Link-based Full Cost Analysis of Travel

Mengying Cui
Center for Transportation Studies
University of Minnesota
cuixx242@umn.edu

David Levinson
Professor of Transport, School of Civil Engineering
The University of Sydney
david.levinson@sydney.edu.au

words + 3 tables × 250 words = 7451 words
September 13, 2018

ABSTRACT

This paper develops a link-based full cost model, which identifies the key cost components of travel, including both internal and external versions of cost, and gives a link-based cost estimate. The key cost components for travelers are categorized as time cost, emission cost, crash cost, user monetary cost, and infrastructure cost. Selecting the Minneapolis - St. Paul (Twin Cities) Metropolitan region as the study area, the estimates show that the average full cost of travel is \$0.68/veh-km, in which the time and user monetary costs account for approximately 85% of the total. Except for the infrastructure cost, highways are more cost-effective than other surface roadways considering all the other cost components, as well as the internal and full costs.

Keywords: Full cost, internal costs, external costs, double-counting

INTRODUCTION

Full cost combines internal plus external cost. The *internal cost* refers to what consumers pay directly for goods or services. Rational economic agents are often assumed to choose the lowest internal cost during decision-making (21). 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" (25). It is called a 'negative' externality if the impact is adverse. Negative externalities cause the full cost to exceed the internal cost, as Figure 1 shows. A social optimum including negative externalities has a higher price than one including only internal costs.

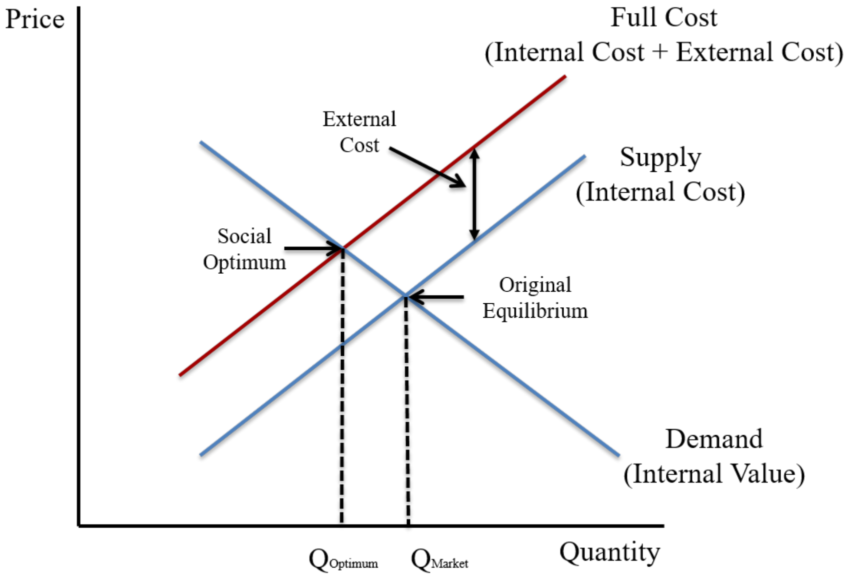


FIGURE 1 : Internal vs. External Cost (Source: Mankiw (25))

Full cost analysis emerged in transport in the 1990s, especially for highways (11, 14, 15, 21, 22). 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.

This paper develops a link-based full cost model for urban travel. It first identifies the key cost components of travel and distinguishes the internal and external versions of the costs (Section 2). Rules are then proposed to combine the internal and external costs for each cost component discussing the external cost internalization (Section 3) and to combine all cost components illustrating the cost transfers from one category to another (Section 4), in order to avoid the double-counting problem. Cost estimations are conducted next by cost component for the road network in the Twin

Cities metropolitan area (Section 5), as well as the total internal and full costs estimates following the rules (Section 6). We summarize the cost estimate results, discuss the potential applications of the link-based full cost analysis, and clarify the further research directions accordingly (Section 7).

INTERNAL VS. EXTERNAL TRAVEL COST

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 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) (21). Considering link properties, traffic and capacity, the marginal cost of travel time represents 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.Care needs to be taken to avoid double counting.

For crash costs, Jakob et al. (17) 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 (51) proposed the externality as an increased crash risk due to higher traffic flow, which implies a marginal cost of crashes (13). Jansson (18) 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 (13). Recognizing this is transferred to insurance costs is essential 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 (26). Notably, damage to human health due to air pollution is the most expensive element. Small and Kazimi (37) 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 (21). 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 user monetary cost, including fuel, vehicle ownership and maintenance, tolls and taxes and fares, and the like, could be totally internal for travelers (3).

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 (21). But other costs, like road wear and tear, when they are uncompensated for by user taxes, are still external to travelers.

TOTAL COST ANALYSIS: RULES FOR COMBINING INTERNAL AND EXTERNAL COSTS

The theory of total cost analysis provides rules for combining internal and external costs for each component addressing the double-counting problems it may have if internal and external costs are added. 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 2.

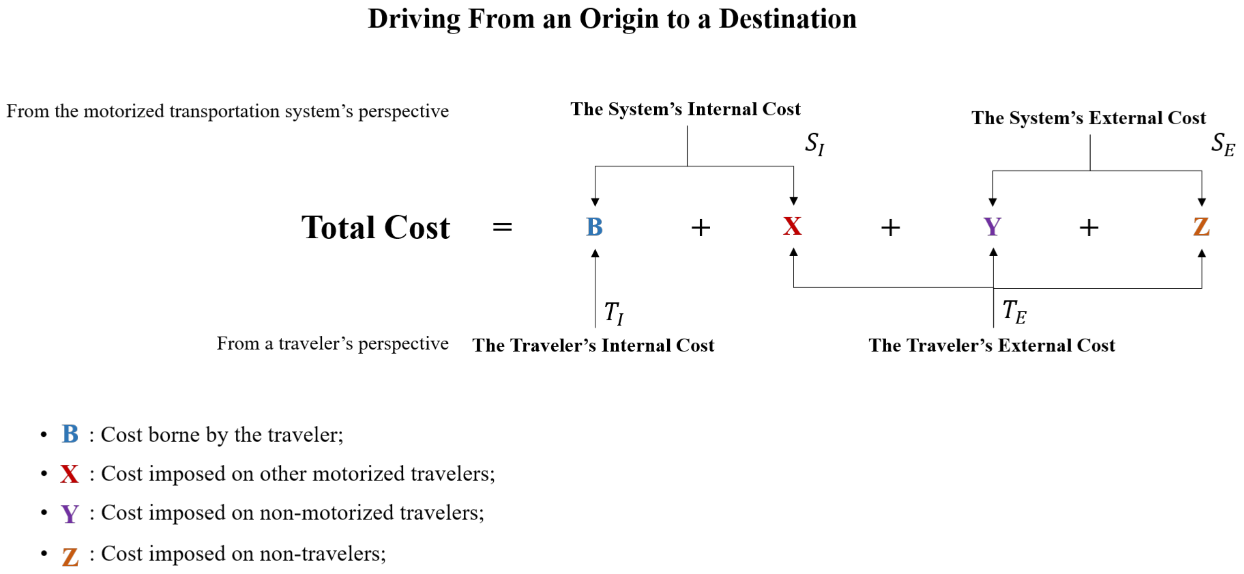


FIGURE 2 : Compositions of Total Cost

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).

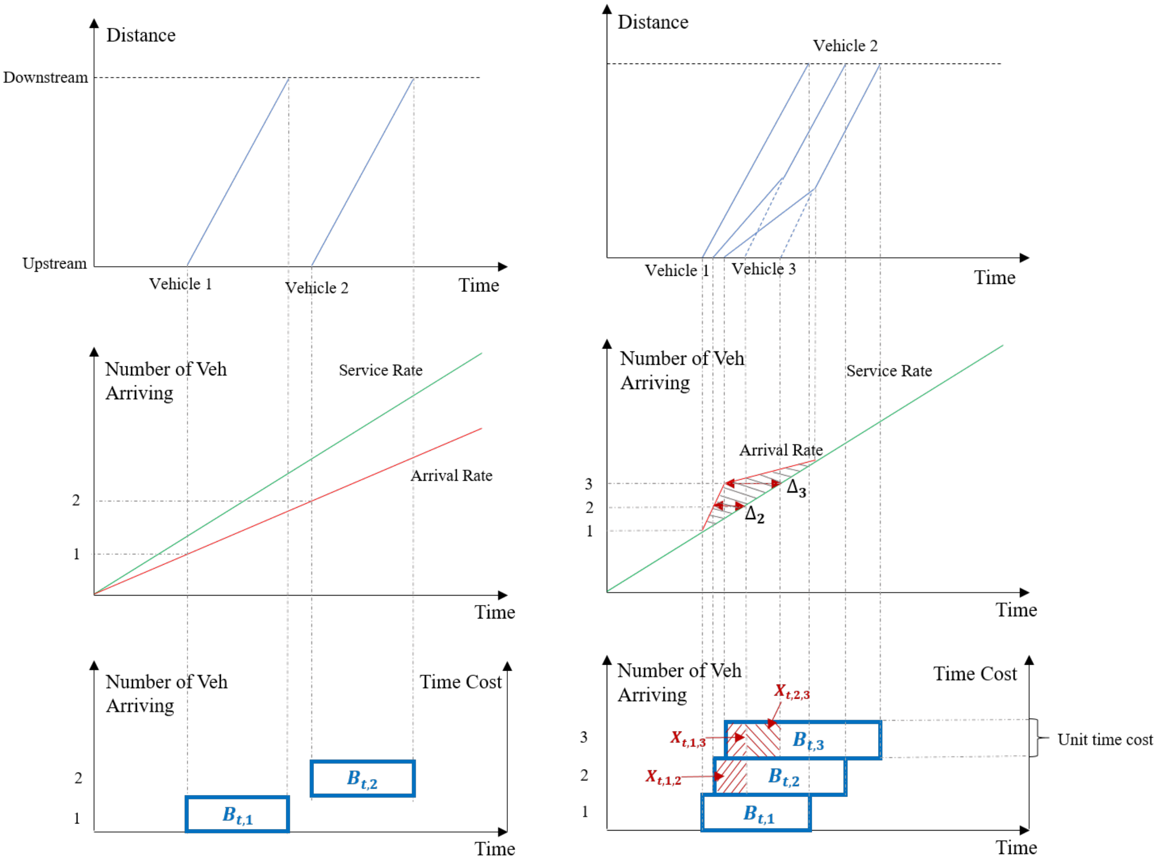
Those compositions of the total cost, however, cannot be added directly, as some parts of the external costs have been internalized based on the cost definitions. The following subsections introduce the factors that would generate the double-counting problems for each cost component of time, safety, and emission, respectively, for combining the internal and external costs. Theoretical diagrams decompose each of those cost component.

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 in the full cost analysis but strongly encourage future research in this area.

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

Figure 3 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.



(a) Two Vehicles with No Delay

(b) Three Vehicles with Former Vehicles Imposing Delay on the Latter Ones

FIGURE 3 : Time Cost Diagram: Internal vs. External

- Scenario 1: Two Vehicles with No Delay (Figure 3a)

  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 3a, assuming that the width of the boxes gives the unit time cost.

- Scenario 2: Three Vehicles with Former Vehicles Imposing Delays on the Latter Ones (Figure 3b)

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 3b, Δ_2 represents the delay of vehicle 2, which equals the length of the $X_{t,1,2}$ area, while Δ_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 3b. 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.

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.

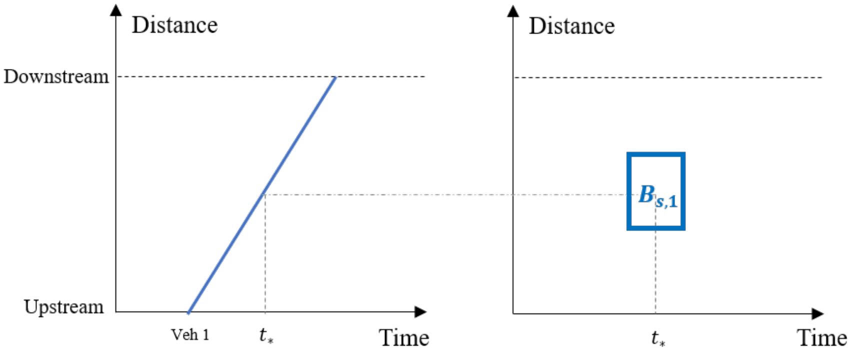
Figure 4 shows the theoretical diagram for an illustration of the total cost of crashes, where $B_{s,k}$ stands for the expected crash cost borne by traveler k, and $X_{s,k,q}$ refers to the increased crash cost due to vehicle k imposed on vehicle q.

- Scenario 1: Single-vehicle Crashes (Figure 4a)

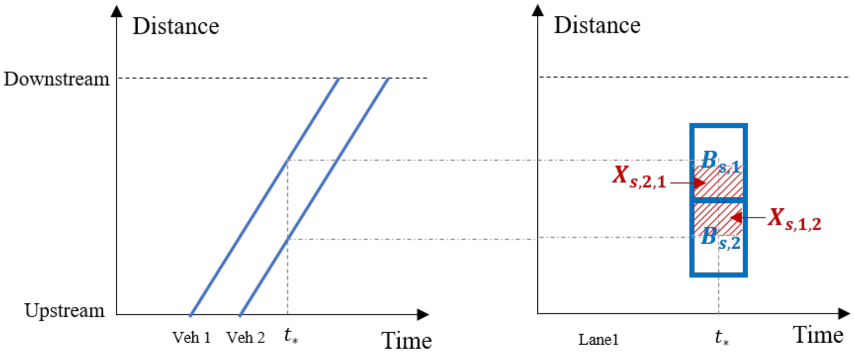
  One vehicle drives through a lane from its upstream to downstream without other surrounded vehicles. In this scenario, vehicle 1 does not impose any external crash cost on others. Its internal crash cost is determined by the expected crash rate of single-vehicle crashes on the lane.

- Scenario 2: Multi-vehicle Crashes (Figure 4b)

  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) Single Vehicle Crash



(b) Multi-Vehicles Crash

FIGURE 4 : Safety Cost Diagram: Internal vs. External

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 4b.

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.

Hence, only the internal crash cost, B_s, would be used to represent the total crash cost in the full cost analysis to avoid the double-counting problem.

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 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.

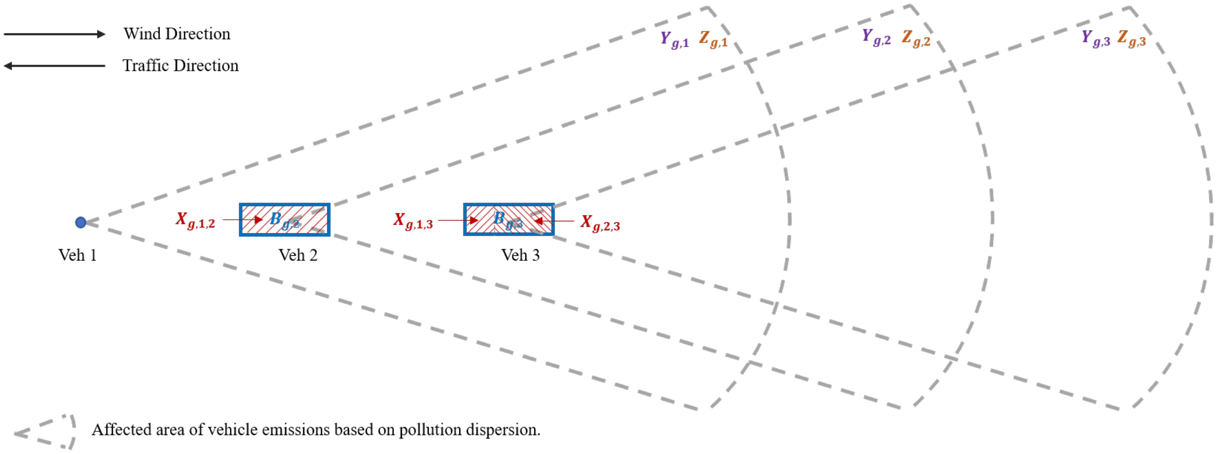


FIGURE 5 : Emission Cost Diagram: Internal vs.external

As shown in Figure 5, 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, Y_g, and Z_g would be used to represent the total emission cost in the full cost analysis, written as $B_g + Y_g + Z_g$.

Based on the total cost analysis rules, the full cost of travel, C_F, is expressed as,

$$C_F = B_t + B_s + B_g + Y_g + Z_g + C_u + C_i - T_c \tag{1}$$

Where:

C_u: User monetary cost;
C_i: Infrastructure cost;
T_C: Transferred cost, which is discussed in detail in Section 4.

FULL COST ANALYSIS: RULES FOR COMBINING ALL COST COMPONENTS

The full cost analysis rule identifies the potential cost transfers among cost components, which should be subtracted from one of the categories to avoid the double-counting problems.

Figure 6 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;

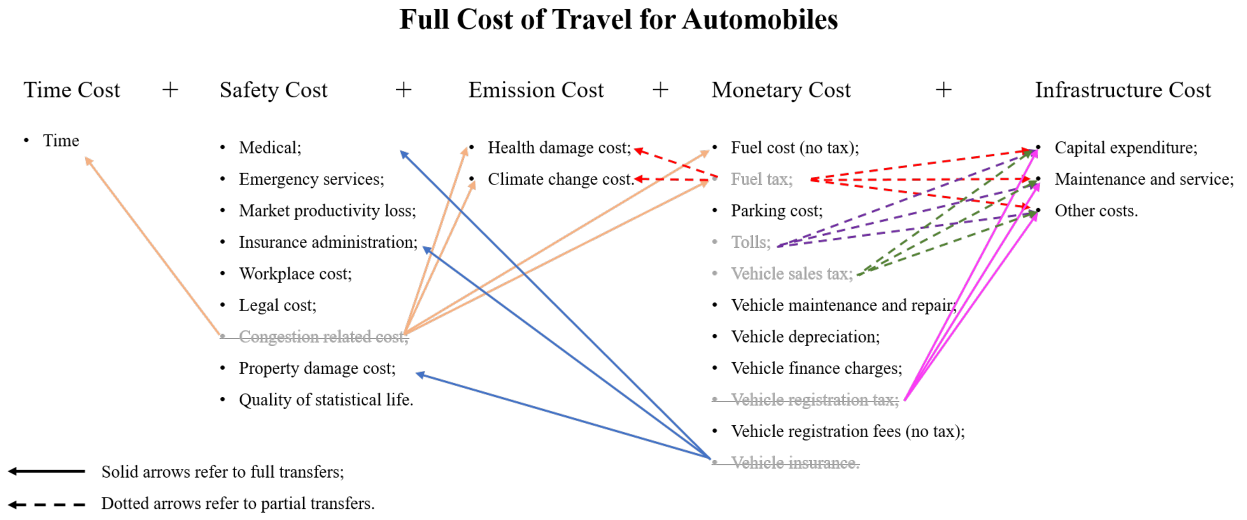


FIGURE 6 : Cost Factors of Auto Travelers

A detailed discussion on these cost transfers is shown in Section 4.1 - Section 4.4, respectively.

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 (5). 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 implementation, 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.

Vehicle Insurance Transfers to Safety Cost

Vehicle insurance cost paid by travelers covers approximately 54% of all crash costs (5). The insurance data developed by the Motorcycle Insurance Committee of the National Association of Independent Insurers classified 7 categories of insurance coverage, including bodily injury liability, property damage liability, own medical payments, personal injury protection, collision, comprehensive, and uninsured and underinsured motorist (5, 30)

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.

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 (42). 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 (29).

The federal motor fuel tax rate is \$0.049/liter (\$0.184/gallon) of gasoline, and \$0.064/liter (\$0.244/gallon) of diesel (45), 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 (42).

For Minnesota, the total state tax rate is \$0.075/liter (\$0.285/gallon) of gasoline, diesel and some gasoline blends after 2013 (6, 29). Based on the 2017 Minnesota Highway Users Tax Distribution Fund (34), 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.

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 (43).

In Minnesota, MnPASS Express Lanes on I-394, I-35W, and I-35E are toll roads, operated by Minnesota Department of Transportation (MnDOT), aiming to manage and reduce congestion on high-occupancy roads by charging an electronic fee on solo motorists (35). 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. Road pricing is not widespread (2).

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 (32). The tax rate is 6.5% of the vehicle purchase price. Based on the Highway Finance Overview (6), 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 (6, 31). 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 (34).

Hence, 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.

COST ESTIMATES FOR EACH COST COMPONENT

Due to the space restriction, this section here introduces the main data and methodology used for the cost estimates by cost component. Interested readers could find the details (9).

Time Cost

TomTom speed data provide speed profiles for each link segment on the Twin Cities road network, using which we could simply calculate the on-road travel time. The standard value of travel time savings for auto travelers recommended by Minnesota Department of Transportation (33), \$18.3/hour, was used to monetize the travel time [1].

The estimates show that the average time cost on the Twin Cities network is \$0.382/veh-km. Comparing the 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. 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.

Crash Cost

Internal crash cost is generated by the personal crash rate, which references the number of crashes per vehicle kilometer traveled (13, 17), and also determined by the unit crash cost.

$$C_{s,int,i_f} = \sum_{z} \frac{N_{s,i_f} * R_{i_f,z} * u_{s_z}}{N_Y * N_D * Q} \tag{2}$$

Where:

C_{s,int,i_f}: Internal crash cost on link i_f, in which f is specific to Functional Road Classifications (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_D: Number of days per year, $N_D = 365$;

Q: Annual average daily traffic (AADT).

For the case of the Twin Cities, we collected the crash records from 2003 to 2014 from the Minnesota Department of Transportation (MnDOT), and applied Safety Performance Functions (1) to estimate the expected crash frequency considering all types of crashes. An ordered-probit model was then used to identify the crash severity giving the probability of each type of crashes (12, 19, 36). Economic costs of crashes by severity specific to different crash cost factors were measured by Blincoe et al. (5), which were used as the unit crash cost to measure the link-based internal crash cost.

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, written as,

---

[1] We do NOT measure the external time cost here because, at first, dynamic traffic and speed data for the scale of the Twin Cities road network are missing, which does not allow us to do so; at second, the full cost could be measured without the external time cost estimates, see Section 3.1

$$C_{s,ext,i_f} = \sum_z \frac{u_{s_z} * R_{i_f,z}}{N_Y * N_D} * \frac{\partial N_{s,i_f}}{\partial Q} \tag{3}$$

Where:

C_{s,ext,i_f}: External crash cost on link i_f.

The estimates show that the average internal crash cost of all link segments is approximately \$0.040/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. Highways are much safer than other surface roadways that the mean value of internal and external crash costs for highways is \$0.020/veh-km and \$0.010/veh-km, respectively, while for other surface roadways is \$0.042/veh-km and \$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) are 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).

Emission Cost

The internal emission cost 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 (16). Considering the continuous changes of pollution concentration due to dispersion, the internal emission cost is written as:

$$C_{g,int,i} = \sum_p u_{g,int,p} * \int_0^{T_i} R_b * \rho_{p,i}(t)\, dt \tag{4}$$

Where:

$C_{g,int,i}$: Internal emission cost of link i;

$u_{g,int,p}$: 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.

The external emission cost of auto travelers is the health damage cost from emitted pollutants imposed on others (non-drivers) as well as the costs of greenhouse gas (CO_2) 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:

$$C_{g,ext,i} = \left(\left(\sum_p \sum_j u_{g,int,p} * H_{D,j} * \int_0^T B_r * \rho_{g,i,j}(t)\, dt \right) + \left(N_{i,CO_2} * u_{CO_2} \right) \right) * Q_i^{-1} \tag{5}$$

Where:

$C_{g,ext,i}$: 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,CO_2}: Quantity of CO_2 generated on link i;

u_{CO_2}: Unit emission cost of CO_2, \$22/ton (2010 US dollar);

Q_i: Traffic flow on link i.

For modeling the emission cost for the Twin Cities road network, we conducted project-level of MOVES simulations first, which is short for Motor Vehicle Emission Simulator, developed by US Environmental Protection Agency (49), to estimate the quantity of localized air pollutants and greenhouse gases (8, 20, 23, 24, 28, 47, 48). RLINE model, which is a dispersion modeling tool developed for concentration simulations for line type emission sources specifically, was used to estimate the on-road and off-road vehicle emission concentrations based on the output of the MOVES simulations (38, 39, 50). 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 (27), which was applied to monetize the health damage due to emission intake and the harm of climate change due to greenhouse gas pollutions.

The estimates show that the mean value of internal emission costs for all link segments is approximately \$0.0009/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 average link-based external emission cost is around \$0.0192/veh-km. The external emission cost is much higher than the internal one 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).

User Monetary Cost

The user monetary cost covers many factors, in which fuel cost, vehicle maintenance and repair cost, and kilometer-based vehicle depreciation cost compose a distance-based operation cost allowing to be assigned on each link.

Fuel consumption and fuel price affect a vehicle's fuel cost. California Department of Transportation (7) measured the fuel efficiency varying with speed from 8 to 128 km/h (5 to 80 mph) giving the pattern of how driving speed affects fuel consumption. A polynomial regression model was then proposed to estimate the pattern which illustrates that travel speed is the determinant for fuel efficiency and explains it quite well (R^2 : 0.96). Applying the TomTom speed data, a link-based fuel consumption is simply measured according to the regression results. The annual average gasoline retail price is used to monetize the fuel consumption (Data Source: US Energy Information Administration (46)).

Barnes and Langworthy (3) gave a full estimation of the vehicle maintenance and repair costs as well as the vehicle depreciation cost due to additional mileage being driven. According to Consumer Price Index (CPI) in motor vehicle maintenance and repair, we give the vehicle maintenance and repair costs for city driving is \$0.0311/km and for highway driving is \$0.0274/km in 2014. The distance-based vehicle depreciation cost is \$0.0483/km for city driving and \$0.0411/km for highway driving based on the CPI in new and used motor vehicles.

Combining those three factors, our estimates show the average link-based user monetary cost on the Twin Cities road network is \$0.219/veh-km. As expected, highways (\$0.142/veh-km) are much cheaper than other surface roadways (\$0.227/veh-km), and 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).

Other user monetary cost factors, including time-based vehicle depreciation costs, finance charges, insurance, vehicle registration fees, e.g., compose a time-based operation cost, which is approximately \$4,021/year in addition to the parking cost and MnPASS tolls if needed for the case of Minnesota.

Infrastructure Cost

Infrastructure cost mainly includes capital expenditure, maintenance and service, administration and miscellaneous, highway law enforcement and safety, interest, and bond retirement. Levinson and Gillen (21) proposed models predicting total expenditures on infrastructure as a function of price inputs, travel-related inputs, and network variables specific to road classifications. Accordingly, we collect highway infrastructures and travel data from US Department of Transportation, Office of Highway Policy Information, Policy and Governmental Affairs (44) showing the corresponding annual statistics broken down by state and functional system, price of labor from US Department of Labor, Bureau of Labor Statistics (40), and price of materials from US Department of Transportation, Federal Highway Administration (41). Applying the same format of regression 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.

Based on the estimates, the link-based infrastructure cost on the Twin Cities road network is shown in Table 1. As expected, the infrastructure cost is much higher on highways than other types of roads as the highway infrastructure expenditures are much higher.

TABLE 1 : Average Infrastructure Cost on the Twin Cities Road Network by Link Type (\$/veh-km)

Road Types	Long run		Short run	
	Average	Marginal	Average	Marginal
Highways	0.145	0.059	0.064	0.032
Minor Arterials	0.021	0.018	0.003	0.002
Collectors	0.032	0.027	0.005	0.004
Local Roads	0.035	0.030	0.002	0.002

LINK-BASED INTERNAL AND FULL COST ESTIMATES

Table 2 summarizes the average internal cost by road type and area type, and the 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

TABLE 2 : Link-based Internal Cost Estimates ($/veh-km)

		Internal Cost	Percentage of Cost Allocation			
			Time	Emission	Safety	Money
Road Types	Highway	0.46	52.49%	0.19%	2.54%	31.05%
	Other Surface Road	0.66	59.37%	0.14%	6.34%	34.37%
Area Types	Core Cities	0.75	61.68%	0.23%	6.39%	31.69%
	Other Urban Area	0.63	59.92%	0.13%	5.80%	34.14%
	Rural Area	0.57	56.38%	0.06%	6.90%	36.66%
	All Links	0.64	59.48%	0.14%	6.22%	34.17%

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. 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.

Figure 7 gives the spatial distribution patterns of the link-based internal cost estimates.

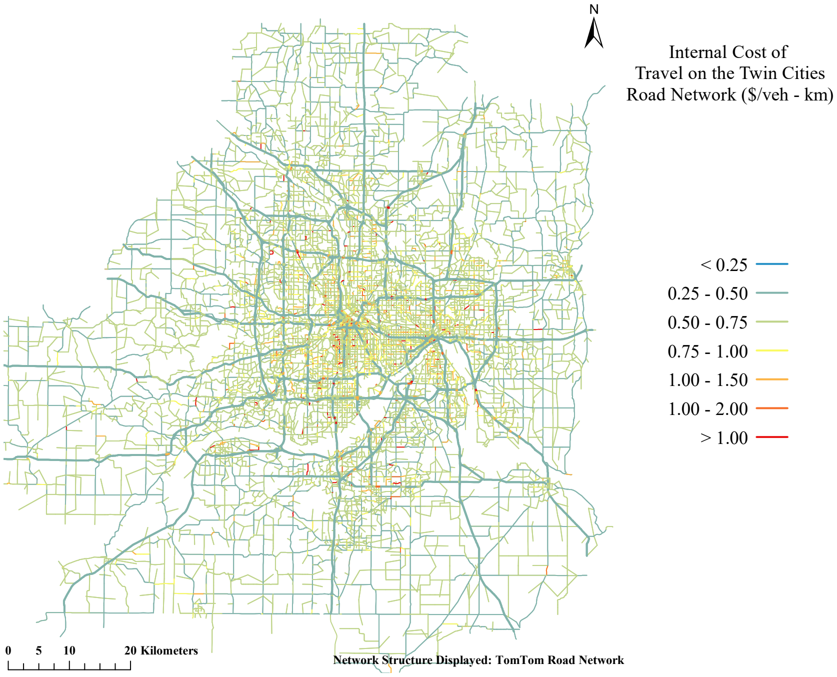


FIGURE 7 : Internal Cost Per Vehicle-Kilometer on Each Link of the Twin Cities Road Network ($/veh-km)

Table 3 illustrates the average full cost by road type and area type, and the percentage of cost allocations among different cost components in the full cost. It indicates that the mean value of full travel cost for all link segments in the Twin Cities is approximately $0.68/veh-km. Most links (93.6%) have a full cost less than $1.00/veh-km.

TABLE 3 : Link-based Full Cost Estimates ($/veh-km)

		Full Cost	Percentage of Cost Allocation				
			Time	Emission	Safety	Money	Infrastructure
Road Types	Highway	0.54	43.91%	2.18%	2.12%	24.20%	18.38%
	Other Surface Road	0.69	56.67%	2.99%	6.05%	29.97%	4.57%
Area Types	Core Cities	0.80	58.40%	3.99%	6.05%	27.33%	4.23%
	Other Urban Area	0.67	56.48%	2.94%	5.47%	29.45%	5.65%
	Rural Area	0.60	53.77%	1.98%	6.58%	32.07%	5.60%
	All Links	0.68	56.29%	2.96%	5.88%	29.57%	5.30%

Similar to the internal cost estimates, 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.

For all types of roads, the time and monetary costs 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.

The spatial distribution patterns of the link-based full cost estimates are displayed in Figure 8.

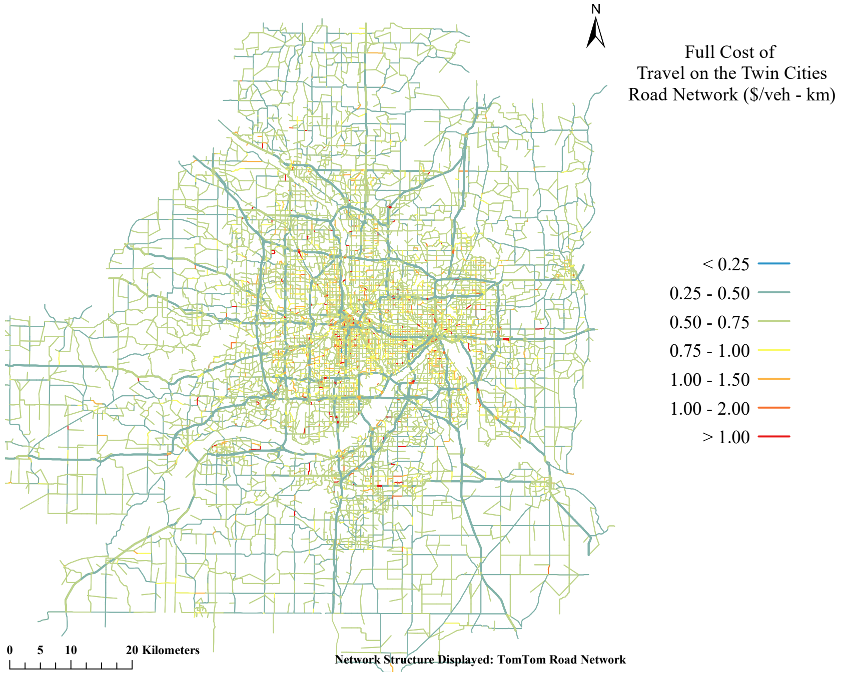


FIGURE 8 : Full Cost Per Vehicle-Kilometer on Each Link of the Twin Cities Road Network ($/veh-km)

CONCLUSION

This study develops a link-based full cost model, which identifies the key cost components of urban traveling, distinguish the internal and external versions of cost, and gives a link-based cost estimate for the Twin Cities metropolitan area. The key cost components considered are time, safety, emission, user monetary and infrastructure costs.

The estimates show that, in the Twin Cities, the mean value of the 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 about 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. Comparatively, the average internal travel cost is about $0.64/veh-km, which implies an un-internalized external cost of \$0.04/veh-km. The amount is small compared to the full cost. However, external costs should still be internalized.

Comparing road types, mostly, highways are cheaper than other surface roadways from the perspective of travelers. However, the infrastructure costs of highways are much higher than surface roads, which 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.

A wide range of applications for the full cost analysis is expected, 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 (4). Generally, the travel cost in the utility function captures the internal version of cost. 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. We think evaluation of accessibility using the full costs of travel is likely to be more socially efficient than simply considering internal costs. (10)

The cost analysis conducted in this study 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 also extend the full cost analysis to other modes, e.g. transit and bicycle, to identify the internal and external costs from the perspective of passengers or bicyclists. A full-benefit analysis could be conducted for modes as well. It is believed that, for instance, health is improved by walking and biking. Happiness might also vary by modes, and so could be reflected in different ways of assessing the value of time. The access provided by transport benefits more than just the traveler.

AUTHOR CONTRIBUTION STATEMENT

Mengying Cui: Literature search and review, data collection and analysis, manuscript writing

David Levinson: Framework building, manuscript editing

REFERENCES

[1] American Association of State Highway and Transportation Officials (AASHTO) (2010), Highway Safety Manual, Technical report.

[2] Anderson, D. and Mohring, H. (1997), Congestion costs and congestion pricing, *in* 'The full costs and benefits of transportation', Springer, pp. 315–336.

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

[4] Ben-Akiva, M. E. and Lerman, S. R. (1985), *Discrete choice analysis: theory and application to travel demand*, Vol. 9, MIT press.

[5] Blincoe, L., Miller, T. R., Zaloshnja, E. and Lawrence, B. A. (2015), The economic and societal impact of motor vehicle crashes, 2010 (revised), Technical report, US Department of Transportation, National Highway Traffic Safety Administration.

[6] Burress, M. (2018), Information brief, highway finance overview, Technical report, Minnesota House of Representatives, Research Department.

[7] California Department of Transportation (2012), 'Transportation benefit-cost analysis, Cal-B/C Model'.
URL: *http://bca.transportationeconomics.org/models/cal-b-c*

[8] Coelho, M. C., Fontes, T., Bandeira, J. M., Pereira, S. R., Tchepel, O., Dias, D., Sá, E., Amorim, J. H. and Borrego, C. (2014), 'Assessment of potential improvements on regional air quality modelling related with implementation of a detailed methodology for traffic emission estimation', *Science of the Total Environment* **470**, 127–137.

[9] Cui, M. (2018), Full Cost Accessibility, PhD Dissertation, University of Minnesota.

[10] Cui, M. and Levinson, D. (2018), 'Full cost accessibility', *Journal of Transport and Land Use* p. in press.

[11] Delucchi, M. A. (1997), 'The annualized social cost of motor-vehicle use in the US, 1990-1991: Summary of theory, data, methods, and results', *University of California Transportation Center* .

[12] Duncan, C., Khattak, A. and Council, F. (1998), 'Applying the ordered probit model to injury severity in truck-passenger car rear-end collisions', *Transportation Research Record: Journal of the Transportation Research Board* (1635), 63–71.

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

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

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

[16] Hassanien, M. A., Abdellatif, N. M., Saleh, E. A. and Mohamed, A. M. (2009), Inhalation intake assessment of air pollutants exposure over Cairo, Egypt, *in* 'Exposure and Risk Assessment of Chemical Pollution – Contemporary Methodology', Springer, pp. 303–315.

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

[18] Jansson, J. O. (1994), 'Accident externality charges', *Journal of transport Economics and Policy* pp. 31–43.

[19] Kockelman, K. M. and Kweon, Y.-J. (2002), 'Driver injury severity: An application of ordered probit models', *Accident Analysis & Prevention* **34**(3), 313–321.

[20] Lee, G., Ritchie, S. G., Saphores, J.-D., Jayakrishnan, R., Ogunseitan, O. et al. (2012), 'Assessing air quality and health benefits of the Clean Truck Program in the Alameda corridor, CA', *Transportation Research Part A: Policy and Practice* **46**(8), 1177–1193.

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

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

[23] Lin, J., Chiu, Y.-C., Vallamsundar, S. and Bai, S. (2011), Integration of MOVES and dynamic traffic assignment models for fine-grained transportation and air quality analyses, *in* 'Integrated and Sustainable Transportation System (FISTS), 2011 IEEE Forum on', IEEE, pp. 176–181.

[24] Liu, H., Chen, X., Wang, Y. and Han, S. (2013), 'Vehicle emission and near-road air quality modeling for Shanghai, China: Based on global positioning system data from taxis and revised MOVES emission inventory', *Transportation Research Record: Journal of the Transportation Research Board* (2340), 38–48.

[25] Mankiw, G. N. (2014), *Principles of macroeconomics*, Cengage Learning.

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

[27] McGarity, T. O. (2012), Final regulatory impact analysis: Corporate average fuel economy for MY 2017-MY 2025 passenger cars and light trucks, Technical report, US Department of TransportationïijŇ National Highway Traffic Safety Administration.

[28] Mensink, C. and Cosemans, G. (2008), 'From traffic flow simulations to pollutant concentrations in street canyons and backyards', *Environmental Modelling & Software* **23**(3), 288–295.

[29] Metropolitan Council, Transportation Committee (2015), 'Overview of Minnesota highway and transit finance'.
URL: *https://metrocouncil.org/getdoc/6c6c4eae-fb53-409d-b314-bae25c5e6c24/BusinessItem.aspx*

[30] Miller, T. R. and Lawrence, B. A. (2003), Motor vehicle insurance in the United States: A 1998-1999 snapshot with emphasis on motorcycle coverage, Technical report, US Department of Transportation, National Highway Traffic Safety Administration.

[31] Minnesota Department of Public Safety (2018), 'Registration tax'.
URL: *https://dps.mn.gov/divisions/dvs/Pages/registrationtax.aspx*

[32] Minnesota Department of Revenue (2017), 'Sales and transfers: Motor vehicle sales tax'.
URL: *http://www.revenue.state.mn.us/businesses/sut/Pages/MotorVehicle/Salesand-Transfers.aspx*

[33] Minnesota Department of Transportation (2015), 'Benefit-cost analysis for transportation projects'.
URL: *http://www.dot.state.mn.us/planning/program/benefitcost.html*

[34] Minnesota Department of Transportation (2017), '2017 Minnesota highway users tax distribution fund'.
URL: *http://www.dot.state.mn.us/safinance/appmt/mnutdf2017.pdf*

[35] Minnesota Department of Transportation (2018), 'MnPASS pricing and revenue'.
URL: *https://www.dot.state.mn.us/mnpass/mnpassmoney.html*

[36] Quddus, M. A., Noland, R. B. and Chin, H. C. (2002), 'An analysis of motorcycle injury and vehicle damage severity using ordered probit models', *Journal of Safety Research* **33**(4), 445–462.

[37] Small, K. A. and Kazimi, C. (1995), 'On the costs of air pollution from motor vehicles', *Journal of Transport Economics and Policy* pp. 7–32.

[38] Snyder, M. G. and Heist, D. K. (2013), User's guide for R-LINE model, a research LINE source model for near-surface releases, Technical report, US Environmental Protection Agency.

[39] Snyder, M. G., Venkatram, A., Heist, D. K., Perry, S. G., Petersen, W. B. and Isakov, V. (2013), 'RLINE: A line source dispersion model for near-surface releases', *Atmospheric Environment* **77**, 748–756.

[40] US Department of Labor, Bureau of Labor Statistics (2018), 'Quarterly census of employment and wages'.
URL: *https://www.bls.gov/cew/home.htm*

[41] US Department of Transportation, Federal Highway Administration (2006), 'Price trends for federal-aid highway construction'.
URL: *https://www.fhwa.dot.gov/programadmin/pricetrends.cfm*

[42] US Department of Transportation, Federal Highway Administration (2012), 'Federal Highway Administration motor fuel tax compliance outreach'.
URL: *https://www.fhwa.dot.gov/motorfuel/faqs.htm*

[43] US Department of Transportation, Federal Highway Administration, Center for Innovative Finance Support (2018), 'Tolling and pricing defined'.
URL: *https://www.fhwa.dot.gov/ipd/tolling_and_pricing/defined/*

[44] US Department of Transportation, Office of Highway Policy Information, Policy and Governmental Affairs (2016), 'Highway statistics 2013'.
URL: *https://www.fhwa.dot.gov/policyinformation/statistics/2013/*

[45] US Energy Information Administration (2014), 'Petroleum marketing explanatory notes, the EIA-782 Survey'.
URL: *https://www.eia.gov/petroleum/marketing/monthly/pdf/enote.pdf*

[46] US Energy Information Administration (2018), 'Weekly retail gasoline and diesel prices'.
URL: *https://www.eia.gov/dnav/pet/PET_PRI_GND_DCUS_SMN_A.htm*

[47] US Environmental Protection Agency (2015*a*), 'Transportation conformity guidance for quantitative hot-spot analyses in PM2.5 and PM10 nonattainment and maintenance areas'.

[48] US Environmental Protection Agency (2015*b*), 'Using MOVES2014 in project-level Carbon Monoxide analyses'.

[49] US Environmental Protection Agency (2016), 'Motor vehicle emission simulator'.
URL: *https://www3.epa.gov/otaq/models/moves/*

[50] Venkatram, A., Snyder, M. G., Heist, D. K., Perry, S. G., Petersen, W. B. and Isakov, V. (2013), 'Re-formulation of plume spread for near-surface dispersion', *Atmospheric Environment* **77**, 846–855.

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