Looking Beyond the Mean for Equity Analysis: Examining Distributional Impacts of Transportation Improvements

Abstract

Activity-based travel demand models can be useful tools for understanding the individual level equity impacts of transportation plans, because of their ability to generate transportation measures at disaggregate (individual and household) levels. However, these capabilities have yet to be fully explored in public practice. In this paper we first discuss a general framework for performing transportation equity analysis using activity-based travel demand models, distributional comparisons, and incorporating equity standards. In addition, we demonstrate the advantages of distributional comparisons, relative to average measures. This demonstration uses the 2000 Bay Area Travel Survey and (activity-based) mode choice model. The findings show that distributional comparisons are capable of clearly revealing the winners and losers that result from transportation improvements, in comparison with average measures. The use of these results will likely result in different conclusions on transportation investments.

Introduction

Addressing inequities across all areas of society is critical for improving public policy development and implementation. The global financial crisis of 2008 drove the subject of inequity into the forefront of public discourse, as income inequity was arguably a key factor that exacerbated this financial meltdown (Vandemoortele, 2009). In the United States, where income inequity is drastically pronounced relative to the worlds other developed nations (Tomaskovic-Devey and Lin, 2011), evidence of inequities can be found in numerous areas of society.

These equity concerns are particularly relevant in the transportation realm. Existing conditions of inequitable transportation accessibility among society have resulted from transportation planning processes which place unfair weight on the preferences of the more advantaged members of society. We are left with the reality that disadvantaged members of society have experienced less-than-fair shares of transportation benefits and disproportionately high shares of transportation externalities. These are long recognized concerns and have led to federal Environmental Justice legislation and directives (1994 Executive Order 12898, and Title VI of the Civil Rights Act of 1964) calling for government agencies (e.g. the US Department of Agriculture (USDA), the US Environmental Protection Agency (EPA), US Department of Transportation (DOT), State DOTs, and Metropolitan Transportation Organizations (MPOs)) to investigate the expected outcomes of proposed infrastructure and policy changes, and confirm that low income and minority (disadvantaged) groups will share equitably in the project benefits and not be overly adversely affected. A Comprehensive discussion on environmental justice and analysis in transportation projects is provided in Forkenbrock, D. J., & Sheeley, J. (2004).

While there are a variety of approaches found in the literature for performing equity analysis of transportation projects, an emerging approach among metropolitan planning organizations is to assess the equity impacts of proposed metropolitan transportation plans using activity-based travel demand models (Castiglione et al., 2006; MTC, 2013). These models represent the best practices in travel demand modeling and are particularly useful for equity analysis of large-scale transportation improvements, because of their use of micro-simulation and ability to generate population and travel-related data at disaggregate (individual and household) levels. The disaggregate population and travel-related data from these models enable us to explore the use of distributional comparison tools and analyze the “winners” and “losers” resulting from transportation plans. Even with the advances of activity-based travel models and the growing use of them in practice (Dong et al., 2006), a number of challenges remain with applying these models for transportation equity analysis.

The critical issues addressed in this paper lie with the approaches taken to analyze equity outcomes of transportation infrastructure and policy improvements. These approaches generally fail to paint a comprehensive picture of individual transportation impacts that result from transportation plans. In many cases the measures themselves are insensitive to the heterogeneity of transportation experiences across different groups. In this paper we present a general framework for performing equity analysis of long-range transportation plans, using activity-based travel demand models, distributional comparison measures, and incorporating equity standards. In addition, we demonstrate the advantages of distributional comparisons, relative to average measures, using the 2000 Bay Area Travel Survey and a nested mode choice model. With this demonstration, we shows that distributional comparisons are capable of revealing the winners and losers that result from different transportation improvements; an analysis that is not possible using average measures. Further, distributional comparisons provide a framework for evaluating what population characteristics and conditions lead to certain distributional transportation outcomes. Ultimately, the use of these results from distributional measures will likely result in different transportation decisions, compared to the use of average measures.

The contributions of this paper include 1) presentation of a general operational approach for performing transportation equity using activity-based travel demand models, distributional comparison, and incorporating equity standards, and 2) demonstrating the types of information gained from performing distributional comparisons of equity indicators, relative to average measures of the indicators. The remainder of this paper is organized as follows: In the background section we discuss definitions of transportation equity and the existing practice for performing transportation equity analysis. In the following section, we discuss our proposed equity analysis approach. In the following section we discuss an application of distributional comparison for simplistic transportation scenario, and then we give concluding remarks.

Background

Defining Transportation Equity

A number of definitions for transportation equity can be found in the literature. To date, there seems to be no consensus among scholars on how transportation equity should be defined (Thomopoulos, 2009; Levinson, 2010). In effort to organize these various definitions and provide a clearer understanding of what is meant by *transportation equity* in this paper, we have structured the definitions in terms of a general equity concept, equity dimensions, and equity standards. Note that we generally take a very technical definition of equity, given that our objective is to operationalize equity in the evaluation of transportation projects.

Concept: Transportation Equity refers to the fair or just distribution of transportation costs and benefits, among current (and future) members of society (Litman,2002). (Note that there are a number of different concepts for whether a distribution is considered *fair* and these concepts will be referred to as *equity standards*, as discussed below.) Transportation costs include the actual costs of building, operating, and maintaining the transportation infrastructure, as well as transportation user costs and environmental costs that result from the transportation operations and use. These environmental costs may include the direct emissions from auto use, traffic congestion, and noise pollution, etc. Transportation benefits range from improvements in accessibility, mobility, and economic vitality on the general scale, to reductions in travel time and travel user costs. Improvement in consumer surplus is also considered an indication of transportation benefit.

Dimensions: Transportation equity can be defined along two primary dimensions: Horizontal and Vertical equity (Musgrave and Musgrave, 1989; Litman, 2002). Horizontal equity, which may include spatial and generational equity, refers to the distribution of impacts (costs and benefits) across groups that are considered to be equal in ability and need. Note that in some cases spatial and generational equity are seen as separate dimensions, but for simplification purposes we group them with the Horizontal equity dimension. Vertical equity refers to the distribution of transportation impacts among sub-populations that differ in ability and need, such as different social and income classes, and disabled or special needs groups.

Standards: We refer to competing principles of equity as equity standards. A number of different standards have been discussed in the academic literature. These standards represent alternative ideas of what distribution (regarding rights, opportunities, resources, wealth, primary goods, welfare, utility, etc.) is accepted as *fair* or most desired. These standards include pareto, egalitarianism, utilitarianism, restorative justice, etc. (Rawls, 1972; Hensher, 1977; Frohlich and Oppenheimer 1992; Khristy, 1996; Forkenbrock and Glen, 2001; Forkenbrook and Sheeley 2004). A sample of these are presented in the Table 4.

The Existing Practice for Transportation Equity Analysis

In public practice, the literature points to two high-level approaches to transportation equity analysis. The first approach, which we refer to as the *modeling approach*, analyzes equity impacts using regional travel demand models, and the second approach, which we refer to as the *non-modeling approach* does not apply travel demand models to evaluate equity outcomes.

The *non-modeling approach*, which tends to be most common among planning organizations (Amekudzi et al., 2012), is characterized by the use of spatial analysis tools to map the residential locations of low income and minority communities in relation to the location of the proposed transportation projects. This is done to discern the level of benefits to these communities based on spatial proximity. In some cases, these analyses include determining whether the communities are being overly exposed to transportation externalities (air or noise pollution, traffic congestion, etc.) (MTC, 2001; Rodier et al. 2009).

Our focus in this paper is on the *modeling approach* to equity analyses, where transportation (and land-use) scenarios are modeled using a regional travel demand model. This is to measure the expected impacts of transportation (and land-use) improvements on defined population segments and to compare these impacts (costs and/or benefits) across the segments in order to judge whether the distributions of impacts is equitable. This existing approach is summarized in the following three steps:

1. Select equity indicators (such as travel times, transit mode share, accessibility to jobs, etc.) and segment the population into two categories: target group(s) and comparison group(s).
2. Calculate indicators for the population segments (the target and non-target groups).
3. Compare the changes in these measured indicators across the groups, and across scenarios (which simulate the expected changes after some transportation improvement has been made).

Critiquing the Existing Equity Analysis Process

There are two critical issues with the existing modeling approach for transportation equity analysis. These issues are regarding the unit of analysis used for segmenting the population and the method of comparing equity indicators.

Regarding the unit of population segmentation, MPOs commonly define the target group as "communities of concern" or Environmental Justice communities (MTC, 2009; SANDAG, 2011; MTC, 2013). While the variables used for segmentation (e.g. income, ethnicity, etc.) can vary, these are generally selected to capture locations with high concentrations low income and minority households. Further, the units of segmentation used are aggregate spatial units, such as travel analysis zones (TAZs) or census tracts. For example, if the communities of concern represent the target group, it is common to use all other zones in the regional together as the comparison group. The issue here is that the use of zones can lead to a high degree of aggregation bias in evaluating the impacts on population segments. In most cases there will be some share of the target group residing in comparison group zones and visa versa. Therefore it is impossible to isolate the impacts to the different groups.

The approach taken to compare the equity indicator(s) across groups can also be problematic. The common approach is to calculate the mean value of the equity indicator and compare across the population segments, from the base-case scenario to some project scenario. The concern is that the mean may mask important individual level outcomes. For example, the mean may indicate that overall, all groups are better off as a result of the scenario, when in reality only 80% of individuals benefit and 20% either stay the same or are made to be worse off.

Proposal Equity Analysis Approach

We propose an equity analysis framework that makes use of disaggregate level data from activity-based travel demand models to overcome the challenges discussed above. This framework outlines the steps for post processing the scenario output data from activity-based travel models, rather than changes to the full modeling process. This proposed framework is summarized in Table 1.

Table 1. Summary of Proposed Framework for Transportation Equity Analysis

Steps	Description
Step 1. Who and What:	Identify the equity indicator(s) and determine how to segment the population (How are the target and comparison groups identified?).
Step 2. Calculations:	Calculate the indicator(s) from the travel model data, for each unit (individual, household, etc.)
Step 3. Distributional Comparison:	Generate distributions of the indicator(s), and evaluate to determine what the distributions indicate about the impacts to the target and comparison groups.
Step 4. Rank via Equity Criteria:	Select and evaluate the equity criteria by which the scenarios should be ranked, and rank the scenarios based on these criteria.

Step 1: Identify Indicators and Segment Population

This first step in our proposed equity analysis process deals with the initial questions of "who?" and "what?" That is, this step involves segmenting the population into target and non-target groups, and identifying the equity indicators to evaluate. Our contribution here is not in recommending the best variables of segmentation or equity indicators, but to give important considerations for approaching population segmentation and identification of equity indicators. Note that for this study, we use a very technical definition of an "equity indicator". We refer to an indicator as a number or ratio (value on a scale of measurement) derived from a series of observations. (Chen, 2010). Therefore, an equity indicator is set of records or observations that measure the costs or benefits associated with implementing a transportation plan.

The data types available from the activity-based travel modeling system can be used to generate a wide range of equity indicators, at all levels of data aggregation: from the individual level to neighborhood and higher levels. These data include population data, travel behavior data, travel network data, and land-use data (which may be endogenous or exogenous to the travel model). These data are outlined of Table 2.

Table 2. Available Data from Activity-Based Travel Demand Models

Category	Data Types	Data Features
Population Data	Individual Level	ethnicity, age, gender, employment status, employment sector
	Household Level	size, income, residential location, # workers, # children, # vehicles
Travel Behavior Data	Trip Level	location, purpose, mode, time-of-day
	Tour Level	tour class (home-based mandatory, home-based non mandatory work-based, etc.), stop frequency, primary mode, primary origin and destination
	Day-Pattern	tour frequency
Travel Network Data	Travel Time Skims (by mode)	in-vehicle times, wait times, access times
	Travel Cost Skims (by mode)	vehicle operating costs, tolls, parking costs, transit fares
	Travel Distance Skims (by mode)	
	Volumes	vehicle-miles-traveled
Land-use Data		locations (i.e. zones, neighborhoods, etc.), population, # households, employment by sector, amenities (shopping, hospitals, banks, etc.)

From these data, analysts are able generate a range of equity indicators. The most common are work travel time, accessibility to employment, and emissions exposure by population segment (MTC, 2009; SANDAG, 2011; MTC 2013). A more comprehensive list of equity indicators used by MPOs is given in Table 3.

Table 3. Common Equity Indicators used in Practice.

Indicator Type	Details/ Variations
Accessibility (by mode)	To jobs
	To schools
	To medical services
	To recreation facilities
Travel Time (by mode)	For all travel purposes
	For mandatory purposes (including work and school)
	For non-mandatory purposes (including for groceries, general shopping, recreation, banking, etc.)
Travel distance	To work
Mode share	By transit modes
	By active (walk and bike) modes
Project Investment proximity	By population segment
Environmental Quality	Exposure to vehicle emissions
	Exposure to noise pollution
Congested vehicle miles traveled	By population segment
Displacement	By population segment

Considerations of Selecting Equity Indicators

When selecting indicators of transportation equity, an important consideration is how well the indicators represent costs or benefits of the transportation plan. It is important that the indicator clearly measures whether travel conditions for different groups are actually being made better or worse. To do this, one may first consider the transportation benefit to be measured. For example, analysts often use transit mode share as an equity indicator, although it is uncertain whether increases in transit mode share actually reflect that conditions are improving for target groups. Increases in transit mode share may indicate that improved transit accessibility is drawing greater ridership from the target population to transit services, or it may be an artifact of rising highway tolls meaning that some travelers are being priced out of their preferred travel option. These two scenarios have conflicting equity implications. An additional consideration is for confounding factors that may be correlated with expected transportation benefits. For example with any consumer surplus-related indicator, the heterogeneity of willingness-to-pay among different income classes is known to bias consumer surplus measurements (Frank, 2000; Martens, 2009), given that consumer surplus is theoretically the difference between ones willingness-to-pay and the price of a given commodity. If the marginal utility of price is not fixed for income groups, this would cause consumer surplus comparisons across income classes to be problematic.

Population Segmentation

The approach to segmenting the population into target and comparison groups involves the use one or more *variables of segmentation* (e.g. income, ethnicity, gender, etc.) and a *unit of segmentation* (e.g. individuals, households, census blocks, travel analysis zones, etc.). In previous analyses, the target group is commonly defined in terms of “communities of concern”. These are zones or census blocks that are identified based on high concentrations of low income and minority residents (MTC, 2009; MTC, 2013b). In this case, the variables of segmentation are income and ethnicity, and units of segmentation are zones or census tracts. The variable(s) of segmentation may be guided based on the equity dimension chosen for the analysis. For example, income, age, and gender are variables that represent vertical equity, while location, travel mode, and time-of-day represent horizontal equity. For the unit of segmentation ("what" we are segmenting), smaller units (i.e. individuals or households) are more desirable, given the aggregation bias that can result from using larger zones (Duthie et al., 2007)

Step 2: Calculate Indicators

The second step involves calculating the indicator for each unit of segmentation in the sample. Given that there are likely multiple ways to calculate the same indicator from activity-based travel model data, a decision needs to be made on the formula to be used. For example, travel time can be measured by mode and time of day as well as activity type (i.e. trip level, tour level, or day pattern level). Similarly, consumer surplus or accessibility can by calculated from multiple choice dimensions available in the model (e.g. mode choice level, destination choice level, residential location choice level, etc.).

There is extensive literature on equity measures and how they are calculated (Ramjerdi, 2006) so we don't repeat this information here. We simply emphasize that measures that are sensitive to level-of-service changes, land-use changes, as well as individual preferences/ circumstances are more desirable. An example of this is the logsum measure, which is comprehensive and individual-specific, can be interpreted as a measure of accessibility or consumer surplus. (DeJong et al., 2005).

Step 3: Compare Changes in Indicators Across Groups

This third step is to compare the disaggregate indicators across the population segments and for each scenario relative to the base scenario conditions. As mentioned earlier, the mean of any indicator will likely mask important information about the distribution of impacts, resulting in misleading equity analysis results. Alternatively, we propose the use of distributional comparisons, where distributions of the selected indicator(s) are generated and analyzed. Here, we describe two types of distributional comparisons: one of the aggregate densities and one of individual-level differences.

The first comparison is of the aggregate density of the equity indicator measured for each scenario being compared (e.g. before and after some transportation improvement(s)). This *Aggregate Density* comparison is illustrated in Figure 1. This first comparison gives a view of the general change experienced by population segments. Analysts may wish to compare the "after" distributions for different population segments to get a sense of overall differences or to identify the presence multiple modes in the distribution. This would indicate that there is a subgroup whose impacts do not follow those of the larger population segment.

The second type of comparison is of the individual or household level differences in the indicator. For this comparison, we calculate the individual differences in a given indicator across planning scenarios and generate distributions of these values for the different population segments. We refer to this comparison as the *Individual Difference Density* comparison. This is shown in Figure 2.

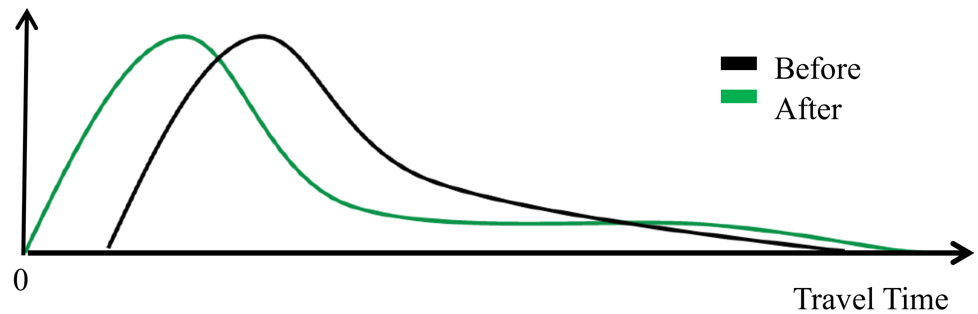

Figure 1. (Hypothetical) Aggregate Density Comparison

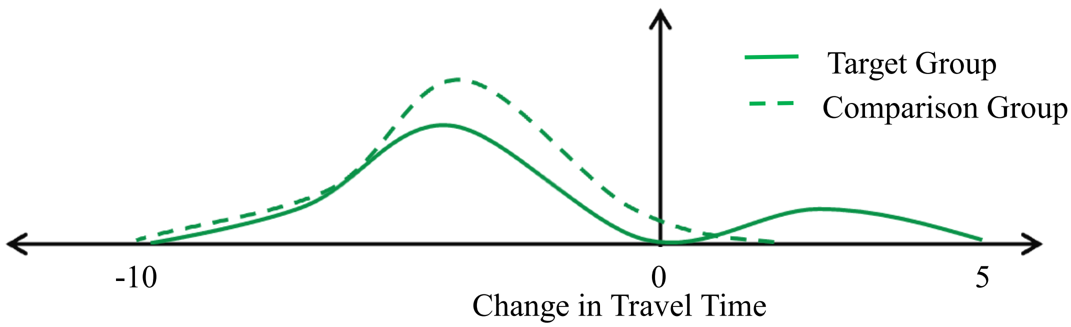

Figure 2. (Hypothetic) Individual Difference Density

The Individual Difference Density comparison evaluates the individual level changes across the population. With this type of comparison, it is possible to identify the portion of each segment likely to experience positive or negative changes: *winners and losers.* Figure 2 illustrates a hypothetical example of the Individual Difference Density comparison, using the individual level changes in travel time for a target group vs. a comparison group. Values to the right of the origin (0) represent increases in travel time (losers), while values to the left of the origin represent decreases in travel time (winners). In this case, a significant share of the target group experiences losses in travel time, while very few in the comparison group experience losses. This type of finding is not possible using the Aggregate Density comparison. A graphical analysis of this individual level comparison provides a meaningful picture of how population segments will be affected by the transportation scenario. This type of analysis also lends itself nicely to cases where the impacts of several groups need to be compared. Further, a number of simple summary measures that can be generated from this type of comparison, including the share of winners, share of losers, total gains, total losses, and relative losses/gains.

Note that the Relative Distribution approach is another distributional comparison approach, which is well known in the literature (Handcock and Morris, 1999). These methods quantify the changes in location and shape between two distributions and have proven to be very informative for equity analysis (Franklin, 2005). However, Relative Distribution methods operate at the aggregate distribution level, where changes at the individual level can go undetected. Further regarding application for equity analysis, Relative Distributions can be difficult to interpret for practitioners and decision-makers. Therefore, there is a need for distributional measures that can supplement Relative Distribution approaches; both with evaluation of disaggregate level changes and greater accessibility to transportation practitioners and decision-makers.

Step 4: Rank Scenarios using Equity Criteria

With transportation equity analysis, the question is not so much whether or not a plan results in equitable outcomes, but the degree to which a plan results in equitable outcomes (Levinson, 2010). This principle lends itself to a ranking strategy, rather than an absolute determination of whether a plan is equitable or not. We address this as a final step in the analysis process. In this step, the alternative scenarios are to be ranked based on a defined equity standard. The tasks are to first identify some equity standard(s) or criteria by which to rank the scenarios. It is then necessary to calculate the degree to which these criteria are satisfied using the comparison results from Step 3.

In the literature, we find a number of proposed equity standards. These are different concepts of what should be considered "fair' with regard to the distribution of benefits. A sample of these is presented in Table 4. Ultimately, the selection of equity standard(s) is at the discretion of the practitioner and agency, based on consultation with community members and stakeholders and federal regulations (Thomopoulos, 2009). Here, we simply want to emphasize the need to select equity standard(s) by which to rank alternative scenarios, in order to identify projects that best meet the transportation equity goals for the region. This step is traditionally lacking from transportation equity analysis in practice.

Table 4. Equity Standards

Equity Standard	Description
Basic Needs	A compromise between egalitarian and market–based equity; first the basic needs to each group are satisfied, then the remainder of the benefits are distributed according to market-based equity (Khristy, 1996; Duthie et al., 2007).
Equality/ Egalitarian	Providing an equal level of benefits among all groups of interest. Note that given the different levels of need and value that individuals place on these benefits, equality of benefits may be achieved without the actual amount of benefits being equal (Miller, 1979; Forkenbrock and Glen, 2001; Rosenbloom, 2009).
Market-based	"You get what you pay for": an allocation in proportion to the price paid for the use of facilities. This is typically evaluated by comparing the amount a group pays in taxes and fees with the level of benefits receive (Forkenbrock and Glen, 2001; Levinson, 2010).
Maxinum Average Net Benefit	Maximizing the average benefit, using a certain amount as a constraint, to ensure that certain groups of interest (the most neglected groups) receive a certain minimum amount of benefit (Frohlich and Oppenheimer 1992, Khristy 1996).
Pareto	A change in benefits that results in at least one individual or group benefiting, without making anyone else worse off (Juran, 1950; Just, et al 2004).
Proportionality	Distributing benefits is proportion to the share that the group represents in the total population (Young, 1995; Forkenbrook and Sheeley 2004, Martens, et al 2010).
Restorative Justice	A distribution of benefits that calls for the "equalizing" of existing differences between groups of interest; that is remediating the existing disproportionality of transportation benefits (Martens, et al 2010).
Utilitarianism	Providing a distribution that produces the greatest utility or level of satisfaction, for the greatest number of people (Hensher,1977).
Rawls-Utilitarianism	Providing the greatest level of benefits to those who are the most disadvantaged (Rawls, 1972).

Applying Distributional Comparisons For Transportation Equity Analysis

The task of generating distributional equity measures using a large scale travel model and a fully representative population can be off-putting. There are numerous population and environmental (transportation and land-use) factors that together shape the transportation experiences of individuals. In a real world setting, for example, one's income level, age, gender, ethnicity, residential location, work location, and access to various travel modes all play key roles in determining how one is affected by transportation system changes. In such a complex system where numerous population, land-use, and transportation factors are at play, the influence of these factors on distributional outcomes can seem impossible to disentangle. For this reason, we simplify the analysis as much as possible by using a single variable of segmentation and simplistic transportation scenarios. The equity indicator is consumer surplus; calculated from a nested mode choice model. We then generate and evaluate distributions of individual changes in consumer surplus. In the following sections we discuss the consumer surplus calculations, the data set, transportation scenarios, and the comparison results.

Equity Indicator

We use the logsum accessibility/consumer surplus measure as the equity indicator. While the logsum has long been used as a measure of transportation benefits (DeJong et al., 2005), it is not commonly used in practice for evaluating large-scale transportation scenarios. Other possible indicators could be calculated based on travel time or cost. However, in the absence of a full travel modeling system to generate travel skims, it is necessary to calculate the expectation of travel time or cost changes; neither of which gives meaningful representations of transportation benefits. In this case, the logsum measure is comprehensive and captures all changes in utility due to the transportation changes. While the logsum measure alone is not a direct measure of transportation equity, it is a comprehensive measure of transportation benefits. It is therefore a desirable measure to use for distributional comparison.

The "logsum" measures the expected maximum utility or welfare derived from a choice situation. This utility-based measure takes the mathematical formulation of the denominator of the logit discrete choice probability. The basic expression for the logsum is as follows:

$$Logsum_n = E\left[max_j(V_{nj} + \varepsilon_{nj})\right] = \left[ln\left(\sum_j exp(V_{nj})\right) + C\right] \quad (1)$$

where $Logsum_n$ is the expected maximum utility for individual n, j is the subscript for all possible alternatives, V_{nj} is the systematic utility expression, ε_{nj} is the random error term, and C is the constant[1]. While the logsum can be a useful measure of transportation accessibility, it is also mathematically equivalent to a measure of consumer surplus (Train, 2009).

The logsum measures the Compensating Variation (CV), which is a Hicksian (compensated demand) measure of consumer surplus, as opposed to a Marshillian or uncompensated demand measure. We do not present a full introduction to CV here, but this measure of consumer surplus is interpreted as the maximum amount of money given to (or taken from) a particular consumer,

[1] The unknown constant *C* represents that the absolute level of utility cannot be measured (Train, 2009).

in order for them to maintain their existing level of utility as before a commodity price change (a function of the old and new utility levels) (Just et al., 2004).

The expression for this logsum consumer surplus measure is as follows:

$$CS_n = (\frac{1}{\alpha_n})\left[ln\left(\sum_j exp(V_{nj})\right) + C\right] \quad (2)$$

where the difference here relative to equation (1) is that the expression is divided by the marginal utility of income α_n, which converts the measure to monetary units.

It is important to note that the marginal utility of income may in reality vary according to the income levels of the decision makers (Abouchar, 1982; Jara-Díaz, 1986**.** However, the use of heterogeneous marginal utilities of income (the inclusion of income effects) would bias the impacts (positively or negatively) across income classes. To control for this, we a constant marginal utility of income, as has been validated and is common in practice (Williams, 1976; Rosen and Small, 1981). Although this measure (with a constant marginal utility of income) is inconsistent with the theoretical consumer surplus measure (using heterogeneous marginal utilities), it allows for useful consumer surplus comparisons across income groups.

Data: 2000 Bay Area Travel Survey

The 2000 Bay Area Travel Survey (BATS) is a regional-scale household travel survey collected by the Metropolitan Transportation Authority (MTC) to support modeling and evaluation of travel across the Bay Area. For this survey, travel diary data for over 14,000 households was collected. This includes household population data (location, income, household size, number of workers, number of children, number of vehicles, etc.) and individual travel records over a two-day period (travel destinations, time-of-day, purpose, travel mode, etc.). For our purposes, we use the work tour data and some household characteristics to estimate our mode choice model. Note that the raw BATS travel records are originally in the form of person-trips. However, we make use of the San Francisco County Transportation Authority's (SFCTA) version of the data, in which the trips are processed into tours (linked trips from primary origin to primary destination) and corresponding level-of-service skims (travel times and costs) are attached. A total of 26701 work tours from across the Bay Area are used for model estimation. Of these tours, 12% are made by low income travelers (earning less than \$30,000 annually) and 30% are made by high income travelers (earning more than \$100,000 annually).

Mode Choice Model

The model is developed to resemble the structure of MTC's mode choice model, as this is the model structure (a component of MTC's activity-based model) that is used for scenario analysis in the Bay Area. The model structure is nested logit with three nests. The first nest includes three auto mode alternatives (drive alone, shared-ride 2, and shared-ride 3); the second nest includes two transit mode alternatives (drive-transit and walk-transit); and the third nest includes two active modes (walk and bike). Note that the auto modes are distinguished by occupancy level: single occupancy (Drive-Alone), double occupancy (Shared-Ride 2), and three or more occupants (Shared-Ride 3). Also, the transit modes are distinguished by access mode: drive-to-transit or walk-to-transit. This nested logit specification allows for a more realistic correlation structure between the choice alternatives, relative to multinomial logit. The estimation results are given in Table 5.

Setting and Planning Scenarios

As previously mentioned, the setting for this evaluation is the nine-county San Francisco Bay. This region is spatially divided into travel analysis zones. Based on MTC's zonal system, there are a total of 1454 zones representing the region. The residential and employment locations of travelers are scattered across the region, although the primary job centers are San Francisco, Oakland and San Jose. As with MTC's model and other mode choice models used in practice, the mode choice set varies across individuals. For example some individuals may not have access to the Drive-Alone alternatives due to a disability or lack of access to an automobile. Similarly, some individuals may not have access the Bike mode if they do not own a bike, or if there is poor bike infrastructure between their residential and work locations. Further, travel takes place at various times-of-day, based on individual needs. Regarding mode share, there are interesting differences across income groups. The low income group is more likely to take Transit and Walk/Bike modes, relative to the high income group. This is shown in Figure 3.

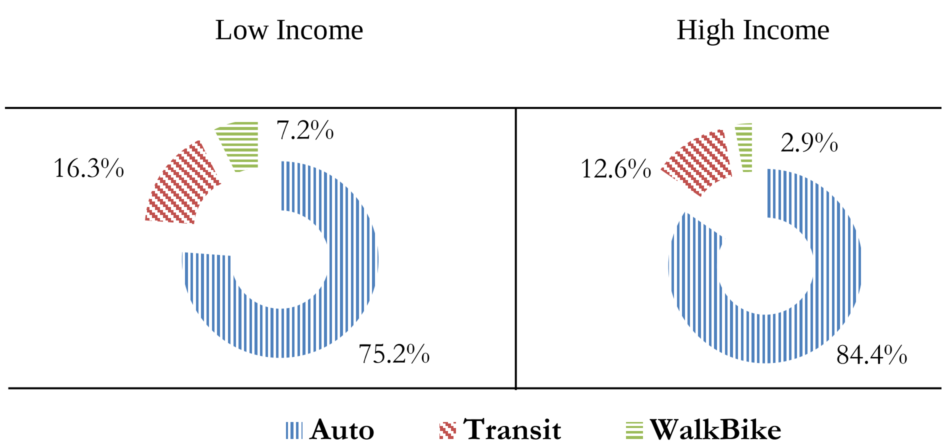

Figure 3. Mode Shares for Low Income and High Income Workers

Table 5. Mode Choice Model Estimation Results

Parameter Name	Estimate
Alternative Specific Constants	
Auto Modes	
Shared-Ride 2	-1.7090
Shared-Ride 3	-2.5825
Active Modes	
Walk	-0.2205
Bike	-1.6223
Transit Modes	
Walk-Transit	0.2987*
Drive-Transit	-1.0560
In-Vehicle Travel Times	
Auto and Transit	-0.0245
Bike	-0.0785*
Walk	-0.0551
Transit Wait Times	
Initial Wait	-0.0365
Transfer	-0.0349
Costs	
Travel Cost	-0.2494
Parking Cost	-0.0416
Income Categories	
Active Modes	
Low Income	0.7076
Low-Medium Income	0.4533
Medium-High Income	0.5112
Transit Modes	
Low Income	0.2331
Low-Medium Income	0.1314
Medium-High Income	0.0003*
Tour Stops (Greater than 1)	
Active Modes	-0.8113
Transit Modes	-0.2292
Nest Coefficients	
Active Modes	1.2633
Transit Modes	1.4365

*Not significant at the 5% confidence level

Results

Travel Cost Scenario

For the first scenario, there is a 20% reduction in travel costs. We start by calculating the average changes in the logsum measure, and then follow with the Individual Difference Density comparison. The average changes in the losgum measure for low and high income travelers are given in Table 6. Here we find that both income groups experience similar average effects: a small but positive change. Higher income travelers experience a (slightly) greater positive impact on average.

Table 6. Average (daily) Change in Consumer Surplus due to Scenario 1
(20% Travel Cost Reduction)

	Average Change in Consumer Surplus	
	Low Income	*High Income*
Change per person	$0.14	$0.15

The findings from the individual difference comparison are consistent with the finding from the average measures. In Figure 4, we see from the relative positions of the curves that high income travelers are likely to experience higher gains, relative to low income travelers.

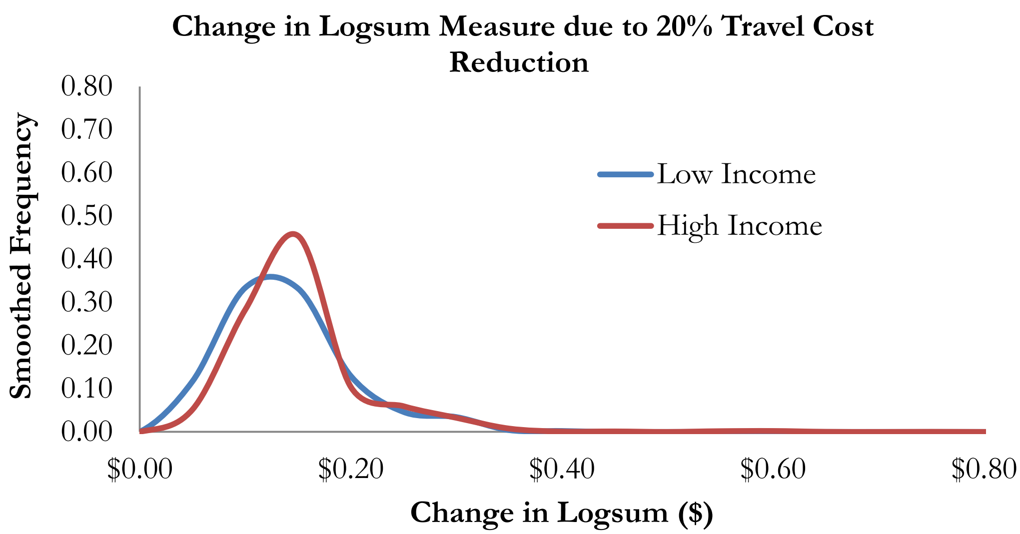

Figure 4. Individual Difference Comparison for Scenario 1
(20% Travel Cost Reduction for auto and transit modes)

Travel Time Scenario

For the second scenario, there is a uniform 20% reduction in travel times for all travel modes. For the active modes, this represents (for example) improvements in walking and biking infrastructure that enhance connectivity (i.e. bike trails, and pedestrian overpasses). The results from the average changes in the logsum measure for low and high income travelers are given in Table 7, and the Individual Difference Density comparison results are given in Figure 5. We find positive average changes in the logsum measures for both low and high income travelers. However, low income travelers experience a higher average benefit relative to high income travelers. Further, the magnitudes of the average changes are almost two times those resulting from the travel cost scenario.

The Individual Difference Density comparison for this scenario produces more interesting results. In Figure 5 (A), we see that the scenario results for overall travel time reductions produce a bi-modal shape. In the first and taller peak (ranging approximately from \$0.00 to \$0.20), the curve for high income travelers is positioned above the curve for low income travelers, indicating that the higher income travelers are more likely to experience smaller gains. For the second peak (ranging approximately from \$0.20 to \$0.50), the low income curve is positioned above the high income curve, indicating that lower income travelers are more likely to experience higher gains.

An important question here is why the travel time scenario results in a bi-modal shape, while the travel cost scenario produces a uni-modal shape. In contrast to the travel cost reductions scenario, all travel modes contribute to the logsum (utility) gains due to the travel time reductions. Only auto and transit modes contribute to the logsum gains that are due to travel cost reductions, as walk and bike modes are assumed to have no travel costs.

To further understand the underlying causes for this shape, we generate three additional scenarios where we improve the travel times for each mode separately. These scenario results are shown in the Figure 5 (B-D). Interestingly, we find that the greatest difference between the impacts to high and low income travelers comes from the reduction in active (walk and bike) travel times. This indicates that low income travelers are more likely to derive higher consumer surplus gains from improvements for active modes. While these results help us to tease out the influence on the overall bi-modal shape, is it not completely clear from the data why we find this result. There are a number of complex relationships at play; specifically regarding mode availability, origin-destination pairs, and income level. Although this result (a great benefits for low income travelers from active mode travel time reductions) is not surprising, it is nevertheless clear from this demonstration the types of information that distributional comparisons can reveal relative to average measures.

Table 7. Average (Daily) Change in Consumer Surplus due to Scenario 2
(20% Travel Time Reduction)

	Average (Daily) Change in Logsum Consumer Surplus	
	Low Income	*High Income*
Overall Travel Time Reduction	$0.27	$0.23
Auto Travel Time Reduction	$0.13	$0.16
Transit Travel Time Reduction	$0.05	$0.04
Active Travel Times Reduction	$0.10	$0.04

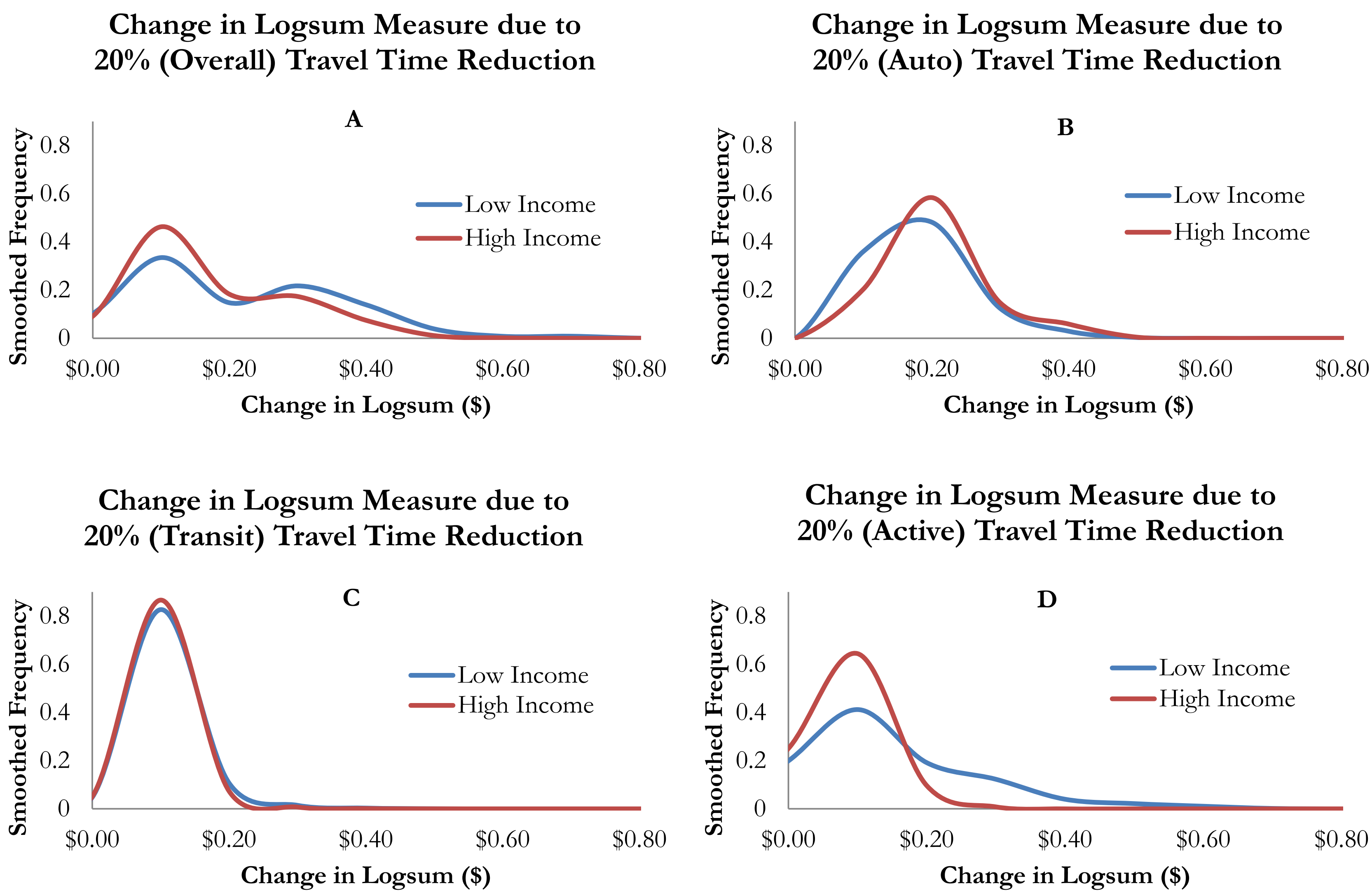

Figure 5. (A) Individual Difference Comparison for a 20% overall reduction in travel times. (B) Individual Difference Comparison for a 20% reduction in auto travel times. (C) Individual Difference Comparison for a 20% reduction in transit travel times. (D) Individual Difference Comparison for a 20% reduction in active (walk and bike) travel times. The bin size is $0.10

Conclusions

We have presented an approach for equity analysis of transportation improvements and demonstrated the use of distributional comparisons of transportation equity analysis, using real-world travel survey data and a realistic (activity-based) mode choice model.

There are four steps in our proposed equity analysis process. The first step is to select the equity indicators to be evaluated and segment the population into target and comparison group(s). In this case we advocate for an individual unit of segmentation (rather than zones) and therefore comprehensive equity indicators, which are sensitive to level-of-service changes, land-use changes, and individual-level circumstances. This minimizes the biases associated with aggregate group segmentation and average equity indicators. The second step is to calculate the indicators from the model data output, which involves determining the exact measures (formulas) for the selected equity indicators. This requires careful consideration given the large variety of data available from activity-based models. The third step in the process is to generate and evaluate distributions of the individual-level equity indicators. In particular, we advocate for the use of what we refer to as the "Individual Difference Density" comparison, which compares distributions of individual-level changes for the population segments across the planning scenarios. This comparison allows for the "winners" and "losers" resulting from the transportation and land-use plans to be identified. The fourth and final step in the process is to identify and evaluate equity criteria (based on the chosen equity standard(s)) and rank the planning scenarios based on the degree to which they meet the equity criteria.

In the second part of the paper, we focus on third step in the framework and provide a demonstration of what it means to apply distributional comparisons for transportation equity analysis. We find that the shapes of the Individual Difference Densities are reflective of which modes generate the greatest benefit for the different income groups. While high income travelers derive much more of their utility gains from auto and transit modes, low income travelers gain significantly more utility from walk and bike modes. In this case, the policy implication is that bicycle and pedestrian investments may provide significant improvements, in terms equitable transportation benefits in the region.

Overall, we find that distributional comparisons are capable of providing a meaningful picture of individual travel experiences due to transportation changes. Further, they provide a means of analyzing these scenario impacts to identify the winners and losers, as well as identifying specifically what factors lead to these transportation (equity) outcomes. This level of analysis is otherwise limited using average measures. It is likely that the use of distributional comparison for equity analysis would result in different conclusions around which transportation improvements are more equitable, as compared to using average measures.

Acknowledgements

This research was partially supported by the Dwight David Eisenhower Transportation Fellowship program and the WTS Helene M. Overly Memorial Graduate Scholarship. We also want to thank Dr. David Ory of the Metropolitan Transportation Commission and Elizabeth Sall of the San Francisco Municipal Transportation Agency, who provided data, insight, and expertise that greatly assisted this research.

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