Transportation Cost Index: A Comprehensive Multimodal Performance Measure of Transportation and Land Use Systems

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Abstract

Recent federal and state laws in the U.S. are placing increasing emphasis on using comprehensive transportation performance measures to guide transportation planning and programming. Although there is a growing list of performance measures of land use and transportation systems largely centered on accessibility, one of the challenges in successfully implementing performance measures in the transportation planning process is the development of measures that present an overall picture of both transportation and land use systems and are relatively easy to interpret for policy makers and the public. There are also certain policy goals, such as the aspect of a balanced transportation system mandated by the state of Oregon’s transportation planning rules, are not well reflected by popular accessibility measures. In response to this demand, Reiff and Gregor (2005) proposed a Transportation Cost Index (TCI) to fill this gap. Building on the concept of the widely-used Consumer Price Index (CPI), the TCI aims to be an accessibility measure that reflects the policy areas including a balanced transportation system, environmental justice, and land use compatibility. This paper reviews the TCI measure and the method for computing the measure and demonstrates it with a proof-of-concept application in Portland, Oregon. We further describe the efforts of an ongoing research project aiming to advance the TCI from the proof-of-concept stage to implementation at the state, MPO, and community levels.

INTRODUCTION

Recent U.S. federal and state laws are placing increasing emphasis using on comprehensive transportation performance measures to guide transportation decision making process covering policy areas ranging from mobility, safety, economy, livability, equity, to environment. While it is relatively easy to build consensus on mobility measures that center on transportation system alone, it is much harder for performance measures of land use and transportation systems, loosely defined as accessibility measures, even with continuous efforts to catalog and design such measures (see, for example, *(1)*).

This paper builds on and further develops a Transportation Cost Index (TCI) of land use and transportation systems in order to fill important gaps in popular accessibility measures. First, we aim to develop a composite indicator that is able to present an overall picture of a community's accessibility, while at the same time make it relatively easy to interpret for policy makers and the public. There are accessibility indicators, such as utility and gravity-based metrics, that can present an overall picture of a community's accessibility level, but they are difficult to communicate to non-technical crowd, which would be critical for transparent decision-making process *(2)* On the other hand, there are indicators that are intuitive, for example, opportunities accessible within certain travel time threshold by a certain mode, but they can hardly be used to present an overall picture of a community, as they reflect only a certain aspect of a much more complex picture *(3, 4)*. We think it is critical to be able to make good on both ends.

Second, one of major rationales for the TCI measure is to fill gaps in policy areas represented by popular performance measures of land use and transportation system. As state DOTs and MPOs move towards performance-based approach to transportation planning, performance measures that reflect more policy areas are needed. . In the state of Oregon, the Jobs and Transportation Act mandates that the Oregon DOT develop a least-cost planning (LCP) process that uses performance measures in comprehensive evaluations of all possible solutions – both transportation and land use strategies - to meet transportation goals including economic vitality, a balanced transportation system, sustainability, adaptability, quality of life, environment justice, system preservation, land use compatibility, affordability, as well as accessibility, mobility, safety and security *(5)*. Reiff and Gregor *(6)* found that some of these policy areas, such as balance, land use compatibility are not well represented by commonly used performance measures. The balance policy area calls for a balanced transportation system, for demand management, land use planning, transportation system management, as well as new infrastructure investment to match demand and supply, and for appropriate allocation of resources across multiple travel modes.

Lastly, we want to develop a measure that can be used to monitor historical and projected trends, evaluate and compare outcomes from what-if scenarios, as well as to report current status. Since current year data and model inputs and outputs are more readily available, reporting current status is usually the easiest to achieve. To enable trend monitoring and scenario evaluation, it requires the measure to use and be sensitive to common transportation and land use model outputs.

TCI is a performance measure that is inspired by Consumer Price Index (CPI). The CPI measures the relative price for acquiring a reference market basket of goods and services. It may be used to compare living costs in different areas and their changes over time. The TCI measures the relative cost of accessing a market basket of travel destinations. It may be used to compare accessibility by trip purpose, income group, and geographic area. Similar to the process constructing CPI, calculating TCI involves steps identifying market baskets of travel opportunities and tracking and summarizing the costs of accessing market baskets. A travel market basket identifies a set of destinations that provide a good set of choices for meeting daily living needs, and the total costs of traveling to destinations in the travel market basket are calculated by travel mode for each Traffic Analysis Zone (TAZ). The costs can then be summarized by origin TAZ, trip purpose, and income group, or into weighted averages by collapsing some of these dimensions.

The TCI is designed to be a measure of accessibility and of the effects of the transportation and land use system on the quality of life. It can also serve as an indicator for policy areas including transportation and land use system compatibility and balance, which are less represented by existing performance measures. The primary purpose of the transportation system, from the standpoint of an individual household, is to provide affordable access (time and monetary-wise) to the goods, services, and daily activities that the household desires. Like the CPI, which may be used to indicate relative change in the cost of the goods and services themselves, the TCI is designed to indicate changes in the costs to access goods and services. The TCI may be used to measure how transportation affordability varies spatially across an urban area, how it changes over time, and how it is affected by various land use and transportation system alternatives. Areas with increased TCI in future year scenarios are indicative of problems with land use / transport system compatibility and balance. Certain population subgroup suffering from higher TCI may suggest inequity in allocating resources. High TCI may result from extreme traffic congestion or limited access to the travel market basket. Such situations might be addressed in a range of policies and investment decisions, including demand management, land use planning, transportation system management (TSM), additional roadway capacity, and investment in alternative modes, any of which may bring down transportation costs. TCI can be computed for each alternative solution to evaluate relative effectiveness and used in trade-off analysis to support resource allocation decisions among these alternatives.

The current TCI algorithm relies on travel demand model to provide all the information needed to define travel market basket and to calculate transportation costs. The TCI works with different travel demand models. We have tested it with two travel demand model systems: Joint Estimation Model in R Code (JEMnR) and VISSUM, and believe the specifications can be readily adapted to other disaggregated discrete choice-based travel demand models. Relying on travel model data makes it difficult to calculate historical TCI or work for areas without a suitable travel demand model. Work is currently underway to enable TCI being computed from commonly available data sources, such as population and household census, Local Employment Household Dynamics (LEHD), household activity survey data, etc, without the need of data from a travel demand model. Once the work is done, we anticipate TCI to cover all three desired use cases: status reporting, trend monitoring, and scenario evaluation.

The remaining of this paper is organized as the following. The next section reviews related literature. The Transportation Cost Index section elaborates our proposed method for calculating transportation cost index, while the Application section demonstrates an application of TCI with data from Oregon. The Discussion and Future Work section discusses the advantage and limitation of the current formulation and of TCI, and ongoing and future work to improve it. The Conclusion section then concludes the paper.

LITERATURE REVIEW

There has been a growing body of literature documenting accessibility metrics and its application as performance measures. Handy and Niemeier *(7)* discuss common used accessibility measure and their limitations. NCHRP 446 *(8)* categorizes a set of performance measures including accessibility by the policy areas they represent, and recommend practice for selecting performance measures.

More closely related to the theme of this paper, Geurs and van Wee *(9)* review accessibility measures that are suitable for evaluation of land-use and/or transportation strategies. They classify accessibility measures by the perspective of a measure: infrastructure-based measures, location-based measures, person-based measures, and utility-based measures. [TODO:explain] While infrastructure-, location-, and person-based measures are relatively easier to interpret, they are more difficult to present an overall picture of systems to be measured; vice-versa for utility-based measures. For example, most travel time-based and opportunity-based accessibility indicators are location- or person-based measures, they are very intuitive for the public and decision makers to interpret what they represent, but they are difficult to present an overall picture of the systems. Within this topology, the TCI is a location-based measure built upon utility-based features, and attempts to be an intuitive measure of overall system performance. With our ongoing research, we aim to turn it into a person-based measure as well. There have been similar efforts of hybridizing different types of measures. For example, TTI's Travel Time Index *(10)* builds a system-level measure from person-based measure (travel time).

The idea of Transportation Cost Index is in line with the approach Koopmans et al *(11)* propose – measuring generalized travel cost as an indicator of monitoring accessibility change. They calculate the average costs per kilometer of trips by transport mode, trip purpose, trip distance, region and time-of-day, and monitor the cost change over time. The measure has the advantage of easy interpretability, but since it only account for per distance costs for motorized trips and thus ignores potential land use changes, it is infeasible as a measure for land use and transportation systems. By tracking the generalized travel cost accessing a pre-defined travel market basket, TCI will be sensitive to changes in both land use and transportation systems.

Geurs et al *(12)* propose to use a disaggregated logsum accessibility measure from a land-use transportation interaction model to compute changes in consumer surplus between policy scenarios. While the goal of their research is similar to that of ours in term of capacity to provide an elegant and convenient solution to measure benefits from land-use and/or transportation policies, their consumer surplus metrics are only meaningful for looking at the difference between two scenarios, and thus not suitable for use to monitor accessibility trend over time, and it also lacks the capacity to examine the balance aspect across geographic regions and population subgroups.

TRANSPORTATION COST INDEX

Analogous to CPI, TCI calculation involves first identifying market areas that provide a good set of choices for meeting daily living needs and then calculating and summarizing the costs of accessing those market areas. Specifically, the method for calculating the TCI involves three steps:

1. Identifying travel market areas and a reference TAZ;
2. Calculating travel costs to access market areas from each TAZ;
3. Calculating TCI values from the travel costs.

Based on the definition in the travel demand model used for calculating the TCI, a travel cost can be calculated for each travel category. For this study, we calculate a travel cost for each income group and trip purpose. The income groups include high, median and low categories, while trip purposes include work, shopping, recreation and other non-school trips made from the home.

Identify Travel Market Areas

Reiff and Gregor's *(6)* define market areas with data and models in traditional 4-step travel demand model. The advantage of this approach is that the data for market definition are readily available from most travel demand models and defining TAZ level travel market areas by trip purpose and income group is very straightforward. Ideally to be consistent how CPI works, a representative travel market basket would be used for each travel purpose and maybe income group for the study area. However methods of defining reference travel market baskets (varying by income group and trip purpose) via identifying a reference TAZ were tested, as an analog to a reference market basket of goods and services used by the CPI measure, and there is variation in the sizes of the identified market baskets because of idiosyncrasy*(6)*. In this study, a reference travel market basket is not used; instead travel market areas are identified for each TAZ and for each income group and trip purpose. Even though such an approach would resemble the actual travel cost for each combination more closely, it deviates from the market basket definition used by CPI, which inspires the original idea of creating TCI. Ideas of non-model-based approach of defining travel market basket are currently being tested.

According to Reiff and Gregor's *(6)* original approach, defining the market areas for TAZ *k* for income group *i* and trip purpose *p* follows these steps:

1. Determine size terms. The size terms of the destination choice model utilities measure the perceived attractiveness of TAZs to trips of different types. They are functions primarily of the numbers of jobs and households in a TAZ, but may include other factors. For example, the size term for home-based recreation trips is calculated with this equation:

$$\mathrm{size}_k = \mathrm{emp}_k + \beta_1 \mathrm{hhs}_k + \beta_2 \mathrm{park}_k \tag{1}$$

where

emp = number of employees of TAZ *k;*
hhs = number of households;
parks = park land in acres;
β = coefficients in the access utility function

2. Identify the potential market area of TAZ *k* for income group *i* and trip purpose *p*. A threshold is used to identify the set of TAZs that is to be included in the market area of a focus TAZ. Two different methods are tested: the first method bases the threshold on

percentage of the total trips attracted to each TAZ from TAZ k, as shown in Equation (2); the second method establishes a log sum threshold as in Equation (3):

$$J_{pik} = \{j: \frac{\text{Trips}_{pikj}}{\sum_{t \in T} \text{Trips}_{pikt}} \geq \text{cutoff 1}\} \tag{2}$$

$$J_{pik} = \{j: \text{logsum}_{pikj} \geq \text{cutoff 2}\} \tag{3}$$

where

T = the set of all TAZs in the model area;
cutoff = chosen threshold for defining the market area;
trips_{pikj} = the number of trips by income group i for purpose p between TAZ k and TAZ j;
logsum_{pikj} = the log sum of the access utilities for travel by income group i for purpose p between TAZ k and TAZ j.

Several percentage cutoffs were tested, in particular 75% and 50%. The log sum threshold in Equation (3) was chosen by examining ordered plots of log sum values for all TAZs and each trip purpose. For our case study, the value of 0.5 was chosen as the threshold for determining the market area, because the average log sum trends for all zones have inflection points of 0.5, as log sums increase rapidly to the left of the inflection points and decline gradually to the right.

Because of the difficulty in describing a market area defined by using a threshold log sum value in common sense terms, a 50% trip percentage cutoff in Equation (2) was used in the Portland, OR case study.

3. Identify a reference TAZ. The purpose of identifying a reference TAZ is to normalize zonal travel costs accessing market areas with that for the reference TAZ. Identifying the reference TAZ begins with calculating a score for each TAZ:

$$\text{score}_k = \sum_{pi} \frac{\text{MB}_{pik}}{\max_k(\text{MB}_{pik})} \text{ and} \tag{4}$$

$$\text{MB}_{pik} = \sum_{j \in J_{pik}} \text{size}_j \tag{5}$$

where

MB_{pik} = market basket for TAZ k for income group i and trip purpose p.

The reference TAZ r is then the TAZ with highest score $r = \underset{k}{\text{argmax}}(\text{score}_k)$.

Calculate Travel Costs Accessing Market Areas

Once we define travel market areas for each TAZ, average costs to access the market areas are calculated for each TAZ. The costs are calculated from the travel model access utilities, which measure the perceived ease of travel between every pair of TAZs for each trip purpose, income group and mode of travel. The utilities are calculated from linear utility equations that were statistically estimated from household activity surveys. The terms of the equations are factors that affect people's perceptions of the ease of travel. The coefficients for the terms indicate the strength of each factor. Some examples of factors included in the utility equations are:

- The time spent traveling in a vehicle,
- The time to walk to get to the vehicle (e.g. walk time to a bus stop),

- The time spent waiting, and
- The money cost of the trip (i.e. operating cost).

Since the utilities are unit-less quantities in preference space, they are not intuitive to understand. They can be easily converted into understandable monetary units in willingness-to-pay space by dividing them by the coefficient of a monetary cost factor *(13)*, such as operating cost:

$$MC_{pimkj} = \frac{U_{pimkj}}{OC_{pi}} \quad (6)$$

where

MC_{pimkj} is the cost for traveling by mode m between TAZs k and j for purpose p by income group i in monetary term;

U_{pimkj} is the utility for traveling by mode m between TAZs k and j for purpose p by income group I;

OC_{pi} is the cost coefficient for purpose p and income group i.

There are a few different approaches to incorporating varying costs by mode. The simplest is to pick the least costly mode:

$$TC_{pikj} = \min_m(MC_{pimkj}) \quad (7)$$

An alternative approach would be average costs weighted by mode probabilities:

$$TC_{pikj} = \sum_m (MC_{pimkj} * P_{pimkj}) \text{ and} \quad (8)$$

$$P_{pimkj} = \frac{\exp(U_{pimkj})}{\sum_{m'} \exp(U_{pim'kj})}$$

A composite approach is to compute a cost from a composite of the access utilities for the travel modes. This is done in the standard traveling modeling approach by calculating the log sum of the mode choice model. It can be thought of as a measure of travel opportunities rather than travel cost. The composite cost for traveling between two TAZs k and j by a household of income group i for purpose p is calculated as follows:

$$TC_{pikj} = \ln\left(\sum_{m'} \exp(U_{pim'kj})\right) \quad (9)$$

The average cost to access the market basket for a TAZ k can be computed as a weighted average of the travel costs from TAZ k to each TAZ j in the market areas for that TAZ k. The weighting factor in calculating the average is the proportion of the size term of each TAZ. Thus the weighted average cost to access the market areas for income group i and purpose p from zone k is calculated as follows:

$$AC_{pik} = \frac{\sum_{j \in J_{pik}} TC_{pikj} * size_{pij}}{\sum_{j \in J_{pik}} size_{pij}} \quad (10)$$

where

J_{pik} - the market areas for TAZ k;

EC_{pikj} is the equivalent cost for traveling between TAZ k and TAZ j for income group i and purpose p;

$size_{pij}$ is the size term for income group i for purpose p in TAZ j.

Following similar logic of how weighted average travel costs are calculated, it is possible to suppress income group or trip purpose dimension and summarize the average costs by TAZ and the rest dimension:

$$AC_{pk} = \frac{\sum_i AC_{pik} * \text{trips}_{pik}}{\sum_i trips_{pik}} \text{ and} \quad (11)$$

$$AC_{ik} = \frac{\sum_p AC_{pik} * \text{trips}_{pik}}{\sum_p trips_{pik}}. \quad (12)$$

where

trips_{pik} is the number of trips produced by income group *i* for purpose *p* in TAZ *k*.

A similar process can be used to aggregate average travel costs to larger geographic units such as districts, cities, and the whole region. In this process, the proportions of trips occurring among the zones within each larger geographic area are used as weights. The average cost *AC* to access the market basket for all TAZs in district *d* for purpose *p* and income group *i* is calculated as follows:

$$AC_{pid} = \frac{\sum_{k \in d} AC_{pik} * \text{trips}_{pik}}{\sum_{k \in d} trips_{pik}}. \tag{13}$$

Calculate the TCI

TCI values are computed from average costs by dividing the values for each TAZ by the values for the reference TAZ. Depending on the method used to aggregate travel costs (Equation 7, 8, or 9), this produces three TCI values for each TAZ by income group and trip purpose.

$$TCI_{pik} = \frac{AC_{pik}}{AC_{pir}}$$

where

AC_{pir} is the average cost to access the market area for the reference TAZ *r*.

TCI values aggregated by income, or purpose, or geographic area may be calculated from the corresponding aggregated market access costs (Equation 11, 12, 13).

The TCI calculation process described in the steps above has been implemented in R and available at http://www.oregon.gov/ODOT/td/tp_res/docs/reports/planningperformancemeasures.pdf .

TCI APPLICATION

In this section we demonstrate the application of the TCI using data and models for the Portland-Vancouver metropolitan area. Figure 1 is a map showing the model area, with the boundaries of the 2126 transportation analysis zones (TAZs). Also shown is the reference TAZ and calculated scores for each TAZ (Equation 4) and their distribution.

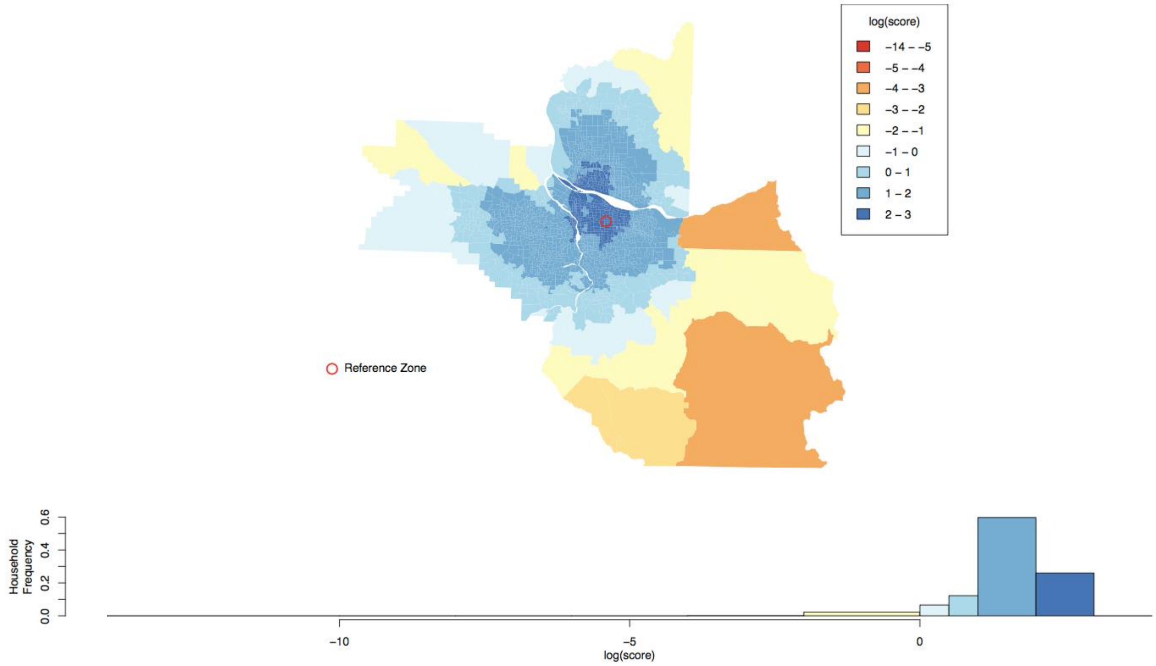

FIGURE 1. Map of the Case Study Area (with TAZ boundaries)

Data and models for this case study are provided by Metro, the MPO for the Portland area, from their four-step travel demand model implemented in EMME. Reiff and Gregor earlier applied TCI to the Rogue Valley Metropolitan Planning Organization (RVMPO) model area *(6)* using data and models from the Joint Estimated Model in R (JEMnR), a four-step travel demand model implemented in the R programming language by Oregon DOT. We believe the current TCI scripts can be easily adapted to work with most travel demand models.

Figure 2 shows the frequency distributions of household average travel costs for each combination of trip purpose and income. The figure demonstrates that reasonable results are calculated by this method. In addition, the results show that the measure is sensitive to differences in trip purposes and income groupings. Work trips have the largest market areas, and this shows up in the largest variation in the market costs for these trips. According to these results, non-work trip costs are similar for the different income groups, and higher income households have higher market access costs.

Figure 3 show the corresponding geographical distributions of TCI values. Several patterns are readily apparent. For work trips, low income households in Vancouver, WA and Gresham have lowest costs, which may indicate that low income households there live close to employment. For non-work trips, lower income households have similar market access costs as middle and higher income households in central areas, but greater variation in costs in fringe TAZs.

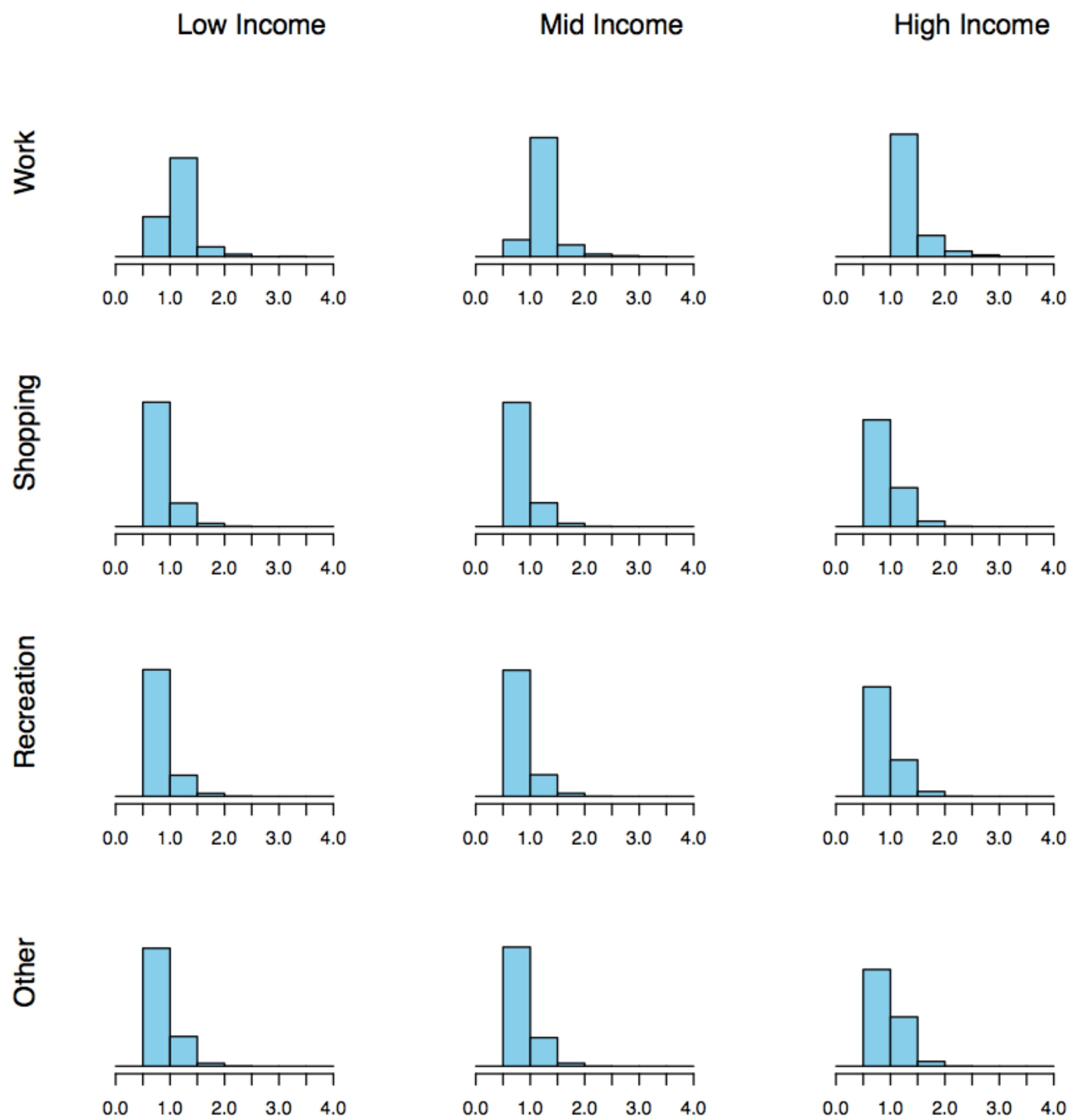

FIGURE 2. Household frequency distributions of average market cost in dollars by trip purpose and income

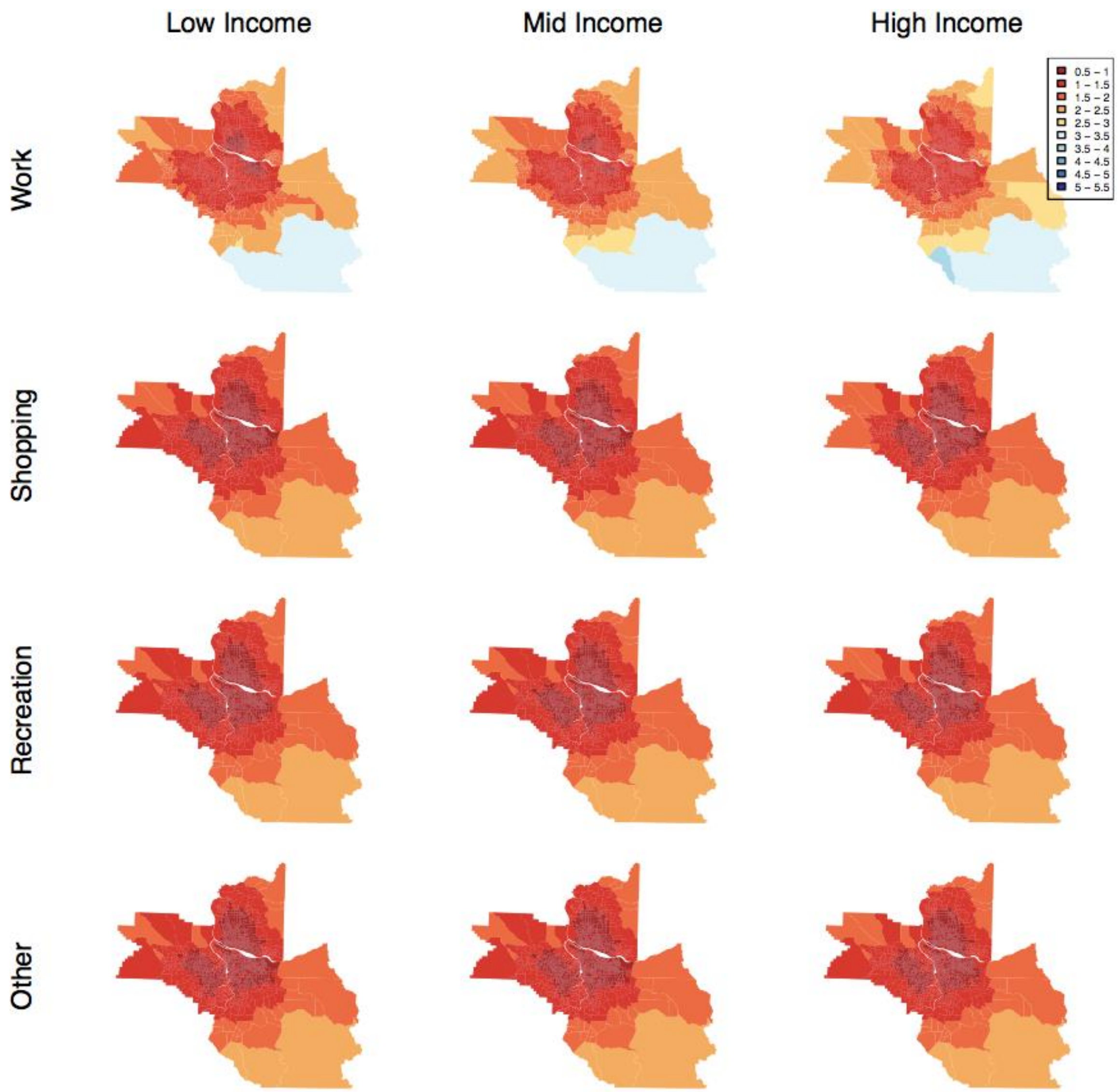

FIGURE 3. Geographic distributions of average market cost in dollars by trip purpose and income

Figures 4 and 5 show household frequency distributions of aggregated TCI values. Figure 4 compares distributions by income category and the three mode aggregation methods. Figure 5 compares distributions by trip purpose and mode aggregation method.

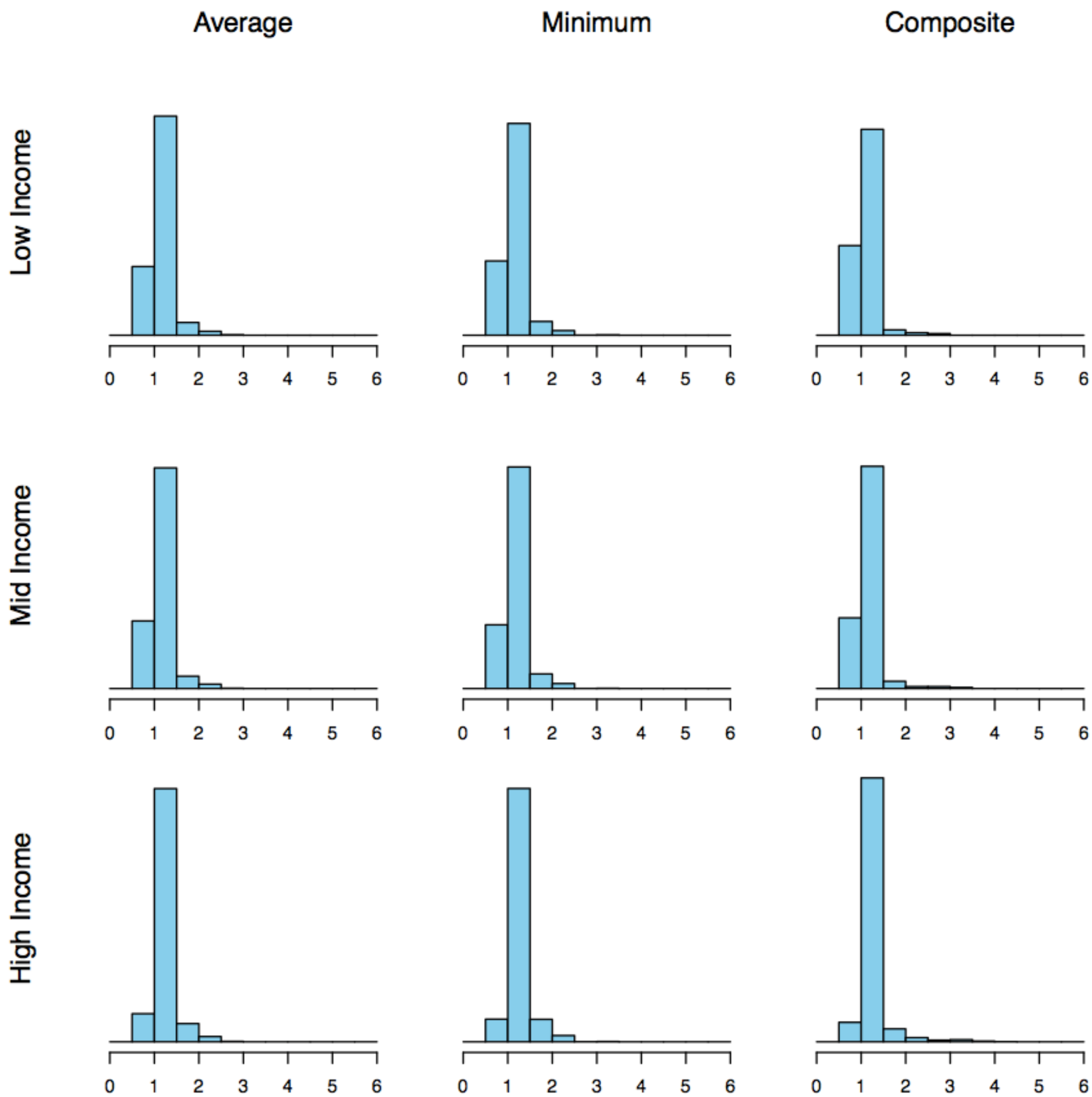

FIGURE 4. Household frequency distribution of TCI by income and mode aggregation method

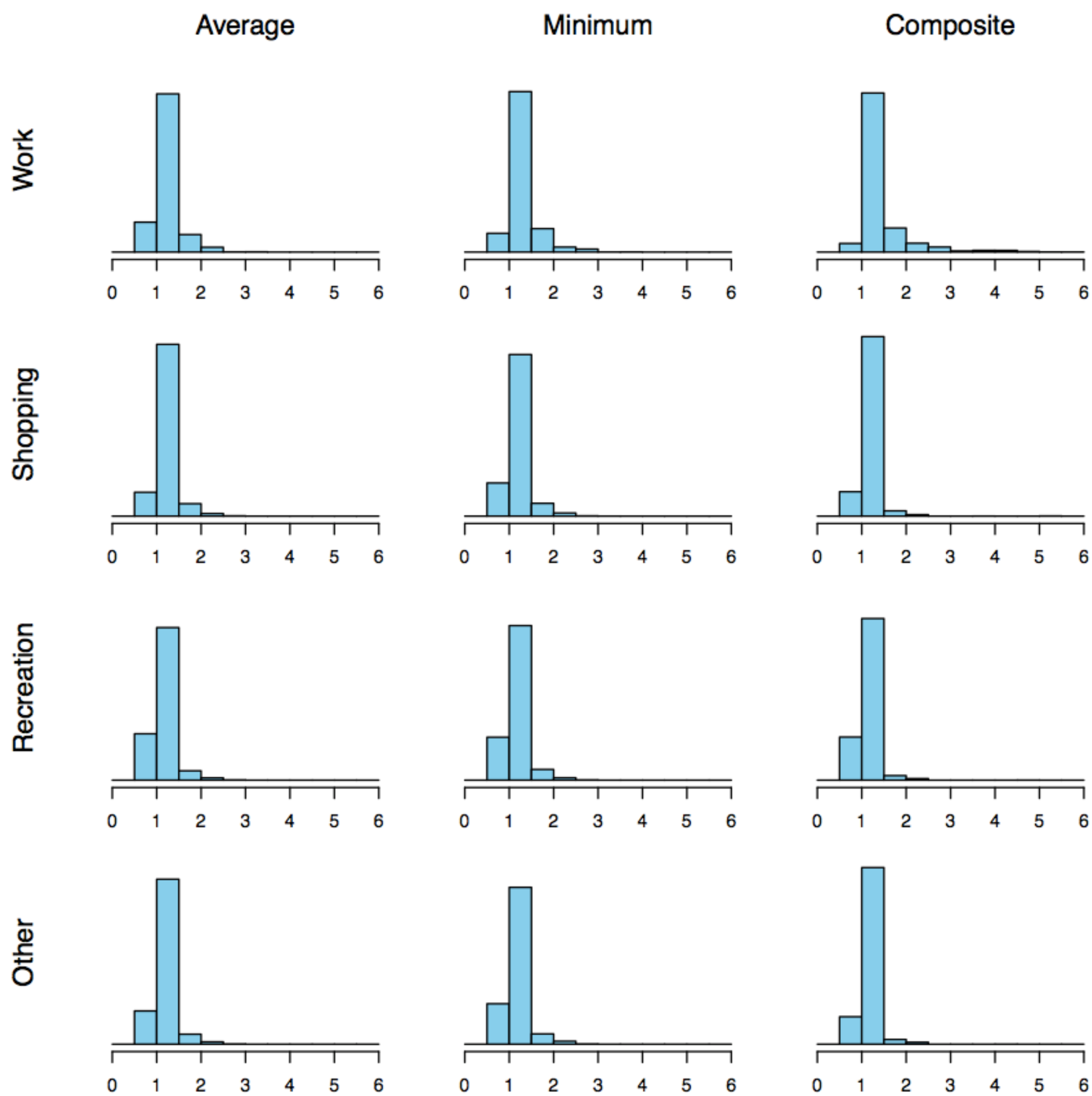

FIGURE 5. Household frequency distribution of TCI by trip purpose and mode aggregation method

Figures 6 and 7 show the corresponding geographic distributions of TCI values for the various cost aggregation methods. The differences in dispersion patterns are readily apparent. All of the methods show strong geographic variations.

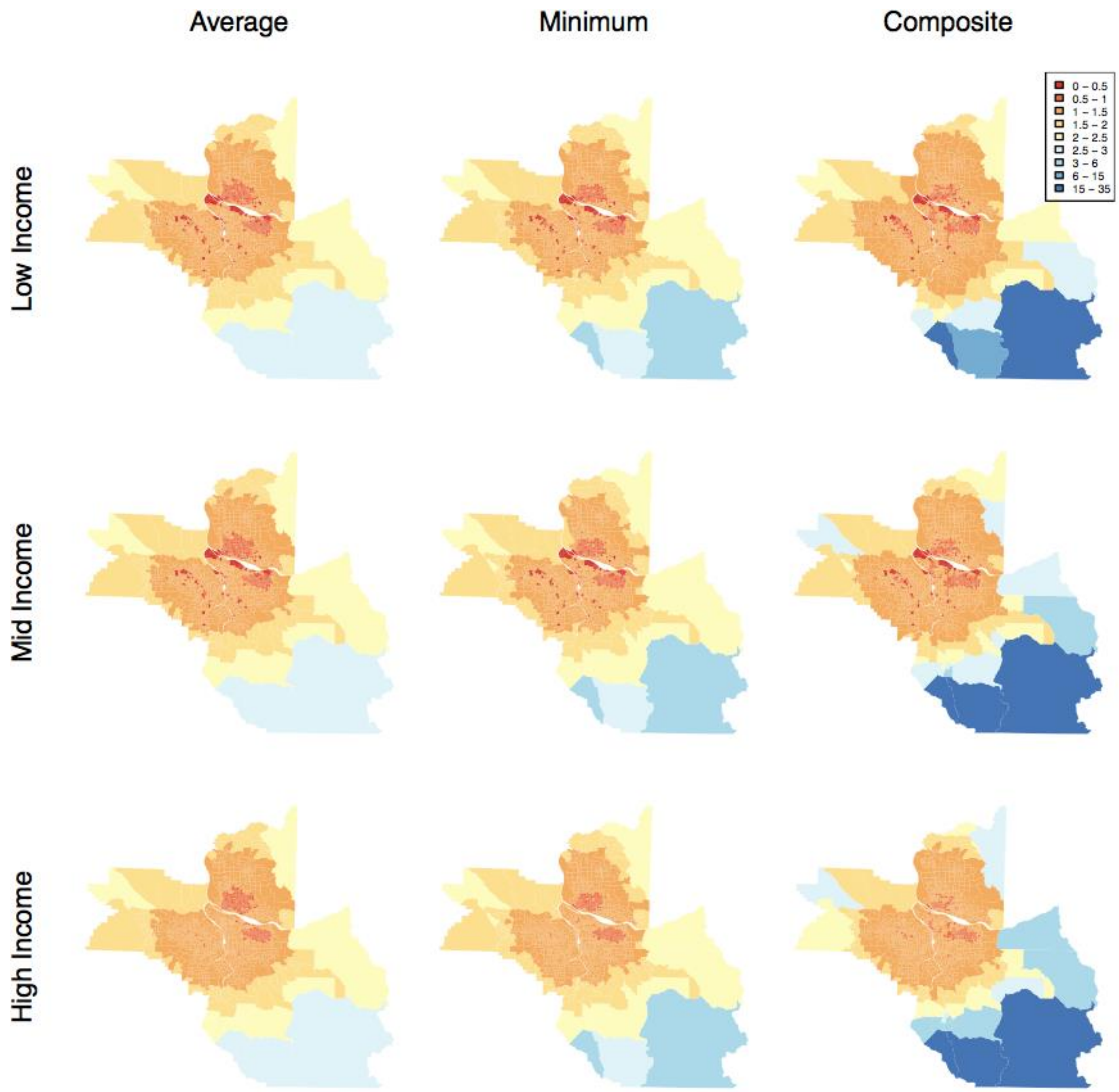

FIGURE 6. Geographic distribution of TCI by income and mode aggregation method

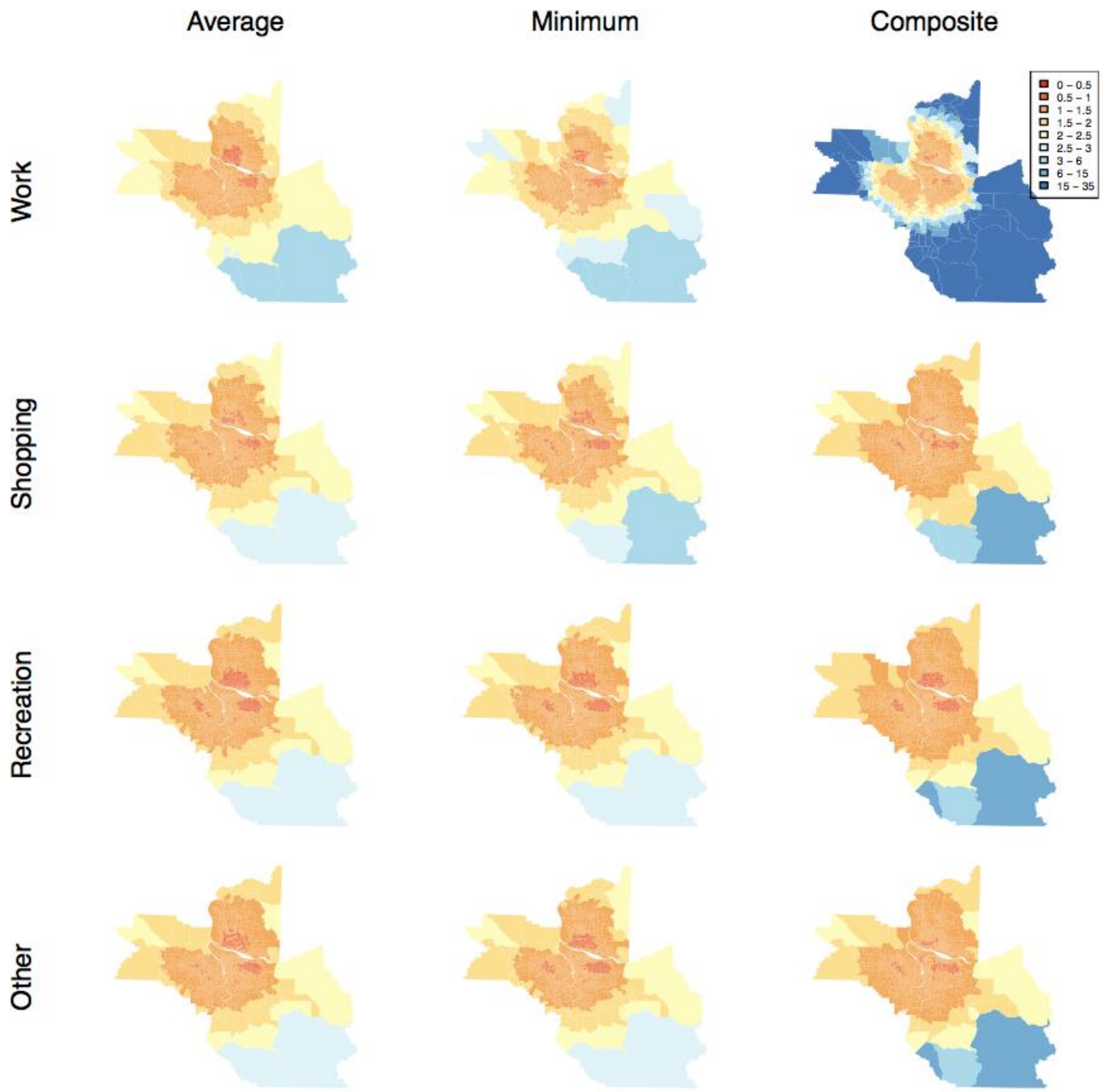

FIGURE 7. Geographic distribution of TCI by trip purpose and mode aggregation method

The maps, particularly those shown in Figure 7, illustrate why it may be useful to have several different approaches to calculating the TCI. Each method handles the interactions between transportation modes and land use in different ways. Because the Minimum Cost method uses auto mode costs for all areas, it primarily shows the effects of land use distributions and the road network on market access costs. The Average Cost and Composite Cost methods show the interactions of modes and land use. The Average cost method shows the addition of modes as increasing average costs. The Composite Cost method shows the addition of modes as increasing opportunities. A significant advantage of the Average Cost method is that it is more understandable and the effects of improving transportation services are more predictable. More research needs to be done on how each measure is affected by changes in the transportation system.

TCI values may be readily aggregated to larger geographic areas such as districts, cities, and the whole metropolitan area using trip-weighted method described above.

Figure 8 shows the district boundaries in the Metro area and Figure 9 compares the average TCI values for the cities located within the area for the three different methods of aggregating costs across modes.

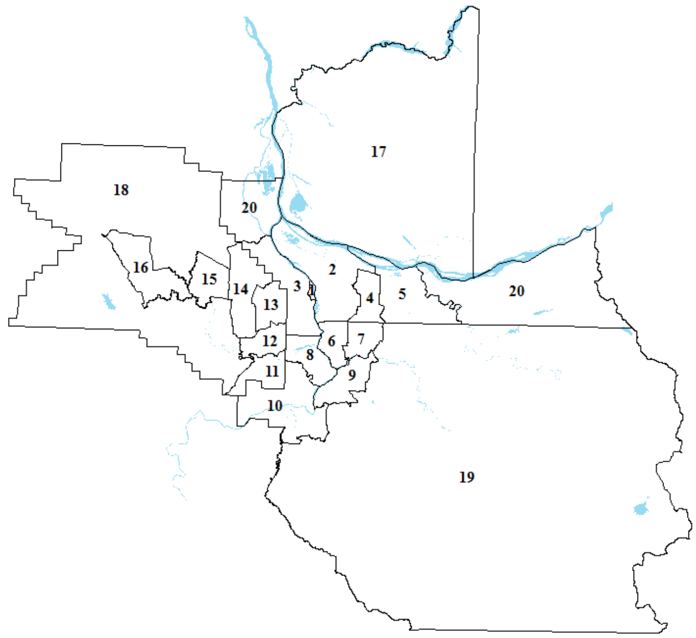

FIGURE 8. District Boundaries in the Metro Area

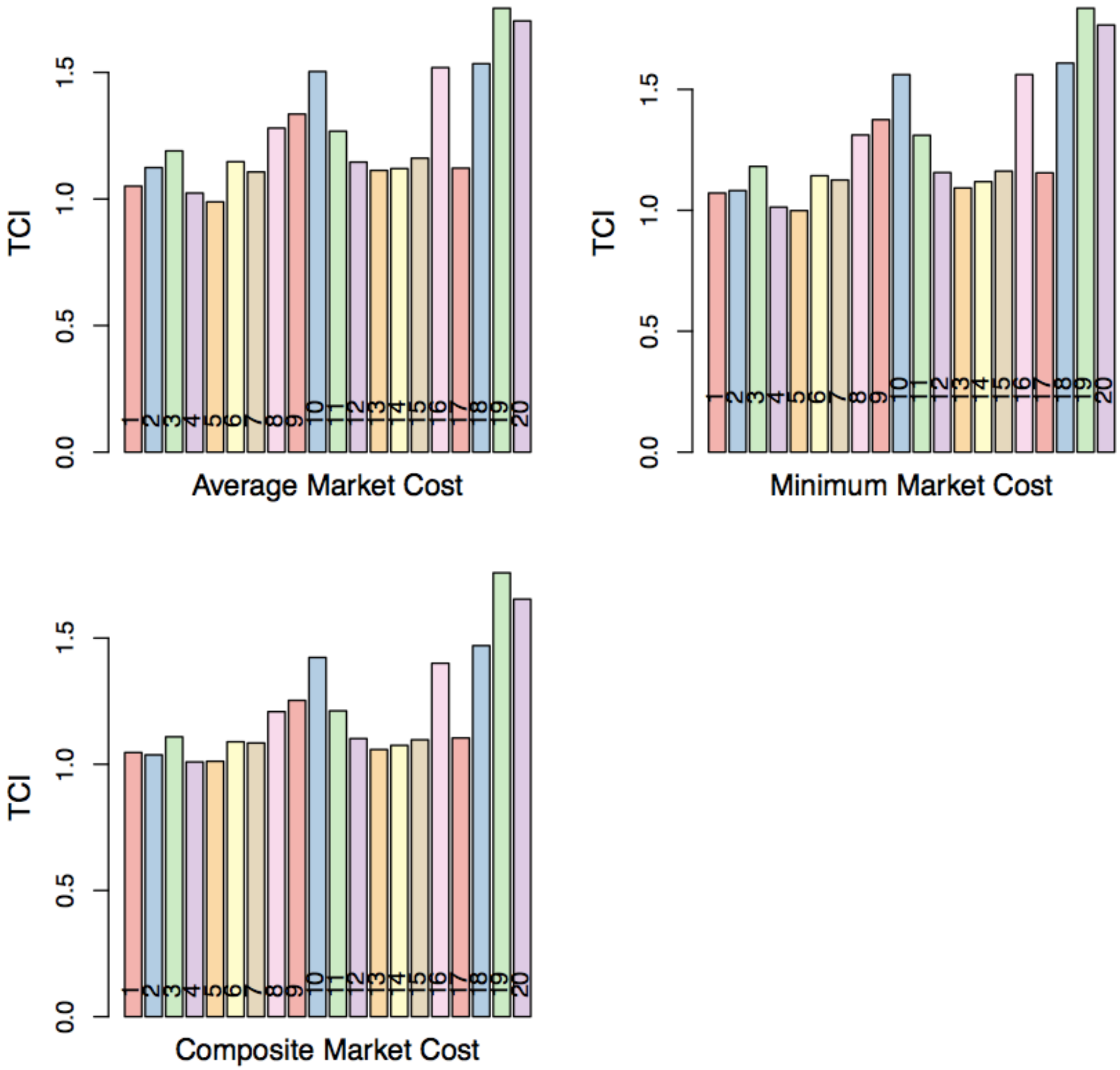

FIGURE 9. TCI values by District

Figure 9 shows that meaningful urban area averages may be calculated by this method. The TCI values vary by cost aggregation method, but the rankings among districts are similar. The minimum market cost method produces the greatest variation.

DISCUSSION AND FUTURE WORK

The Transportation Cost Index (TCI) has been shown in this paper to be a useful way to describe and map urban accessibility. It can be computed and aggregated by geographic level, income stratum, and trip purpose, and can be weighted to develop regional averages. The parallels between the popular Consumer Price Index “market basket” concept and the TCI could be further cultivated to result in a measure of overall land use / transport system performance that the public can relate to. As a result of the logic appeal of the TCI and its niche in filling gaps in policy areas including transportation and land use system compatibility and balance, TCI was adopted by the

Accessibility Indicator Development Team (IDT) for the Oregon LCP project *(14)*. Research is currently underway to address questions in the TCI implementation reported in this paper, and to further test and eventually move TCI to operational use.

Top on the list of future work is to re-evaluate approaches to define reference market baskets. The method for identifying the reference zone using log sums of access utilities was found to do a good job of identifying a TAZ that has a high level of accessibility. However, defining a reference market basket as the market area for the reference TAZ produces results are too variable to be reliable. The current approach of identifying a market area for each TAZ moves one step away from the CPI analogy. The trip percentage used to determine the size of the market basket (Equation 2) should be evaluated more carefully. The higher the value, the more the result will measure regional accessibility and mask accessibility to local attractions. Testing of alternative percentages will be an important early step in applying the methods.

Additional research and analysis needs to be applied to questions of how the methods affect equity analysis. The current TCI implementation uses the same cost coefficients to convert utilities to dollar cost equivalents for all income groups. Future research may test this setup. More research needs to be done on the question of whether market baskets should be different for different income groups. To some extent, income constrains opportunities, so constraining the market basket for lower income households creates a bias against those households. On the other hand, incomes are associated with other household attributes that significantly affect travel needs. Higher incomes are associated with more workers in the household and greater needs to purchase goods and services that are not provided by the household. Elderly households often have low incomes and fewer needs for travel. Research should be done on testing the use of other variables such as household size, number of workers and age instead of income to establish market baskets.

The TCI tests show that the method used to aggregate market access costs by different travel modes has a significant effect on the results. All three methods (average cost, minimum cost, and composite cost) were found to provide useful perspectives and are recommended for application and further testing.

The model area “edge effects” should be taken into account. Where the model area encompasses the entire urbanized area, as in the Medford example, the increased transportation costs at the edges are realistic. But where the urbanized area represented by the model is near other urbanized areas (the southern edge of metropolitan Portland, for example), a portion of the “market basket” for edge TAZ’s may be obtainable in the adjacent urban area. In those instances, the representation of trips that traverse the external cordon, by income group, purpose, and mode of travel, should be considered.

Finally, to maximize the potential usefulness of the TCI, there should be ways to translate the “market basket” of opportunities to real-world conditions as revealed by the proposed annual cross-sectional household activity surveys. The estimated (modeled) TCI should be compared to that calculated from annual revealed data from a representative sample of households.

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