The Greenest Path: Comparing the Effects of Internal and External Costs of Motor Vehicle Pollution on Route Choice and Accessibility

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ABSTRACT

On-road emissions are a dominant source of urban air pollution, which damages human health. The "greenest path" is proposed as an alternative pattern of traffic route assignment to minimize the costs of emissions or exposure, pursues an environmentally optimal. The framework of a link-based emission cost analysis is built for both internal and external environmental costs and applied to the road network of the Twin Cities Metropolitan area based on the EPA MOVES model. The greenest (internal/external) path is skimmed for all OD pairs to compare the work trip flows on the roads and accessibility distribution. It is shown that the emission cost that travelers impose on others is greater than which they bear. Considering only external emissions costs thus produces a lower accessibility than considering only internal emissions costs. This research contributes to understanding the full cost of travel.

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 (1), Pope III et al. (2)).

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).[1] [2]

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 transportation 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 affect vegetation, materials, aquatic ecosystems, visibility, and climate as well as human health (11). Notably, damage to human health due to air pollution is the most economically expensive element. Small and Kazimi (12) found that particulate matter is the primary cause of mortality and morbidity.

The social cost of pollution depends on highly localized intake and health effects. There remains uncertainty about the operating characteristics of vehicles which minimize pollution, as this depends very much 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.

If travelers took alternative routes with reduced pollution generation or intake (exposure), the economic measure of environmental externalities of travel would be lower (13, 14). The full private or internal costs depend on the relative value of reduced pollution intake vs. increased travel time and distance. The full external costs depends on the value of reduced pollution emissions and

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[1] 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 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 (3, 4, 5). Thus, even with electrification, automobile pollution will not disappear.

[2] Recent health-effects research highlights the potential importance of very small particles of which vehicles are a major contributor to emissions and exposures. Ultrafine particles (UFP), PM with diameter less then 0.1μm, have drawn increasing research interest because they are:

1. more toxic to lab animals (6, 7),
2. harder to remove by the lung's macrophage clearance mechanism (8, 9), and
3. able to enter the circulatory system and travel to the heart, brain, and other organs (10).

To date, no criteria pollutant standards have been established for UFPs, and estimates are not produced by standard approaches like the EPA MOVES model. Future research should aim to incorporate UFPs in the kind of analysis presented herein.

increased total travel costs. The full costs combine the internal and external costs.

Some pollution effects would be larger due to increased travel distance or different performance characteristics, so designing such routes requires great care. We find traffic routing patterns which minimize the costs of air pollution emissions and exposure. These Environmentally User Optimal (EUO), considering exposure, and Environmentally System Optimal (ESO), considering emissions, traffic route assignments will aim to find routes, hereafter called *greenest paths*, that minimize intake or emissions respectively for internal or external cost versions, subject to travelers engaging in the same sets of activities at the same location.[3]

This study first measures the internal and external emission cost for each link segment on the road network based on the EPA MOVES model and provide a link-based emission cost analysis. This paper estimates the average and incremental pollution produced by travelers along various routes. This paper then estimates the traveler pollution intake along various travel paths as a function of endogenous traffic levels.

The greenest path was found for all the OD pairs in the seven county Minneapolis - St. Paul (Twin Cities) Metro Area. These paths were then aggregated into an accessibility measure. The resulting accessibility measures are compared with traditional measures (travel time based accessibility). We then analyze the accessibility loss of using the greenest path, which indicates the penalties of it to pursue the minimum emission cost expressed by accessibility. Moreover, we also estimate traffic that would take the greenest path for the actual OD pairs in Twin Cities, if that were the selected path for individual travelers.

The data, introduction of MOVES, methodology, accessibility measurement and conclusion of this research are shown in sections 3-7 respectively.

DATA

Several sources of data used.

- **TomTom Data**

  Speed and road network data were acquired by the research team from the Metropolitan Council, which has licensed the data from TomTom. The speed data were aggregated and processed based on millions of GPS logging and navigation devices (15). The speed data were categorized by road classification, time period, and speed percentile. Depending on 8 Functional Roadway Classifications (FRC), speed data were separated into 4 groups, in which the five categories representing the highest level roads, FRC0 to FRC4, were combined as one. This analysis uses the morning peak period travel times and the 50th percentile (median) speed on each link for shortest path estimation. The road network, a GIS shapefile that contains the geographic information of each link in the Twin Cities, was joined with the speed data, and were used as an input of MOVES to estimate emissions and to search the greenest path and the shortest travel time path by joining the emission or time cost with the road network.

- **2010 Transportation Analysis Zone (TAZ) system**

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[3] We recognize that not all intake is equal, and someone who breathes in 10 units of pollution may be more than 10 times worse off than someone who breathes in a unit of pollution, but we anticipate that the existing research cannot fully establish these nonlinear effects in the context we describe given the available data about existing health status.

The Transportation Analysis Zone (TAZ) system in Twin Cities was developed by the Metropolitan Council. This data is a polygon shapefile that shows the 2010 TAZ boundaries, aggregations, and the employment and household information for each TAZ (16). The features in the seven county Metro area were selected and the centroid of each polygon was extracted as the origin and destination for accessibility measurement. Its employment data were used to express the number of jobs in each TAZ.

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

  The Longitudinal Employment Household Dynamics (LEHD) Origin-Destination Employment Statistics dataset (LODES7.0) was acquired from the United States Census Bureau (17). The data contains tables of Workplace Area Characteristics (WAC), Residence Area Characteristics (RAC) and Origin and Destination Census blocks for each worker. LODES data was used to estimate the work trip flows on link segments based on the definition of betweenness with the assumption that all workers in the dataset would select the greenest path or the shortest travel time path.

- **Pavement Condition Data**

  Pavement condition data was collected by the research team from Minnesota Department of Transportation (MNDOT). It includes the pavement quality indicator (PQI), ride quality index (RQI), surface rating (SR), and, most relevant for our analysis, truck percentage (P) 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. Pavement condition data of the Seven County Metropolitan area of Twin Cities were selected and the truck percentage (P) was used to measure the link type source, which is an important input of MOVES.

- **AADT**

  An estimate of Annual Average Daily Traffic (AADT) from MnDOT, which reports AADT from 1992 to 2014. Data from 2007-2014 from the Twin Cities was joined with road network AADT was used as an input of MOVES as well.

POLLUTION ESTIMATION

The Motor Vehicle Emission Simulator (MOVES), developed by United States Environmental Protection Agency (18), is a modeling system that is widely used to estimate air pollutants, greenhouse gases, and air toxics at the level of nation, county, or project. To estimate the air pollutants for each link segment on the scale of network in the metropolitan area, the project level of simulation was conducted for each county in the Twin Cities. The inputs, such as meteorology and fuel type, vary across counties. The results are subsequently combined for the whole road network. Most of the importers for the simulations were set as the defaults specific to time and location except the tables for links and link source types.

- **Links**

  The link table defines the individual roadway links containing the properties as segment length, traffic flow, average speed and road grade. Segment length was directly measured based on the shapefile of the road network. Traffic flow, representing the units of vehicles per hour, was extracted from the AADT data and a morning peak hour (7AM-9AM) volume ratio of 6.09 (The number is a average ratio of morning peak hour flow to AADT based on the data from MnDOT's IRIS traffic database for the Twin Cities (19)).The average speed for each link was set as the 50th percentile speed in the morning peak hour of the speed data. The road grade for all the links were set as 0, which could be improved with Digital Elevation Model Data.

- **Link Source Type**

  Link source type describes the fraction of the link traffic flow that is represented by each vehicle type (source type). There is no available link source type data that could be directly used for each link segment on the Twin Cities road network. Hence, we estimated the vehicle type fraction based on truck percentage P. For highway link segments, P was collected from the pavement condition data, which covers different types of trucks, single unit trucks, buses, combination trucks. Combining the vehicle source type defined in MOVES, the setting of the vehicle type fraction for highway link segments shows as Table 1. The truck percentages of other link segments were estimated based on the regression of highway truck percentage P on AADT ranges, which is shown in Table 2 (20). And the fraction settings followed the rules in Table 1 based on the estimated P as well.

TABLE 1 : Vehicle Type Fraction Setting for Highway Link Segment

MnDOT use type	Avg Percentage	MOVES use type	Value
Autos, pickups	1-P	21.Passenger Cars	0.698*(1-P)
		31.Passenger Truck	0.292*(1-P)
		11.Motorcycle	0.010*(1-P)
Buses, Trucks w/ Trailers	0.207*P	41. Intercity Bus	0.207*P/3
		42. Transit Bus	0.207*P/3
		43. School Bus	0.207*P/3
Single Unit Truck (SU)	0.505*P	51. Refuse Truck	0.505*P/3
		52. Single-Unit Short-Haul Truck	0.505*P/3
		53. Single-Unit Long-Haul Truck	0.505*P/3
Combination Truck (TST)	0.288*P	61. Combination Short-Haul Truck	0.288*P/2
		62. Combination Long-Haul Truck	0.288*P/2

[1] The fractions of Buses (0.207), Single Unit Truck (0.505), and Combination Trucks (0.288) were based on average statewide vehicle classification (20).

[2] The fractions of passenger cars (0.698), passenger trucks (0.292) and motorcycle (0.001) were based on the MnDOT Procedure Manual for Forecasting Traffic on Minnesota's Highway Systems (21).

TABLE 2 : Truck Percentage Estimation Based on AADT Range

Variables		Estimate	Std. Error	Sign
Intercept		10.4168	0.251	***
AADT Range	400-1499	0.928	0.2677	***
	1500–7000	-1.1968	0.261	***
	>7000	-2.4428	0.2618	***
R^2		0.049		

METHODOLOGY

Internal Emission Cost Estimation

The internal emission cost for each traveler is defined as the health damage cost borne due to pollution intake during trips, which highly depends on the concentration of pollutants, travelers' breathing rate, exposure time and unit damage cost of pollutants (22).

$$Q_{I,p} = \int_0^T B_r * C_p(t)\, dt \quad (1)$$

$$E_{c,I} = \sum_p Q_{I,p} * u_{I,p} \quad (2)$$

Where:

$Q_{I,p}$ stands for the quantity of intake-emission of pollutant p,

$E_{c,I}$ stands for the internal emission cost,

$C_p(t)$ stands for the concentration of pollutant p, which varies with the time,

T stands for the total exposure time,

B_r stands for the breathing rate,

$u_{I,p}$ stands for the unit intake damage cost of pollutant p.

A link-based intake emission cost estimation ($E_{c,I,i}$) considers the pollution concentration ($C_{p,i}$) and travel time (T_i) needed for a specific link segment (i).

- **Concentration by Link Segment**

  Generally, concentration of pollutants could be expressed as air pollutant part per million by volume ($ppmv$) or milligrams of pollutant per cubic meter of air (mg/m^3). On the basis of the quantity of emissions from MOVES, concentration could be measured by air pollution dispersion models (23).

  Notably, concentrations of nodes (or intersections) on link segments are much higher than those of edges (or links) since a node could connect many edges and the vehicles passing through it from different directions affect its concentration. Hence, to measure the concentration, each link was divided into three parts, including one part representing the link exclusive of the junction, and two parts representing buffers of the end junctions, as shown in Figure 1.

  A buffer was set for each node referring to its boundary (red circles in Figure 1). It was assumed that, in a windless scenario, the concentration of a node equals the sum of the concentrations of all edges passing through it, which could be expressed as,

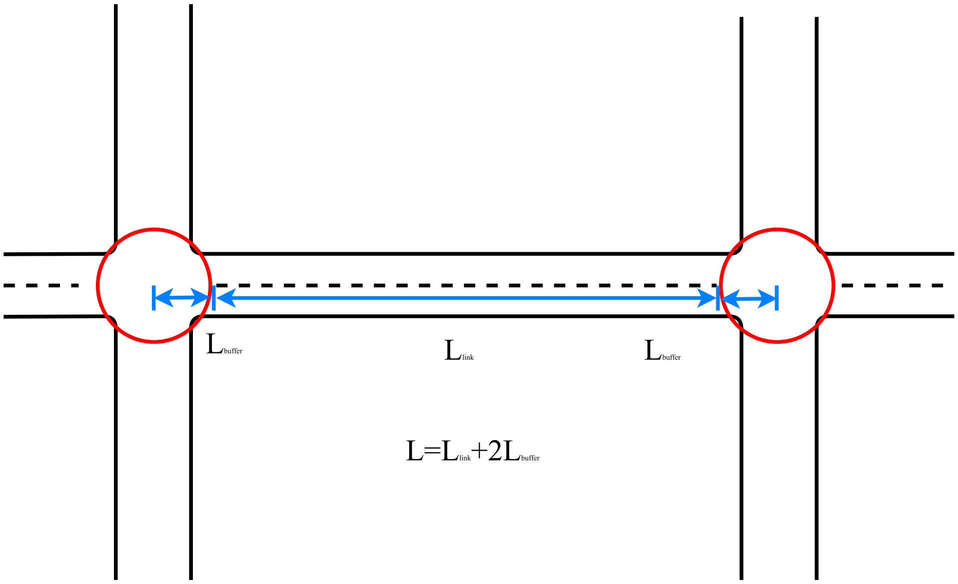


FIGURE 1 : Link-based Concentration Measurement

$$C_{p,n_i} = \sum_{k \in n_i} C_{p,e_k} \tag{3}$$

Where:
C_{p,n_i} stands for the concentration of pollutant p on a node n_i ,
C_{p,e_k} stands for the concentration of pollutant p on link k, which connects with node n_i.

The concentration of an edge was assumed to be only affected by the vehicles in its own direction. The concentration of a buffer considers traffic on the link and in the relevant crossing direction.

- **Air Pollution Dispersion Model**

The windless air pollution dispersion model, in which the speed of wind is 0.4m/s or less, could be expressed as (24),

$$C_{p,i} = \frac{2q_{p,i}}{(2\pi)^{3/2}} \int_{l_1}^{l_2} \frac{1}{\beta^{r^2}} dl \tag{4}$$

Where:
$q_{p,i}$ stands for source strength of pollutant p, which is determined by its emission factor $E_{f,p,i}$ and vehicle fraction s_i,
r stands for the distance from the observed point,
β_1 is a coefficient.

The source strength is calculated by (23)

$$q_{p,i} = \frac{\sum s_i E_{f,p,i}}{3600} \tag{5}$$

$$E_{f,p,i} = \frac{\sum_k Q_{E,p,i,k}}{V_{KT,i}} \tag{6}$$

where:
$Q_{E,p,i,k}$ stands for the quantity of pollutant p emitted by vehicle k on link segment i;
$\sum_k Q_{E,p,i,k}$ stands for the total emission of pollutant p on link segment i considering all different types of vehicles
$V_{KT,i}$ stands for the activities (vehicle-kilometer traveled) associated with pollutions on link segment i.

- **Unit Intake Damage Cost**
  As the key cost component of travel, emission is more likely to be categorized into external cost, which results in the lack of assessment of unit intake damage cost. Considering the correlations between the emitted and breathed in emissions, the unit intake damage cost could be estimated by,

$$u_{I,p} = \frac{u_{E,p}}{F_I} \tag{7}$$

Where:
$u_{E,p}$ stands for the unit emission cost of pollutant p;
F_I stands for the intake fraction, which is the fraction of emissions that are taken in by people (25).

National Highway Traffic Safety Administration (26) estimated the unit emission cost ($u_{E,p}$), which shows the values of reductions in health damage costs per ton of emission of each pollutant that is avoided. Assuming that the intake fraction is 10 per million (25), the unit cost of both intake-emission and emission of each pollutant is showing in Table 3.

TABLE 3 : Unit Cost of Emission Intake and Emissions

	Unit Intake-Emission Cost (\$/g)	Unit Emission Cost (\$/ton)
Nitrogen oxides	670	6,700
Particulate matter	30,650	306,500
Sulfur dioxide	3,960	39,600
Carbon dioxide	0	22

[1] CO_2 has external effects on climate change, but no internal effect on health damage,

[2] Unit emission cost of CO_2 varies with different years, \$22 is the value of 2010.

External Emission Cost Estimation

The external emission cost from the perspective of travelers refers to the health damage cost from emitted pollutants imposing on others and climate change cost due to CO_2.

Two types of external emission cost would be considered, average external emission cost ($E_{C,E,Avg}$) and marginal external emission cost ($E_{C,E,Mar}$), in which the marginal cost represent the increased external emission cost due to an additional vehicle on the road.

$$E_{C,E,Total} = \sum_{p} Q_{E,p} * u_{E,p} \tag{8}$$

$$E_{C,E,Avg} = \frac{E_{C,E,Total_{Auto}}}{P_{Auto}} \tag{9}$$

$$E_{C,E,Mar} = \frac{\partial E_{C,E,Total}}{\partial P_{Auto}} \tag{10}$$

Where:

$E_{C,E,Total}$ stands for the total external emission cost, $E_{C,E,Total_{Auto}}$ is specific to the external emission cost generated by auto;

P stands for the population, P_{Auto} refers to the population of auto;

$Q_{E,p}$ stands for the quantity of emission for pollutant p;

$u_{E,p}$ stands for the unit emission cost of pollutant p;

In practice, to reduce simulation noise, we measured the incremental emission cost instead of the marginal cost by simulating 100 more vehicles than observed, calculating the increase of emission cost, and dividing by 100. The expression of incremental external emission cost could be written as:

$$E_{C,E,Inc} = \frac{\Delta E_{C,E,Total}}{\Delta P_{Auto}} \tag{11}$$

The Greenest Path

The greenest path, the route with the lowest emission cost, was proposed as a new rule of traffic route assignment to minimize the emission cost. From both the internal and external cost versions, greenest (internal) Path ($P_{g,i}$) pursues an Environmentally User Optimal (EUO) to minimize the on-road intake-emission. A complement to this, greenest (external) Path ($P_{g,e}$) pursues an Environmentally System Optimal (ESO) considering the emissions.

For a given OD pair, the greenest path could be expressed as,

$$E_{C,OD,k} = \sum_{i \in P_{OD,k}} E_{C,i} \tag{12}$$

$$E_{C,OD} = min(E_{C,OD,k}) \tag{13}$$

Where:

$E_{C,i}$ stands for the emission cost of link segment i. In this case, it could be the internal or external (average/incremental) emission cost,

$P_{OD,k}$ stands for the k^{th} path between origin O and destination D;

$E_{C,OD,k}$ stands for the emission cost of the k^{th} path between O and D;
$E_{C,OD}$ stands for the minimum emission cost between O and D.

The route with an emission cost of $E_{C,OD}$ is the greenest path as we defined.

Betweenness

Betweenness, as a network structure measure, was defined by Freeman (27) that quantifies the times of a link on a roadway network that is passed by particular paths between OD pairs. In our study, these paths refer to either the greenest path or the shortest travel time path. Its expression is shown as,

$$B_i = \frac{q_i}{Q} \tag{14}$$

Where:

B_i stands for the betweenness of link segment i,
q_i stands for the number of trips passing through i by using the shortest path,
Q stands for the total number of trips.

Depending on the OD table of LEHD data, the total number of trips (Q) in Twin Cities (both origin and destination are located in the Seven County Metro area) is fixed for both the greenest path and the shortest travel time path. The changes of q_i for using the greenest path ($q_{G,i}$)and the shortest travel time path ($q_{T,i}$) are the parts that we are more concerned about, which we called the work trip flows.

Cumulative Opportunity Measure

Accessibility measures the ease of reaching activities (28). It combines the correlations between the cost and benefit of travel into a single metric, which represents the strengths and weaknesses of the interactions of transport network and land use, that makes accessibility a reliable tool for comparing the effectiveness of proposed land-use and transport network scenarios in planning projects (29, 30).

Various methods have been proposed to measure accessibility. A very basic one is the Cumulative Opportunity Measure that counts the number of opportunities that can be reached within a given threshold (31, 32). Comparing with other measures, Gravity-based Measure (28, 33), Utility-Based Measure (34), e.g., Cumulative Opportunity Measure is more applicable on the metropolitan area scale to a more straightforward cost function. This measure does generate artificial distinctions among destinations based on its binary cost function (35, 36), but a time-weighted accessibility, which combines the cost impedance with the measure, mitigates the distinctions (30, 37).

Most commonly, accessibility metrics have been analyzed from the perspective of the mean or expected travel time by considering the time cost of travel (38). In this study, accessibility measurement from the aspects of emission cost (internal and external) would be focused on.

The cumulative opportunity measure for job accessibility is typically expressed as:

$$A_O = \sum_D O_D f(W_{OD}) \tag{15}$$

$$f(TC_{OD}) = \begin{cases} 1 & if C_{OD} \leq W \\ 0 & if C_{OD} > W \end{cases} \tag{16}$$

Where:

A_O stands for the job accessibility of origin O,

O_D stands for the number of jobs in destination D,

C_{OD} stands for the travel costs between origin O and destination D. From the perspective of emission cost, C_{OD} refers to the $E_{C,OD}$ (minimum emission cost). While from the perspective of time cost, it refers to the $T_{C,OD}$ (minimum time cost),

W represents travelers' willingness-to-pay for corresponding travel costs (thresholds).

Moreover, accessibility loss was proposed to express the penalties to pursue the optimal path from one aspect rather than another in terms of the reduction of reachable destinations with the same willingness-to-pay. For instance, the accessibility loss of using the greenest path from the perspective of time cost (A_{C_E,O,W_T}) is calculated by,

$$A_{C_E,O,W_T} = A_{O,T,W_T} - A_{O,E,W_T} \tag{17}$$

Where:

A_{O,T,W_T} stands for the accessibility of origin O based on the shortest travel time path within a time threshold of W_T,

A_{O,E,W_T} stands for that of using the greenest path within the same time threshold.

RESULTS

Internal vs. External Emission Cost

The mean value of internal emission cost of link segments in the Twin Cities is approximately \$0.0025. Most (90%) link segments have an internal emission cost less than \$0.010. External emission costs are much higher than internal costs, the mean value of the external emission average cost is \$0.0064 and incremental cost is around \$0.0066 (It is reasonable that the incremental external emission cost is slightly larger than the average one since congestion affects the incremental emission cost more significantly). About 90% of link segments have an external emission cost below \$0.015. Figure 2 shows the patterns of on-road emission cost per kilometer traveled.

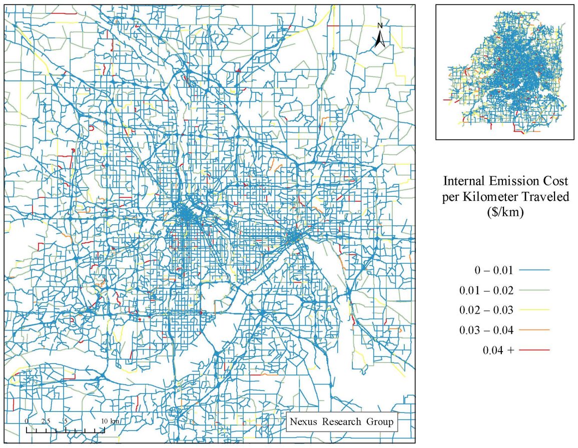
Figure 2 indicates a similar pattern, the external emission cost is higher than the internal one. It implies that the emission costs travelers impose on others are greater than those borne by themselves, which is to be expected, as the external unit costs include damage to non-travelers, while the internal costs here exclude pollution costs from non-transport sources.

Work Trip Flow Estimation

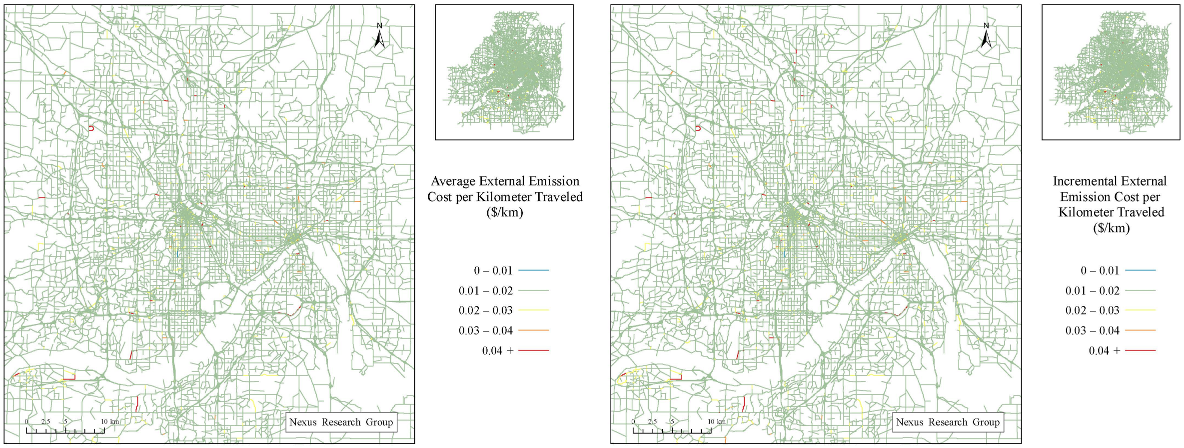
Figure 3 shows the work trip flow if all workers in the LODES data followed the greenest path between home and work, and the resulting pollution were unchanged (i.e. this is a partial equilibrium analysis, we are not recomputing pollution costs based on the resulting traffic flows).

Generally, using the greenest internal path (Figure 3a), highways carry more traffic than local roads, which is consistent with shortest path analysis (and observed data), since they are faster, travelers have less exposure to pollution.

Considering the optimization of external emission cost, Figure 3b and 3c shows the work trip flows based on the greenest (external) path considering average and incremental cost respectively. Generally for greenest external path, the routes which are selected are more direct and thus have shorter distances over which to emit pollutants. These differ from Figure 3a in that the trips are more evenly distributed on the highway network except some critical links or interchanges, such as the interchange of I-94 and I-35W, considering the external emission cost.



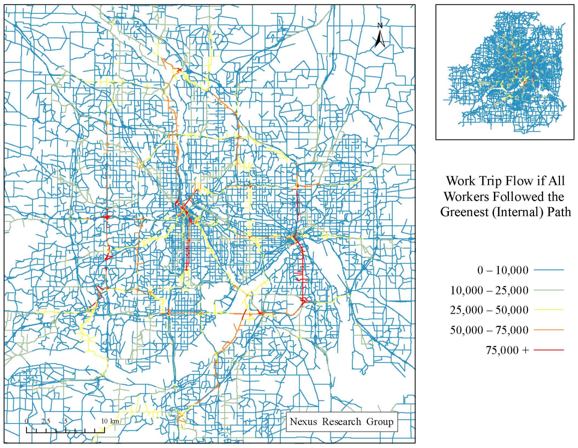
(a) Internal Emission Cost



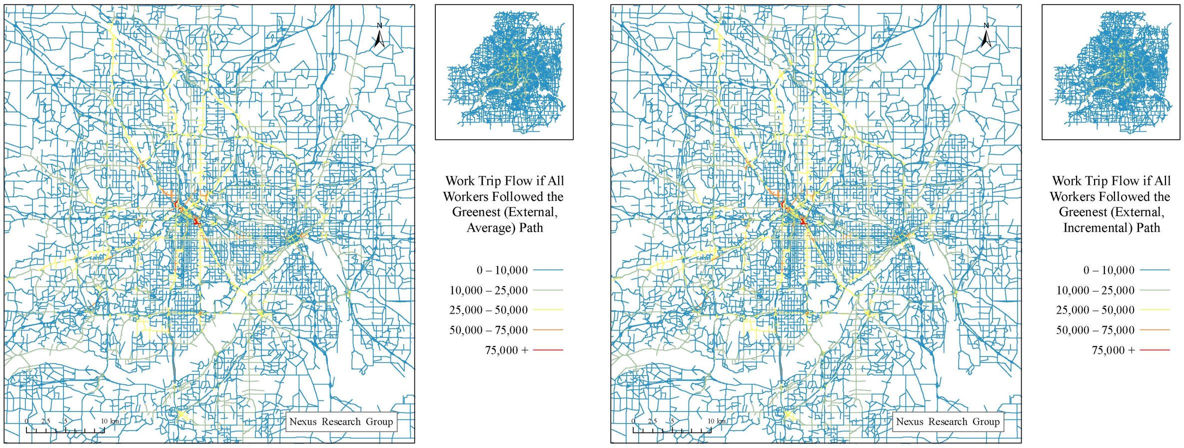
(b) External (Average) Emission Cost

(c) External (Incremental) Emission Cost

FIGURE 2 : Emission Cost Per Kilometer Traveled



(a) Greenest (Internal) Path



(b) Greenest (External, Average) Path (c) Greenest (External, Incremental) Path

FIGURE 3 : Work Trip Flows

The work trip flows based on the average and incremental greenest (external) path do not have critical differences, consistent with the results shown in Figure 2

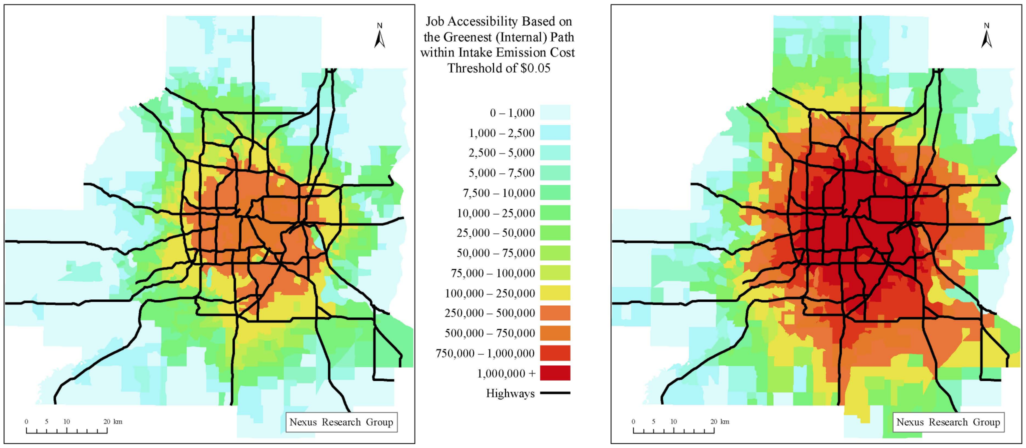
Accessibility Measurement

Greenest (Internal) Path

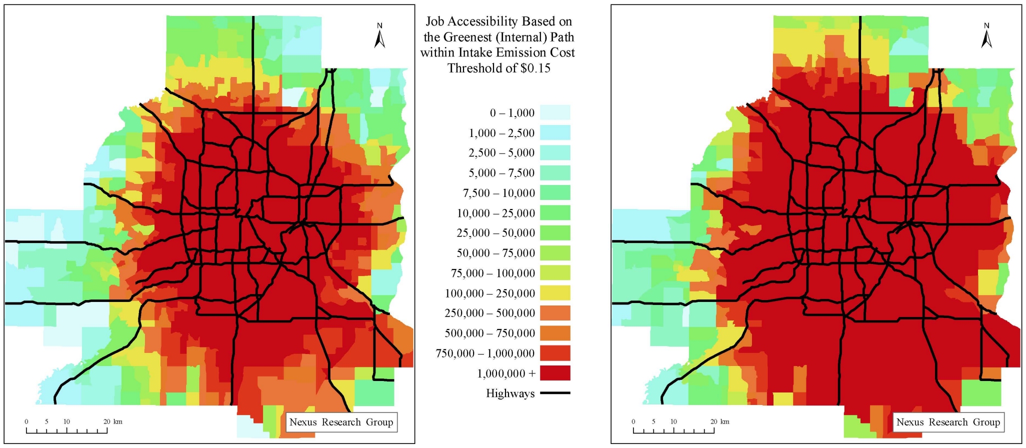
Job accessibility based on the greenest (internal) path are shown in Figure 4. The intake emission cost threshold (W) changes from \$0.05 to \$0.30.

The basic distribution pattern of job accessibility in the realm of internal emission cost is expected that the zones with higher job accessibility are centered on downtown Minneapolis (red color zones). In each figure, the accessibility declines gradually with the increase of distance to the downtown area, and the exurban area has the lowest job accessibility.

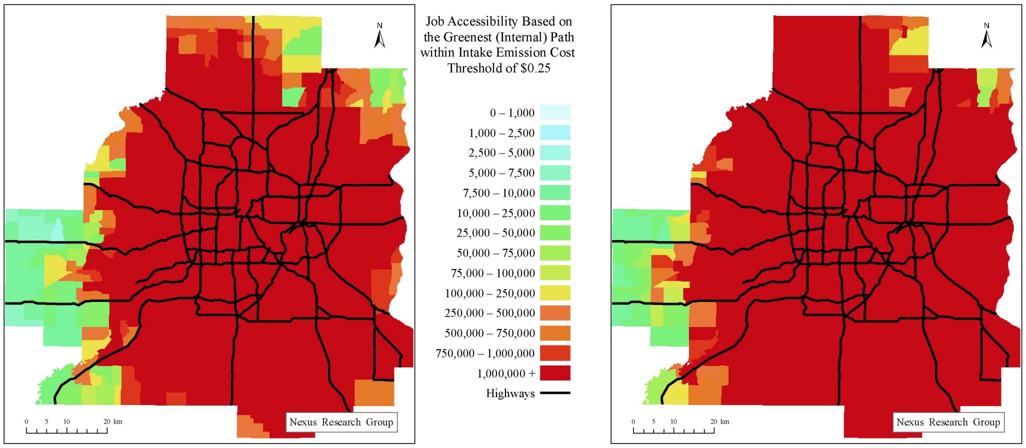
The major reason for such a pattern is that job opportunities are centered on downtown Minneapolis in the Twin Cities region. Residents living in suburban and exurban area require more time to reach the same number of job opportunities, which represents more exposure time for intake emissions.



(a) $0.05 (b) $0.10



(c) $0.15 (d) $0.20



(e) $0.25 (f) $0.30

FIGURE 4 : Job Accessibility Based on the Greenest (Internal) Path with Different Intake-emission Cost Thresholds from $0.05 to $0.30

From Figure 4a to 4f, job accessibility increases significantly due to a higher level of cost threshold. Within \$0.30 of internal emission cost, most of the region's residents can reach most job opportunities. It reflects the effects of travelers' willingness-to-pay for intake-emission on accessibility.

Greenest (External) Path

Using the greenest (external) path, the job accessibility within different cost thresholds (again from \$0.05 to \$0.30) are displayed in Figure 5 and 6.

As expected, for both average and incremental external emission cost, accessibilities are distributed as the similar pattern as Figure 4. However, within the same cost thresholds, the accessibilities are much lower when the greenest (external) path is pursued rather than the greenest (internal) path. Such a result corresponds with the emission cost assessment that the external emission cost is higher than the intake cost.

Comparing Figure 5 and 6, accessibility based on the average external emission cost is slightly larger than incremental cost. Figure 7 shows the differences directly. A clear ring of this difference is shown on each map in Figure 7. The radius of the ring increases along with a higher cost threshold.

Accessibility Difference Analysis

Figure 8 shows the accessibility loss of using the greenest (internal) path comparing to the traditional shortest travel time path.

Accessibility loss is higher in downtown Minneapolis with a lower willingness-to-pay for time cost. It indicates that using the greenest (internal) path affects job accessibility for the residents living close to the downtown area the most if they have a lower willingness-to-pay for time cost. The major reason is that residents living in or around downtown Minneapolis can reach more opportunities in less time. While using the greenest (internal) path extends their travel time, say more than 10 min, which results in a greater accessibility loss with a 10 min time threshold.

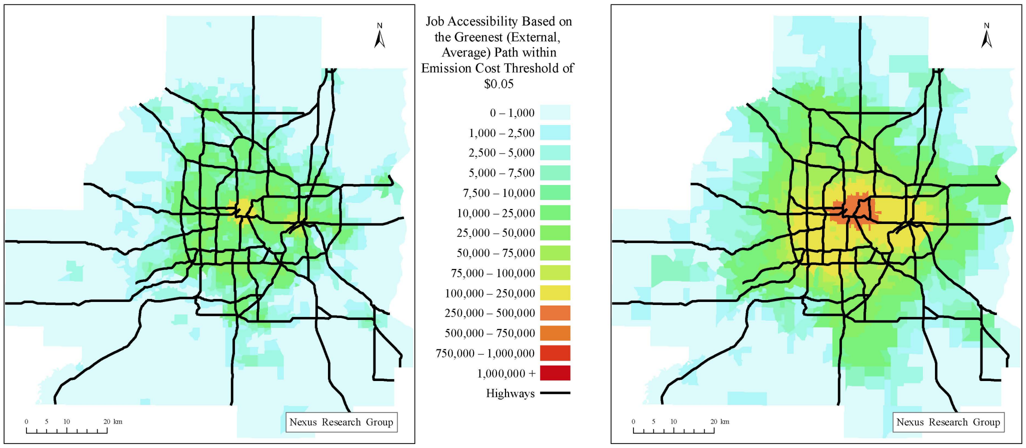
From Figure 8a to 8f, accessibility loss in the downtown area declines first with an increased time threshold as the greenest path is by definition not as efficient from a time-perspective as the shortest path, so jobs that were within 10 minutes on the shortest path are not within 10 minutes on the greenest (internal) path. As time thresholds increase, the exurban areas are more affected, as jobs that were within, say, 60 minutes of shortest path, are not within 60 minutes of greenest path.

CONCLUSION

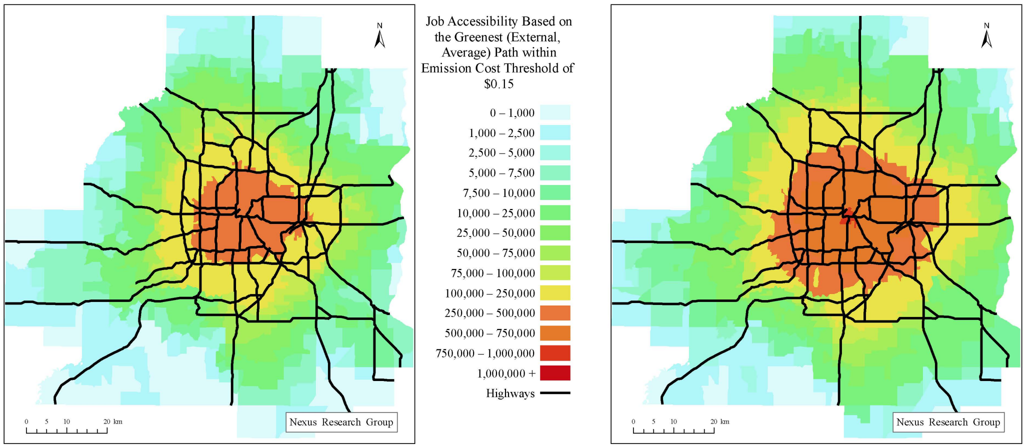
Generally, on-road emissions are categorized as external cost expressing the health damage cost from emitted pollutants imposed on others. However, as active agents in transportation system, travelers bear health damage costs due to pollution intake, which logically should be considered as an internal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

Referring to the traditional shortest travel time path, the greenest (internal/external) paths were proposed to estimate the minimum pollution exposure and emissions costs during traveling. The greenest path presents the optimal solution of route choices for travelers (internal) or society (external) from the perspective of pollution costs.

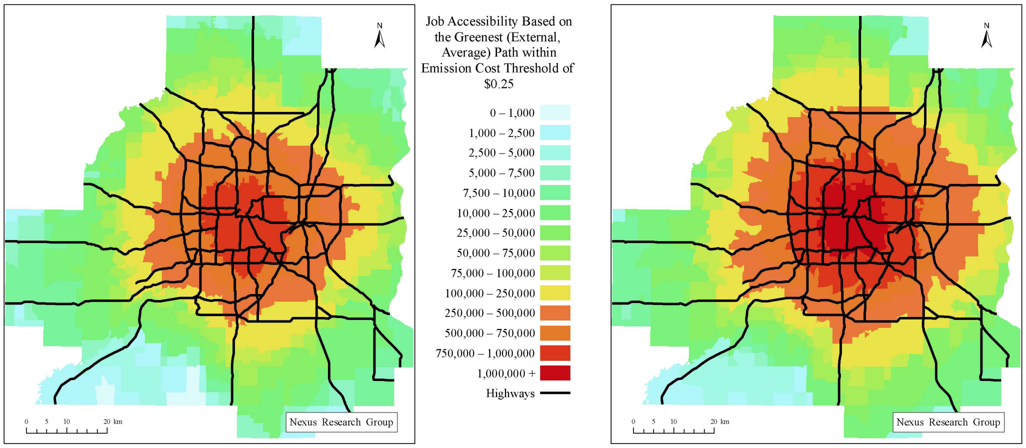
This study analyzed the internal and external emission cost on the scale of road network in the metropolitan area, and evaluated the job accessibility for the Minneapolis-St.Paul region in the realm of emission cost based on the greenest (internal or external) path.



(a) $0.05 (b) $0.10

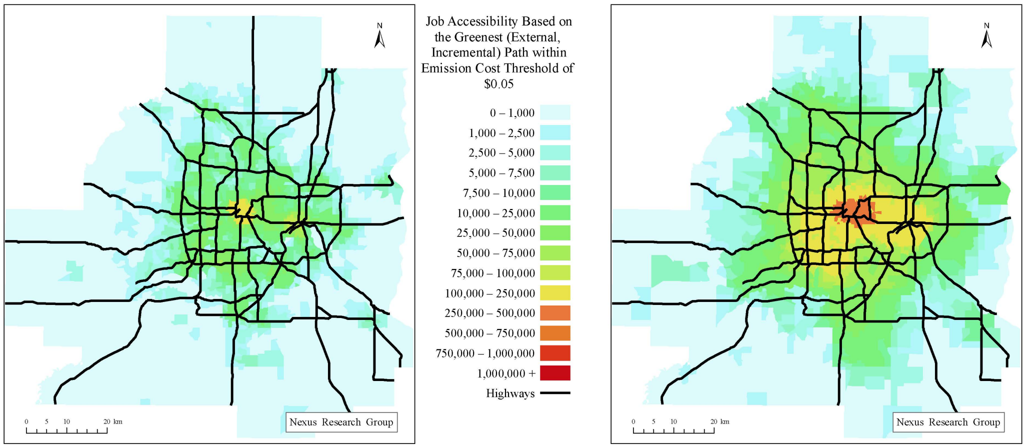


(c) $0.15 (d) $0.20

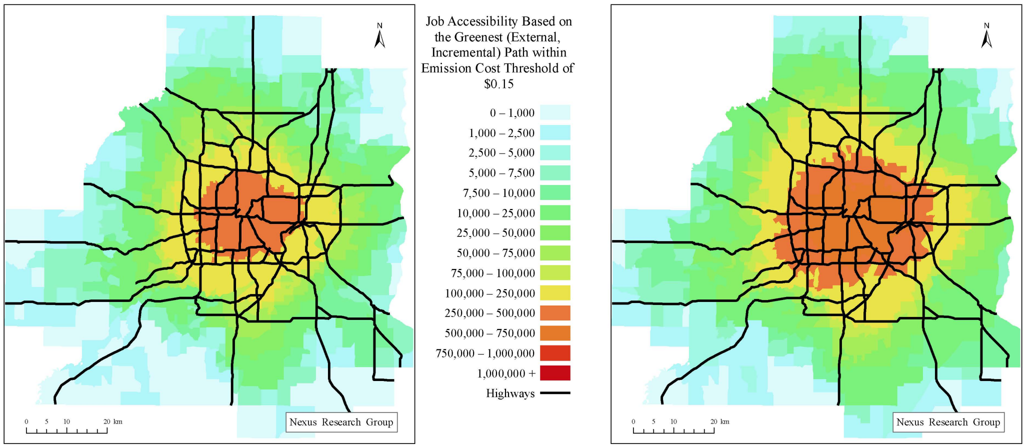


(e) $0.25 (f) $0.30

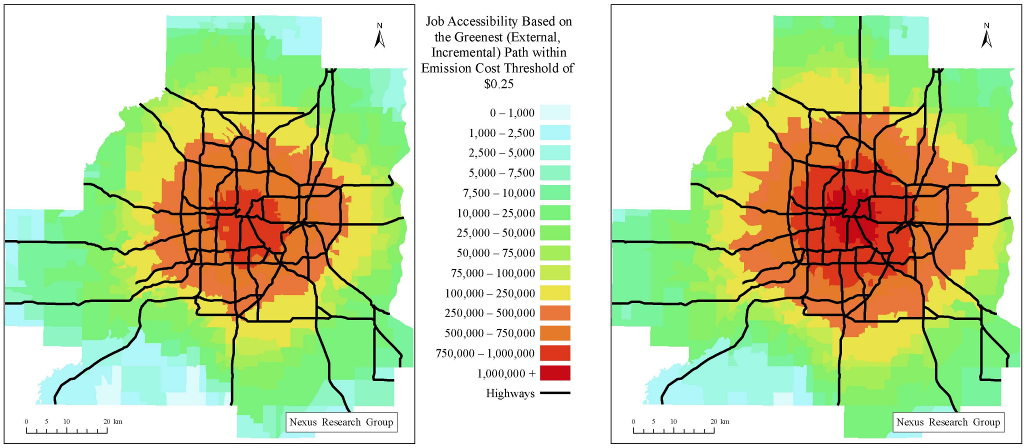
FIGURE 5 : Job Accessibility Based on the Greenest (External) Path (Average) with Cost Threshold from $0.05 to $0.30



(a) $0.05 (b) $0.10

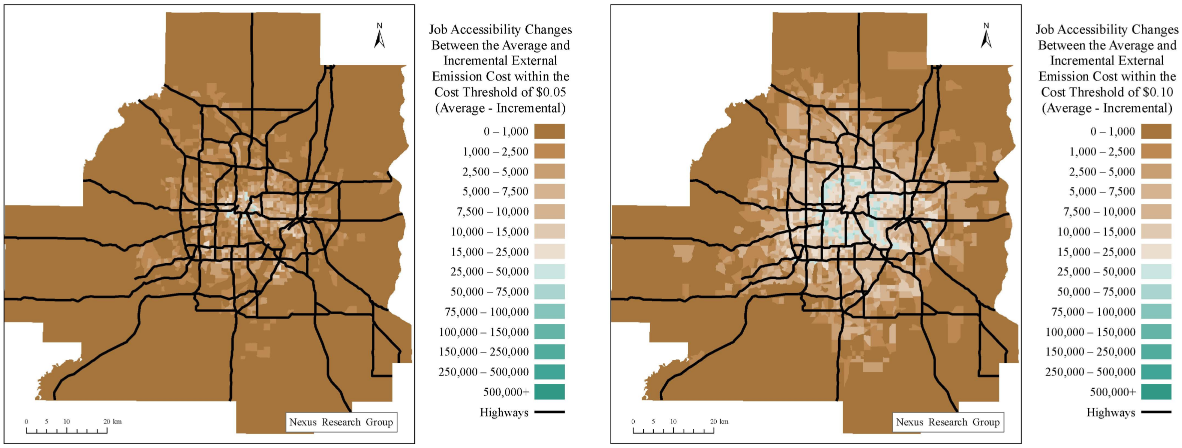


(c) $0.15 (d) $0.20



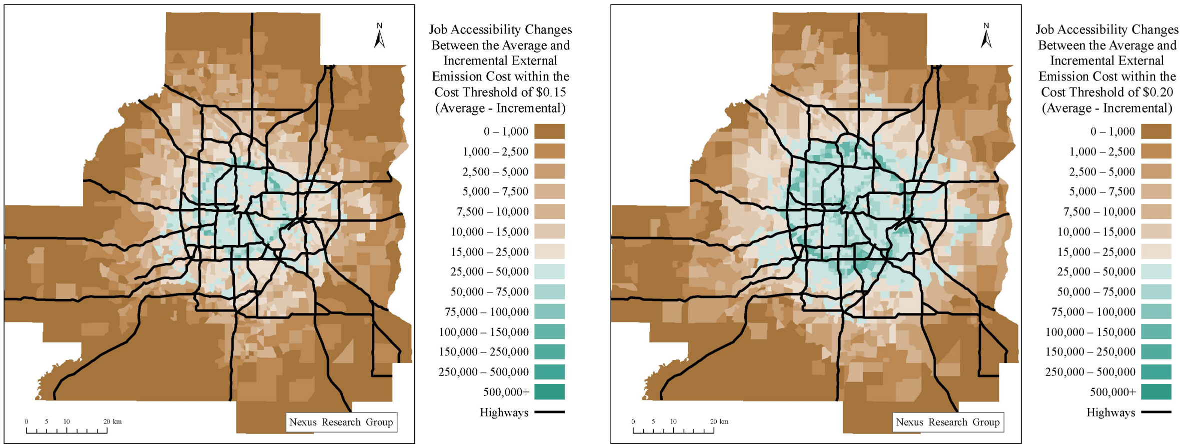
(e) $0.25 (f) $0.30

FIGURE 6 : Job Accessibility Based on the Greenest (External) Path (Incremental) with Cost Threshold from $0.05 to $0.30



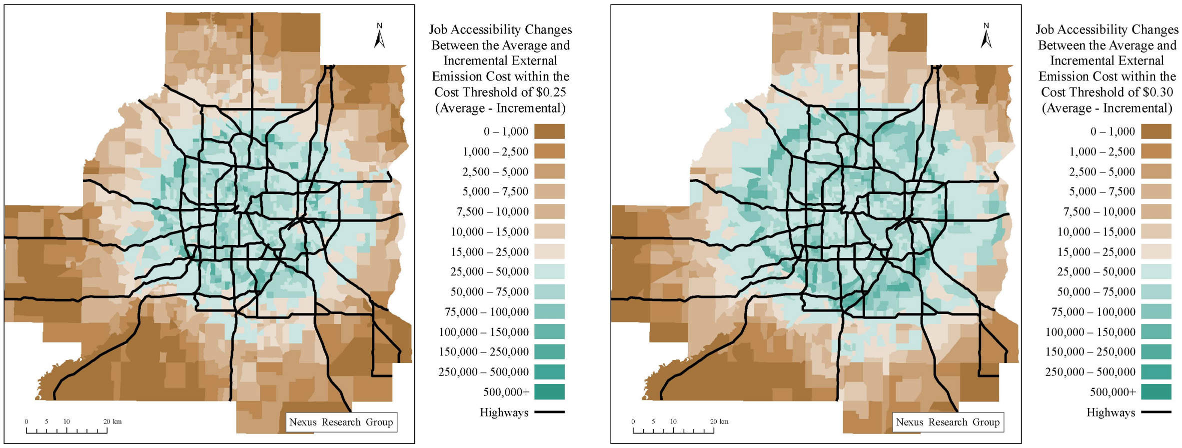
(a) \$0.05

(b) \$0.10



(c) \$0.15

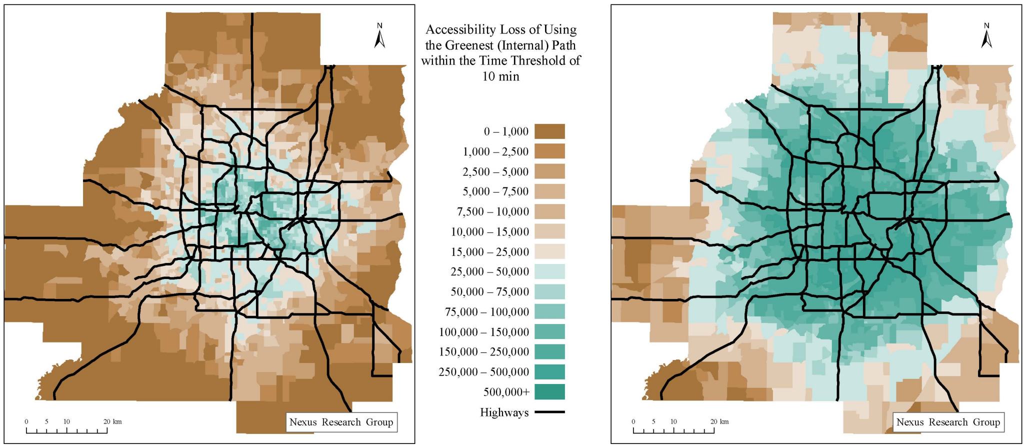
(d) \$0.20



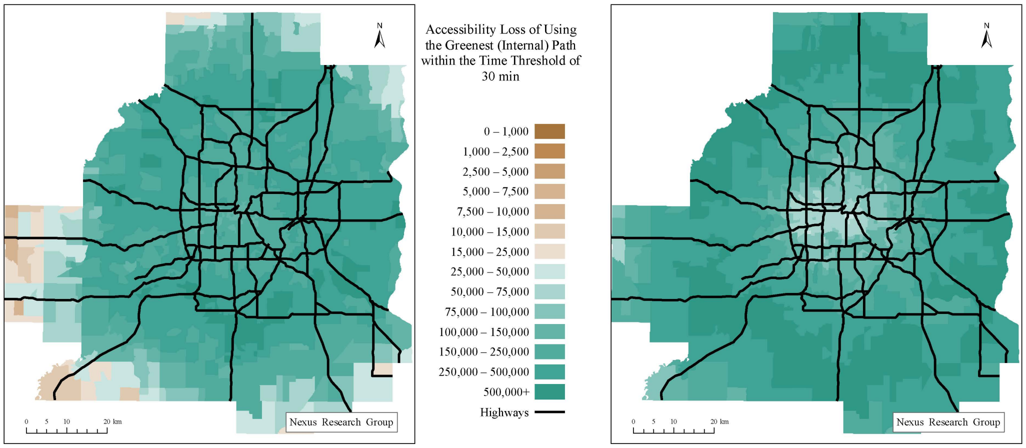
(e) \$0.25

(f) \$0.30

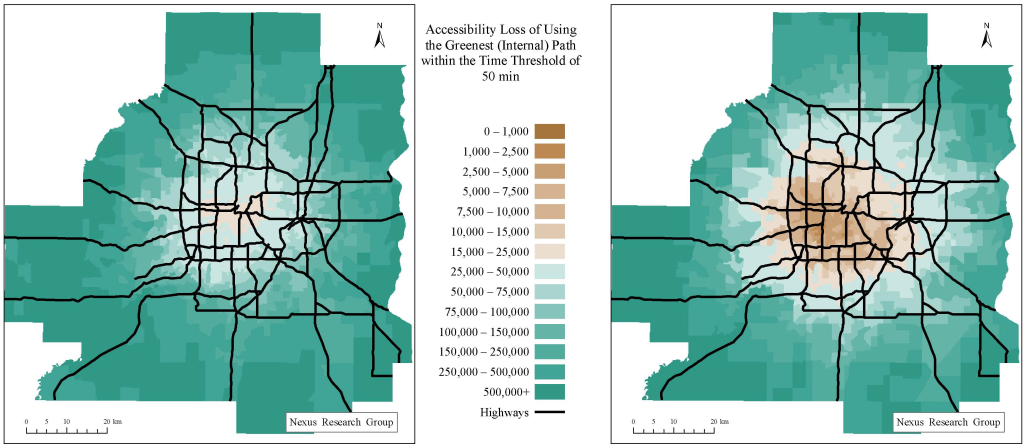
FIGURE 7 : Differences of Accessibility between the Average External Emission Cost and the Incremental External Emission Cost with Cost Threshold from \$0.05 to \$0.30



(a) 10min (b) 20min



(c) 30min (d) 40min



(e) 50min (f) 60min

FIGURE 8 : Accessibility Loss of Using the Greenest Path Comparing with the Shortest Path with Different Time Threshold from 10min to 60min

Depending on the cost analysis, basically, the emission cost travelers impose on others (external) is greater than that borne by themselves (internal). The average external emission cost is slightly lower than the incremental one.

The environmental cost accessibility metrics show similar patterns as traditional travel time based measures – downtown Minneapolis has a higher job accessibility. Accessibility decreases along with an increase of the distance to downtown. Exurban areas have the lowest job accessibility under all conditions. Emission cost threshold, for both internal and external costs, affects accessibility as a higher emission cost threshold results in a higher job accessibility overall.

Job accessibility based on the greenest (internal) path is much greater than that based on the greenest (external) path, which is consistent with emission cost analysis. Comparing externality measures, the accessibility based on the average emissions cost is slightly larger than incremental emissions cost, and their differences generate a clear ring, which represents a greater difference, on the maps. Using the greenest path illustrates a higher accessibility loss in downtown Minneapolis when there is a lower willingness-to-pay for time cost. It declines with the increase of time threshold and the accessibility compensation in the exurban area rises at the same time.

From a policy perspective, road pricing presents a family of potential mechanisms to encourage 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.

Future research should consider a full cost analysis of other key cost components of travel and evaluate the accessibility from the perspective of alternate cost components, time, safety, money, e.g.. Moreover, a full cost model should combine those elements together, including both internal and external cost, and measure the accessibility based on the lowest internal cost and external cost path. The accessibility by alternate traffic modes based on travel cost analysis will also be measured.

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