission cost.

Accessibility difference assessment was measured as the accessibility based on the new path types minus that based on the shortest travel time path in the same time cost thresholds. The differences are negative in any given time threshold since the shortest path is the optimal solution with the restriction of the time cost, and using other path types makes the trips longer. It reflects a cost-benefit trade-off that, for instance, travelers need to spend more time on-road than on the shortest path to pursue a full cost optimization based on the lowest full cost path, which results in a population-weighted full cost savings of $0.24/veh-km.

12.2 Discussions

FCA framework comprises three stages, each of which shows the potential of applications in other transportation research domains in addition to the full cost accessibility evaluations. Travel cost analysis aims to investigate alternate cost components and measure the full cost of travel. It has a wide range of applications, on which an input of travel cost is required. For instance, in mode choice modeling, travel cost, including travel time, is a critical characteristic expressing the utility of transport services, which allows to measure
the probability of choosing a given mode (Ben-Akiva & Lerman 1985, Levinson et al. 2018). Generally, the travel cost in the utility function captures the internal version of cost. While incorporating the external travel cost is capable of changing the observed utility and affecting the mode choice accordingly. We expect that considering the full cost of travel, including both internal and external cost, would lower the probability of choosing auto. It is valuable to evaluate the extent of the effects.

New path types propose alternative patterns of traffic route assignments to minimize the internal and external versions of travel cost for each cost component, which enables to find new equilibrium traffic assignments associating with the iteration of travel cost analysis due to traffic rerouting (Wardrop 1952). The work trip flow estimates shown in each chapter from Chapter 6 to Chapter 10 give the first iteration of traffic assignment results pursuing the shortest path from the perspective of each cost component. More importantly, the user optimal equilibrium considering the total internal cost and the social optimal equilibrium considering the full cost provide more comprehensive evaluations of route assignments compared to the time-based equilibrium solutions. Individual internal cost savings and systematical full cost savings could then be measured based on the user or social optimal equilibrium in comparison with travelers’ actual route choices.

Component accessibility analysis, which assesses accessibility from the aspect of a single alternate cost component, provides valuable measures for project evaluations with specific needs. For example, accessibility measurements in the realm of crash cost could be used as an index for evaluations of safety improvement projects, e.g., road realignments on dangerous link segments; accessibility measurements in the realm of emission cost could be applied to assess the environmental benefits of the wide applications of electric vehicles.

Full cost accessibility itself is a more comprehensive index for project or scenario evaluations. For instance, full cost accessibility measurements by connected or autonomous vehicles could give a full assessment on the applications of the connected or autonomous vehicles concerning their travel cost borne by both travelers and the society. For the case of the Twin Cities, full cost accessibility could also be applied for the MnPASS Lanes scenario evaluations, identifying the costs and benefits of the MnPASS users. In addition, the comparison between internal and full cost accessibility measures the accessibility changes with-and-without the internalized external cost, which could be used to explain the effects.
of the external cost internalization.

12.3 Limitations and Future Research

TomTom speed data are the most significant data source in this travel cost analysis. They have been used as the input of travel time calculation, crash risk estimation (as independent variables in negative binomial regression and ordered probit models), assessment of quantity of emissions (as link property input in MOVES simulation), and fuel efficiency estimation. However, the accuracy of the speed estimation of TomTom speed data is not guaranteed. TomTom speed data, as described, were aggregated and processed data. It is difficult to accurately estimate travel speed for specific links with low penetration rate, low polling frequency, and limited types of probe vehicles (Liu et al. 2009, Jenelius & Koutsopoulos 2013, Liu et al. 2016). In this speed dataset, 60 (out of 48,000) links have a travel speed lower than 5 km/h, for which their upstream or downstream link segments have a much higher travel speed. This causes some unexpected higher travel cost, like the strange red lines shown in Figure 9.3, but these are the best available speed data.

In Chapter 7, we used negative binomial regression and ordered probit models to estimate the crash frequency and crash severity, which are the foundations for the link-based crash cost analysis. The models, however, do not separate the road segments from intersections on the road network. At this point, it remains difficult to accurately differentiate crashes by location when joining with the TomTom network, and there is a lack of intersection attribute data that could be used for systematic intersection crash analysis. We anticipate future research with better and more geographically precise data will allow these kinds of analyses. In addition, due to the data limitation, the regression models did not include more attributes showing the roadways’ geometric properties such as number of lanes, speed limit, curvature, and slope, which would be expected to improve the predictive capability of the models. Future studies should focus on the improvement of the crash frequency and severity estimation models, which would enhance the accuracy of the crash cost analysis.

Pollution concentration estimates are the determinant inputs for emission cost analysis. In Chapter 8, run options selected in the RLINE model generated potential errors of the estimates. Considering the number of emission sources (48,000) and receptors (48,000
for on-road estimates; 54,000 for off-road estimates), the analytical rather than numerical solution was used to reduce the runtime, at the cost of accuracy. In addition to the accuracy of the speed data, the analytical solution results in unreasonable pollution concentration outputs for specific links and blocks, as with the strange red dot shown in Figure 8.2b. The final estimates of internal and external emission cost are then affected, which brings additional errors.

Moreover, the cost analysis conducted in this dissertation is a population-weighted average without considering the effects of personal characteristics. The time cost was measured based on a standard value of time which reflects Minnesota’s average income rate. The true time value of individual travelers may differ from the standard one as it highly depends on travelers’ income. Crash frequency and crash severity are estimates based on statistical models, which vary significantly according to individual driving behaviors. An aggressive driver may have a higher crash risk. In addition, unit crash cost factors, like the quality of statistical life, may be affected by age and income as well. The exposure allowance of on-road travelers, used for emission cost estimates, differs from the average intake fraction depending on factors like age or health conditions. For instance, children and the elderly may have a higher internal emission cost than the average, and even higher than the external cost. For the monetary cost, vehicle model and age are the determinants, which are also highly related to income. Future research should consider personal characteristics for an individual-based cost analysis, and provide appropriate adjustment factors for different age and income categories.

Future studies should extend the framework to other traffic modes, e.g. transit and bicycle, especially for the cost analysis part, to identify the internal and external costs from the perspective of passengers or bicyclists. A full-benefit analysis could be conducted for non-motorized modes as well. It is believed that, for instance, health is improved by biking. Happiness might also vary by modes, and so could be reflected in different ways of assessing the value of time. Furthermore, building the FCA framework for other traffic modes would yield illustrate the mode-combined accessibility measurements on real networks.
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