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Method of Obtaining Consumer Welfare from Regional Travel Demand Models

CAROLINE J. RODIER AND ROBERT A. JOHNSTON

The need for more comprehensive traveler welfare measures is highlighted by the U.S. Intermodal Surface Transportation Efficiency Act (1991) requirement that transportation projects and plans be evaluated for economic efficiency. However, to date, there has been a discrepancy between this requirement and the methods used by regional transportation organizations to evaluate transportation policies in the United States. Kenneth Small and Harvey Rosen illustrate how a consumer welfare measure known as compensating variation can be obtained from discrete choice models. A method of application is developed for the mode choice models in the Sacramento Regional Travel Demand Model. The results of the method's application to the model for light rail transit, high-occupancy vehicle lanes, and auto pricing scenarios are examined for both total consumer welfare and consumer welfare by income class.

Transportation agencies in the United States typically use criteria such as lane-miles of congestion, hours of travel delay, travel distance, and mode share to evaluate proposed transportation policies. Such criteria are limited because they fail to account for the balance of effects on travel accessibility from changes in transportation policies. For example, high-occupancy vehicle (HOV) lanes may reduce travelers' hours of delay but increase their full unobserved travel costs because of increased vehicle kilometers traveled; the uncalculated balance between these two effects may be a loss or a gain in overall traveler accessibility. The need for more comprehensive criteria is highlighted by the U.S. Intermodal Surface Transportation Efficiency Act (ISTEA) (1991) requirement that transportation projects and plans be evaluated for economic efficiency.

A complement to the goal of efficiency in transportation is the goal of equity. A highly efficient transportation system that excludes certain groups of people from access to employment and essential services would not generally be considered socially desirable. Consumer welfare measures can be used to calculate the gain or loss in accessibility to specific groups (usually income groups) due to transportation policies, which can then be compared to determine whether one group benefits more than another or whether one group gains at the expense of another. With this knowledge, it may be possible to redesign policies to redress losses to certain groups.

Quantification of consumer welfare measures is limited by transportation organizations' time, budgetary, and technological constraints (1). This may help explain the inadequacy of consumer welfare measures implemented by transportation agencies in the United States to date and the discrepancy between the requirement in ISTEA and the methods for evaluating transportation policies currently used by regional transportation organizations. What is needed, then, are theoretically valid consumer welfare measures that are quantifiable within the agencies' technological and budgetary limits.

Kenneth Small and Harvey Rosen (2) illustrate how a consumer welfare measure known as compensating variation (CV) can be obtained from discrete choice models (hereafter referred to as the Small and Rosen method). Our review of the published literature suggests that this method has not been applied to normal (aggregate) regional travel demand models in the United States. A method of application is developed and applied to the mode choice models in the Sacramento Regional Travel Demand Model (SACMET 94). The results of the method's application to the model for light rail transit, HOV lanes, and auto pricing scenarios are examined for both total consumer welfare and consumer welfare by income class.

SMALL AND ROSEN METHOD

Small and Rosen (2) develop the expression for obtaining the compensating variation measure of consumer welfare from discrete choice models. In this study, the application of the method is examined in the context of a mode choice model that takes the specific discrete choice formulation of the logit equation.

Consider, for example, that traveler n faces a number of discrete modal choices $m = 1, \dots, M$ (e.g., car, transit, bike, or walk) for a trip; traveler n chooses the mode that maximizes utility. Traveler n 's utility for mode m (U_{nm}) is given by the sum of both the systematic or indirect utility (V_{nm}), which is a function of modal and household attributes, and a random component (e_{nm})

$$U_{nm} = V_{nm} + e_{nm} \quad (1)$$

The probability of traveler n choosing mode l is equal to the probability that the utility of mode l is greater than or equal to the utilities of all other alternatives in the choice set. This probability can be expressed as

$$P_{ln} = \Pr\{V_{ln} + e_{ln} \geq V_{nm} + e_{mn}, \text{ all } m \neq l, m \in C_n\} \quad (2)$$

In this example, the indirect utility of a mode m (V_{nm}) might take the following form

$$V_{nm} = \beta_1 + \beta_2 P_{nm} + \beta_3 T_{nm} + \beta_4 Y_n \quad (3)$$

where

P_{nm} = travel cost by mode m for traveler n ,

T_{nm} = travel time by mode m for traveler n and

Y_n = traveler n 's household income

Assuming the error terms are Gumbel distributed, the probability of traveler n choosing mode l is

$$P_{ln} = e^{V_{ln}} / \sum_{m \in C_n} e^{V_{nm}} \quad (4)$$

It has been shown that the total indirect utility or expected maximum utility of the choice set is equal to the logsum of the denominator of the logit equation given different choices, household income, and the goods' price

$$V_n(\text{total}) = \ln \sum_{m \in M} e^{V_{mn}} = \ln[e^{V_{1n}} + e^{V_{2n}} + \dots + e^{V_{Mn}}] \quad (5)$$

where $\ln$ is the natural log (3,4). This quantity has been called a measure of the desirability of the choice set (5), a measure of "inclusive value" (3), and—perhaps most appropriately in the context of transportation policy—a measure of accessibility (4). Therefore, it is possible to measure the change in the traveler's total indirect utility by subtracting the logsum of the denominator of the logit equation in the base case scenario p^0 from that of the policy scenario p^f

$$V_n(\text{change}) = \left[\ln \sum_{m \in M} e^{V_{mn}(p^f)} \right] - \left[\ln \sum_{m \in M} e^{V_{mn}(p^0)} \right] \quad (6)$$

The change in total indirect utility can be converted to dollars by the factor, $1/\lambda_n$, or the inverse of the traveler's marginal utility of income (i.e., the change in individual utility given an extra dollar of income)

$$Y_n(\text{change}) = V_n(\text{change}) * 1/\lambda_n \quad (7)$$

Small and Rosen (2) term the result compensating variation. Marginal utility of income is assumed to be constant for small price changes (as is the case in this study). Given this assumption, CV is equal to change in consumer surplus—that is, the area left of the demand curve and above the current prices (5, p. 22, 6, p. 402).

Small (5) describes how the marginal utility of income can be obtained from the coefficient of the cost variable in a logit mode choice model

because portions of the utility V_n that are common to all alternatives cannot be estimated from the choice model, $\lambda_n \equiv \partial V_n / \partial Y_n$ cannot be estimated directly, but if a price or cost variable P is included, λ_n can be determined from Roy's Identity

$$\lambda_n = -1/x_n * \partial V_n / \partial P_n \quad (8)$$

where x_n is the number of trips per time period. However, in the strict context of the mode choice model, $x_n = 1$, because the model estimates the probability of choice for one trip.

To summarize, Small and Rosen's (2) expression for obtaining the CV measure of consumer welfare from the base case scenario to the policy scenario is

$$CV_n = 1/\lambda_n \left\{ \left[\ln \sum_{m \in M} e^{V_{mn}(p^f)} \right] - \left[\ln \sum_{m \in M} e^{V_{mn}(p^0)} \right] \right\} \quad (9)$$

APPLICATION OF THE SMALL AND ROSEN METHOD

The Small and Rosen method of obtaining the CV measure from discrete choice models was applied to the SACMET 94 home-based work, shop, and other mode choice models. The SACMET 94 model was developed for Sacramento Area Council of Governments (SACOG) with a 1991 travel behavior survey conducted in the

region. SACMET 94 is a five-step travel demand model that includes auto ownership, trip generation, trip distribution, mode choice, and traffic assignment steps. The model makes use of over 1,000 travel analysis zones. Some of the key features of this model include (1) full model iteration of level of service variables, (2) auto ownership and trip generation steps with accessibility variables, (3) a joint destination and mode choice model for work trips, (4) mode choice models with separate walk and bike modes, walk and drive access to transit modes, and carpool modes, (5) mode choice models with land use, travel time and monetary costs, and household attribute variables, (6) all mode choice equations in logit form, and (7) a trip assignment step with separate morning and afternoon peak (both 3-h and 1-h peak) and off-peak periods. The model system is iterated on level of service variables until the criterion for convergence is met (i.e., morning peak trip assignment impedance is within 3 percent of that in the last iteration). SACMET 94 meets the U.S. Environmental Protection Agency's modeling requirements for nonattainment regions [See DKS & Associates (7) for detailed documentation of the model].

The SACMET 94 model uses the classification aggregate forecasting technique and segments households according to number of persons, number of workers, income, and auto availability. Person trips are generated for each household class. In the mode choice model, there are three income/worker categories (or number of workers by income class), thus, for example, if two households have equivalent incomes, but the first has one worker and the second has two workers, then the latter may fall into a lower income/worker classification. Within the income/worker categories, home-based work trips are classified by number of workers by number of autos, and home-based shop and other trips are classified by number of people by number of autos.

The CV formula (Equation 9), above, was adapted to suit the specifications of the SACMET 94 mode choice models. To obtain compensating variation for each income/worker category ($h = 1, \dots, H$), the following formula was applied for all modes m and all trips Q with origins ($i = 1, \dots, I$) and destinations ($j = 1, \dots, J$)

$$CV_h = 1/\lambda_h \left\{ \sum_{i \in I} \sum_{j \in J} \left[\left(\ln \sum_{m \in M} e^{V_{ymh}(p^f)} * Q_{ijh} \right) - \left(\ln \sum_{m \in M} e^{V_{ymh}(p^0)} * Q_{ijh} \right) \right] \right\} \quad (10)$$

The marginal utility of income λ_h is provided by the negative of the coefficient of the travel cost variable in the mode choice equations. The coefficients for the cost divided by wage variables were estimated for the SACMET 94 mode choice models, however, these coefficients were divided by wage and become the coefficients of the cost variables used in the SACMET 94 simulations. Total CV was obtained by summing the CV obtained from each income/worker group

$$CV = \sum_{h \in H} CV_h \quad (11)$$

Measures of CV could not be obtained for the nonhome-based and home-based school mode choice models. This is because both models lack income variables for the equity analysis and the school model lacks the cost variable needed for the total welfare analysis. Approximately 63 percent of the region's total trips are included in

the analysis of consumer welfare. However, work trips are more highly valued than nonwork trips, and thus the analysis captures a large percentage of the net benefit of the policy scenarios examined in this study.

Based on a review of the literature (e.g., 5,8), total auto operating costs are assumed to be \$0.40/mi. The mode choice models in SACMET 94 include perceived operating costs (\$0.05/mi) rather than total operating costs. To include the total unobserved auto operating cost in the consumer welfare estimates, vehicle miles traveled (VMT) for each scenario were multiplied by \$0.35, change in total operating costs from the base case to the alternative was calculated, and the result was added to the consumer welfare figure.

The use of the average of \$0.40/mi for total operating costs is based on the assumption of constant miles per vehicle per year and constant real total internal (private) costs per vehicle per year. The 1995 Nationwide Personal Transportation Survey (9) data show approximately constant average annual miles per vehicle per year (11,600 in 1969, 10,679 in 1977, 10,315 in 1983, and 12,452 in 1990) with only a 7 percent increase from 1969 to 1990. Because the model is cross sectional and thus represents long-term equilibrium (i.e., vehicle ownership changes are included), full private costs are used. It is assumed that all policies were put into place by 2010 at the latest, thus, 5 or more years have elapsed to the model year 2015.

In the scenario that includes pricing policies, it is assumed that all charges will be returned to the travelers in some way (e.g., lower sales or income taxes). Small (10) outlines a practical method for refunding revenues from pricing policies that comes close to achieving this level of compensation and that would also have appeal to key interest groups. The parking charges and total revenues from the congestion pricing policy and gas tax were extracted from the mode choice model for each income group and then added back into the CV estimate.

CONSUMER WELFARE AND FULL MODEL ITERATION

The SACMET 94 regional travel demand model is run in the theoretically correct manner with full model iteration on level of service variables. Thus, in the model, expanded roadway capacity will induce more and longer trips. The value of the new induced trips provide less benefit than existing travel, because the former are trips that are foregone in the presence of congestion and thus have less value. The benefits due to new trips are about half of those of existing trips (i.e., benefits of new trips compose the triangle rather than the rectangle underneath the demand curve). New trips and increased trip lengths due to increased roadway capacity will counteract much of the travel time savings benefits of roadway expansion projects.

The recent National Academy of Sciences panel report, *Expanding Metropolitan Highways*, reviewed research on the elasticity of demand (VMT) with respect to capacity (lane-miles) (11). Several studies found medium-term elasticities in the range from 0.5 to 1.0. Hansen et al. (12), for example, studied California urban counties with longitudinal data sets and found elasticities from 0.4 to 0.6 after an average of 16 years. The Standing Advisory Committee on Trunk Road Assessment in the United Kingdom (13) reviewed many studies and concluded that elasticities of 0.5 in the short term and 1.0 in the long term are reasonable.

UNCERTAINTIES IN METHOD OF APPLICATION

SACMET 94 cannot capture the effect of changes in the transportation system (i.e., travel time and cost) on the location of activities and the subsequent effect of location changes on travel. Such effects would likely be significant for large regional transportation projects or policy changes (e.g., new beltway freeways). As a result, SACMET 94 would tend to underestimate the benefits of such policies.

Savings in travel time comprise a large portion of consumer benefits created by new transportation policies and projects. The level of sophistication in modeling congestion will play an important role in the accuracy of the estimated consumer welfare measure. SACMET 94 uses the user-equilibrium traffic assignment method (capacity restrained) and models separate peak (1 h and 3 h) and off-peak periods. SACMET 94 does not include a time-of-day choice model and cannot simulate peak spreading or departure time shifts. Thus, the volume of travel during peak hours may be overestimated in very congested scenarios because the propensity of travelers to move off the peak is not represented. As a result, the benefits of a scenario that reduces congestion from the no-build scenario may be overestimated in this analysis.

Travel demand models typically use discrete choice models to make aggregate forecasts and thus must employ an aggregate forecasting technique. Available techniques include the average individual, classification, statistical differentials, explicit integration, and sample enumeration. Koppelman (14) and Ben-Akiva and Lerman (15) review these methods and find that the sample enumeration method is most accurate and policy sensitive. However, the application of the classification method in which classes are segmented according to similar choice sets (e.g., auto availability) can produce results that are nearly as accurate, though less policy sensitive. As described previously, SACMET 94 uses the classification aggregate forecasting technique and segments households according to demographic categories and choice sets. Although it is likely that some aggregation error exists in the consumer welfare estimates, it is difficult to identify the direction of this error. In the equity analysis, aggregation in the three income groups may mask losses to specific demographic segments within those groups.

The assumption of constant VMT per vehicle per year may result in an overestimation of private costs for policy scenarios that increase VMT (e.g., scenarios that include expanded roadway capacity), conversely, for policy scenarios that decrease VMT (e.g., pricing and expanded transit), travel cost reductions may be overestimated. However, travel reductions may be underestimated for pricing policies because the auto ownership step is not sensitive to travel costs.

RESULTS FROM METHOD APPLICATION

The application of the Small and Rosen method to the SACMET 94 mode choice models to obtain measures of total welfare and welfare by income class is illustrated by four policies for the Sacramento region in the year 2015. These scenarios include a no-build scenario, a light rail transit scenario (with 61.5 lane miles of light rail added to the transit network), an HOV scenario (with 184.5 lane miles of HOV lanes added to the freeway network), and a pricing and no-build scenario (with a \$0.10/mi freeway toll during congested conditions, a \$2.00 average daily parking charge for all trips, and a \$2.00/gal fuel tax). The long-run elasticity of demand for travel with respect to fuel cost is about -0.3 because of a shift to higher mile-per-gallon vehicles. As a result, the fuel tax is adjusted to \$0.60/gal.

TABLE 1 Total CV Measure of Traveler Welfare

Scenarios	Daily Total in Dollars	Per Trip in Dollars
Light Rail	120,005.05	0.02
HOV	-310,142.69	-0.04
Pricing & No-Build	1,915,367.93	0.26

Fleet mileage was assumed to be 20 mi/gal. Hence, the per mile auto operating cost in the model was increased by \$0.03.

The total consumer welfare results for the 2015 scenarios in the Sacramento Region are documented in Table 1. Note that a full social welfare analysis would include the capital, operation and maintenance, and external costs of the scenarios. The results of consumer welfare for the light rail and HOV scenarios would be reduced because of cost increases in these categories. The pricing and no-build scenario produced the greatest increase in total traveler welfare because of reductions in travel delay resulting from the imposition of pricing policies. As noted previously, it is assumed in this analysis that all pricing charges are returned to travelers through lower sales and fuel taxes. If pricing charges were not returned to travelers, the benefits of the policies would be reduced considerably. The light rail scenario also produced a modest increase in traveler welfare because of lower transit travel time costs. Interestingly, the HOV lane scenario produced a decrease in traveler welfare because this scenario did not generate enough time savings to offset the full operating costs of the additional auto travel. Thus, it appears that the pricing and no-build scenario resulted in more efficient use of existing roadway capacity because perceived auto operating costs begin to approach the actual costs. When the perceived costs of travel do not match actual costs, new roadway capacity induces additional auto travel, the full private cost of which may exceed the reductions in time costs resulting from transportation improvements. Expanded transit capacity serves to lower transit travel time costs and thus increase consumer welfare.

The consumer welfare results by trip for each of the three income groups are presented in Table 2. The pricing and no-build scenario resulted in a loss to the lowest income group. The pricing charges to this income class are not compensated for because of comparatively small time savings to households with lower time values. It appears that some pricing policies may be inequitable without compensatory payments or investment programs. All income groups lost welfare in

the HOV lane scenario. In contrast, all income groups benefited from the light rail scenario; the lowest income group benefited the least.

SUMMARY AND CONCLUSIONS

The Small and Rosen method of obtaining the CV measure of consumer welfare from discrete choice models was applied to the regional travel demand model SACMET 94. The application of this method required only a small number of travel model outputs, programming changes, and subsequent calculations. As a result, this method would be relatively easy for regional transportation planning agencies to apply, but the application of the method is restricted to travel models that include discrete choice models. The CV measure may be more difficult for officials and the public to understand than the traditional expenditure-based consumer welfare measure [see, for example, FHWA (16)]. However, because the CV measure captures the same value obtained from the traditional expenditure-based measure, its easier to understand graphical illustrations can be used to explain the concept behind the measure presented. Limitations of the consumer welfare measure obtained from SACMET 94, typical of most regional travel demand models in the United States, were identified; these include a failure to represent the interaction between transportation and land use, the absence of a time-of-day choice model in traffic assignment, and aggregation error.

The application of the method to SACMET 94 for expanded light rail, expanded HOV lanes, and road pricing scenarios did yield some interesting results. The light rail scenario increased total consumer welfare and consumer welfare for all three income classes. The pricing and no-build scenario had a relatively large increase in consumer welfare, however, a loss in consumer welfare was borne by the lowest income group. The HOV lane scenario resulted in a loss in total consumer welfare and a loss for each income class. Significantly,

TABLE 2 CV of Traveler Welfare by Income Class Per Trip in Dollars

Scenario	Net* Income Class One (0 to \$10,000)	Net Income Class Two (\$10,000 to \$35,000)	Net Income Class Three (\$35,000 and above)
Light Rail	0.00	0.01	0.02
HOV	-0.03	-0.04	-0.04
Pricing & No-Build	-0.24	0.07	0.32

* Net Income = $[0.6 \times (\text{Gross Household Income} - \$20,000)] + \$20,000$

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TABLE 2 CV of Traveler Welfare by Income Class Per Trip in Dollars

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