DEVELOPMENT OF A MULTI-CRITERIA EVALUATION BENEFIT CALCULATOR TO SUPPORT TRANSPORTATION PLANNING ALTERNATIVES ANALYSIS

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ABSTRACT

Oregon Metro developed a Multi-Criteria Evaluation (MCE) toolkit to support transportation planning alternatives analyses by estimating the quantitative “triple-bottom-line” (economic, environmental, and social/equity) of transportation investment scenarios. The objective of the toolkit is to enhance the agency’s transportation decision-support methods by including a more comprehensive set of criteria, more comparability between criteria, more explicit priorities, and more explicit equity analysis.

The toolkit builds upon previous benefit-cost analysis (BCA) tools and methods developed for the Federal Highway Administration, San Diego Association of Governments, Metropolitan Transportation Commission, Puget Sound Regional Council, and others. The toolkit consists of three tools: a benefits calculator to determine monetized benefits of transportation projects based on outputs from the regional travel demand model, a project costing tool, and a visualizer that calculates benefit-cost (B/C) ratios, and summarizes and visualizes results. The toolkit is open source and available online.

A comprehensive set of benefits is estimated by the benefits tool. These benefits include traditional BCA benefits such as travel time savings, vehicle operating costs, safety, and emissions, as well as new benefits such as travel time reliability, vehicle ownership costs, the health benefits of physical activity, and accessibility improvements as the options value of additional mode and destination choice alternatives.

This paper shares the experience of researching and defining the benefit measures, integrating the benefits calculator with the regional travel model, and analysis of the results for a transportation planning alternative. The paper concludes with recommendations for MPOs or DOTs interested in developing a similar benefits calculator.

Keywords: Benefit-Cost Analysis, Travel Modeling, Travel Forecasting, Open Source Software

INTRODUCTION

Oregon Metro developed a Multi-Criteria Evaluation (MCE) toolkit to support transportation planning alternatives analyses by estimating the quantitative "triple-bottom-line" (economic, environmental, and social/equity) (1) of transportation investment scenarios. The objective of the toolkit is to enhance the agency's transportation decision-support methods by including a more comprehensive set of criteria, more comparability between criteria, more explicit criteria priorities (weights), and more explicit equity analysis.

The toolkit builds upon previous benefit-cost analysis (BCA) tools and methods developed for the Federal Highway Administration (2), San Diego Association of Governments (3), Metropolitan Transportation Commission (4), Puget Sound Regional Council (5), and others. The toolkit consists of three tools: 1) a benefits calculator to determine monetized benefits of transportation projects based on outputs from the regional travel demand model, 2) a project costing tool that calculates total project costs by type and Net Present Value, and 3) a visualizer that takes as input the benefits and costs, calculates benefit-cost (B/C) ratios, and summarizes and visualizes results. The toolkit is open source and available online (6).

A comprehensive set of benefits is estimated by the toolkit. Several of these benefits, such as safety, travel time savings, vehicle operating costs, and emissions, have been standard components of transportation BCA for many years. Transportation BCA has been criticized in the past for focusing too narrowly on these benefits (7, 8). In part in response to these critiques, methods for quantifying other benefits have emerged more recently and are increasingly being adopted and employed by transportation agencies across the country. These new benefits, such as travel time reliability, vehicle ownership costs, the health benefits of physical activity, and transportation options or accessibility improvements (as the options value of additional mode and destination choice alternatives) are included in the toolkit.

This paper shares the experience of researching and defining the benefit measures, including the method, monetization assumptions, and use for equity analysis, integrating the benefits calculator with the regional travel model, and analysis of the results for a transportation planning alternative. The paper concludes with recommendations for MPOs or DOTs interested in developing similar travel model-based benefits calculator.

BENEFITS

The first task in this effort was to research and define a set of benefits for the new toolkit. For readers unfamiliar with transportation BCA, an excellent introduction is AASHTO's *User and Non-User Benefit Analysis for Highways* (9), as well as Victoria Transportation Policy Institute's *Transportation Cost and Benefit Analysis Techniques, Estimates and Implications* (10). In short, a set of benefits should be mutually exclusive, comprehensive, and countable. Mutually exclusive benefits are extremely important since there is a tendency in BCA to double count benefits. A comprehensive set of benefits accounts for as much of the triple-bottom-line as possible. Countable benefits are benefits that are measurable (i.e. can be added up). In addition to this broad definition for a good set of measures, Metro required that the toolkit leverage their existing travel modeling tools since they operate at a level of geographic, mode, and market segmentation detail that provides a wealth of useful information for the framework.

An additional important consideration when defining a set of benefits is to understand how those benefits can and will be reported for different populations, sometimes called equity groups or communities of concern. There are two general approaches to summarizing the demand-related benefit measures for equity groups. The first is a direct classification using the equity group definition and market segmentation available from the demand model. In the case of the Metro trip-based travel model (11), some of the models are segmented by household income group (low, medium, and high) and therefore model outputs are also often available by household income group. The second approach is to externally identify different geographic equity groups by assigning shares of each model zone to a group based on Census data and other information in order to use residence location as a proxy for group membership. It is important to carefully apply geographic-based membership so that benefits are not misrepresented by equity group. Metro's current externally defined equity groups are minority, low English proficiency, persons less than 18 or greater than 65, and low-income households.

Network level benefit measures are not usually summarized by equity groups since network assignment is typically only segmented by user class (SOV, HOV, etc.). Network links could be tagged with equity groups by assigning each link to a model zone and then a share of each model zone to an equity group based on Census data and other information as described above. For some cases, as for emissions, such an approach may be appropriate, although even this can be complex, as emissions may not impact residents of nearby homes if those emissions occur in the middle of the day, for instance, while the residents are elsewhere at work or school, etc. Therefore, allocating link benefits to the surrounding zone needs to be done with great caution in order to avoid misrepresenting benefits by group since network links often have little to do with their intersecting zone for many types of benefits (e.g., motor vehicle crashes). Therefore, it is not generally recommended to summarize network level benefits by equity group.

Review of Benefit Cost Analysis in Use by Other MPOs

Traditional transportation BCA has focused primarily on network level benefits: travel time savings, vehicle operating cost savings, reduction in crashes, reductions in emissions, etc. There are many examples of network level BCA models in use across the country, including by Washington Department of Transportation, Minnesota Department of Transportation, Ohio Department of Transportation, and others (8). BCA models that include the triple-bottom-line are relatively new in travel forecasting. These improved BCA models add components such as the health benefits of physical activity, multi-modal accessibility benefits, and more comprehensive equity analysis. The likelihood of a region having a triple-bottom-line BCA model depends on a number of factors, but the two key factors in our opinion are whether the regional transportation planning agency is being asked to address a new, more comprehensive set of planning and policy questions, and whether the region maintains a travel model with the appropriate resolution for the question at hand.

Like Metro, the Metropolitan Transportation Commission, the San Diego Association of Governments, the Puget Sound Regional Council, and the Sacramento Area Council of Governments, are all being asked triple-bottom-line questions. In addition, each agency maintains an advanced travel model with the additional spatial, network, and population detail required beyond many traditional travel models (12, 13, 14, 15). There are advanced travel models in other regions as well, but to our knowledge, these regions have yet to develop triple-bottom-line BCA tools, probably due to insufficient need (and thus motivation to invest) in such analysis. Thus, these examples represent an emerging state-of-the-practice in BCA methods for transportation.

The BCA measures implemented by the reviewed agencies are summarized below (Table 1, 2, 3, 4). In general, the range of measures included in the BCA models are similar, although some differences exist in the actual method (or calculations) for each measure. For example, there are different approaches to measuring one of the relatively new benefits, reliability of travel time. Another new benefit which is defined later in this paper, is the destination and mode logsum-based accessibility benefit. This benefit measures the availability of alternative modes or destinations (accessibility) and its value to the region. It is sometimes called a travel options (or choices) benefit. This is a relatively new benefit in the industry (2) and has therefore only been implemented by a few agencies at this time.

TABLE 1 Metropolitan Transportation Commission Benefit Measures

Benefit	Type	Notes	Equity Analysis
Travel time	Disaggregate	For each mode	yes
Travel costs	Disaggregate	Tolls, operating costs, and fares	
Physical activity	Disaggregate	Amount of walking and biking daily	
Vehicle ownership cost	Disaggregate	Household level	
Truck travel time	Aggregate	For each user class	no
Truck costs	Aggregate	Toll and operating costs	
Crashes	Network	Based on link VMT and other inputs	
Reliability	Network	Based on link performance	
Emissions	Network	Including GHG	
Noise	Network	Based on link VMT and other inputs	

TABLE 2 San Diego Association of Governments Benefit Measures

Benefit	Type	Notes	Equity Analysis
Travel time	Disaggregate	For each mode	yes
Travel costs	Disaggregate	Tolls, operating costs, and fares	
Physical activity	Disaggregate	Based on WHO HEAT method (16)	
Vehicle ownership cost	Disaggregate	Household level	
Travel options (2)	Aggregate	Destination, mode accessibility logsum	
Truck travel time	Aggregate	For each user class	no
Truck costs	Aggregate	Toll and operating costs	
Crashes	Network	Based on link VMT and other inputs	
Reliability	Network	Based on link performance	
Emissions	Network	Via EMFAC	
Noise	Network	Based on link VMT and other inputs	

TABLE 3 Puget Sound Regional Council Benefit Measures

Benefit	Type	Notes	Equity Analysis
Travel time	Disaggregate	For each mode	yes
Travel costs	Disaggregate	Tolls, operating costs, and fares	
Travel time reliability	Disaggregate	For auto	
Vehicle ownership cost	Disaggregate	Household level	
Travel options (2)	Aggregate	Destination, mode accessibility logsum (in development)	
Truck travel time	Aggregate	For each user class	no

Truck costs	Aggregate	Toll and operating costs	
Truck travel time reliability	Aggregate	By user class	
Crashes	Network	Based on link VMT and other inputs	
Emissions	Network	Via MOVES	

TABLE 4 Sacramento Area Council of Governments Benefit Measures

Benefit	Type	Notes	Equity Analysis
Travel time	Disaggregate	For each mode	yes
Travel costs	Disaggregate	Tolls, operating costs, and fares	
Physical activity	Disaggregate	Based on WHO HEAT method (16)	
Vehicle ownership cost	Disaggregate	Household level	
Truck travel time	Aggregate	For each user class	no
Truck costs	Aggregate	Toll and operating costs	
Crashes	Network	Based on link VMT and other inputs	
Reliability	Network	Based on link performance	
Emissions	Network	Via EMFAC	

Oregon Metro's Triple-Bottom-Line Benefit Measures

The benefits implemented for Metro's benefit calculator reflect best practices based on our knowledge and review of travel benefit estimation techniques applied by the reviewed peer agencies, as well as recent research for FHWA (2). Even though some of these methods are applied with Metro's aggregate trip-based travel model, some of the methods developed for disaggregate activity-based models are applicable because of the nested destination and mode choice models in Metro's trip-based model. The monetizable benefits implemented for Metro's MCE toolkit are enumerated below (Table 5). Each benefit is briefly summarized in the next section, with a full description available in the toolkit's technical documentation (17).

TABLE 5 Oregon Metro Benefit Measures

Benefit	Type	Notes	Equity Analysis
Travel time	Aggregate	For each mode	yes
Travel costs	Aggregate	Tolls, operating costs, and fares	
Travel time reliability	Aggregate	Based on link performance, which is then skimmed as an OD level measure	
Vehicle ownership cost	Aggregate	Household level	
Physical activity	Aggregate	Via ITHIM (18)	
Travel options (*2*)	Aggregate	Destination, mode accessibility logsum	
Truck travel time	Aggregate	For each user class	no
Truck costs	Aggregate	Toll and operating costs	
Crashes	Network	Based on link VMT and other inputs	
Emissions	Network	Via MOVES	
Surface water	Network	Based on link VMT and other inputs	
Noise	Network	Based on link VMT and other inputs	
Vehicle operating costs	Network	Based on link VMT, fuel cost, and other inputs	

Travel Time and Cost

Travel time and cost savings are generally the most significant component of user benefits for many transportation projects, plans and policies. For existing trips, travel time and cost savings is simply the decrease in travel time and cost for that trip. However, when trips are induced or suppressed, the benefit is calculated based on consumer surplus theory (9). The basic idea is that for induced demand, although the traveler was unwilling to make the trip given the original travel time (cost), as the cost decreases, at some point the traveler would choose to make the trip; the travel time savings for their trip should be measured as any further decrease in travel time beyond the point at which the trip is induced. In the absence of other information, the "Rule of Half" (ROH) assumes that trips induced between a baseline cost and an alternative scenario costs would, on average, be induced at the average of these costs and hence should accrue half of the travel time savings as existing trip-makers. In economic terms, the benefit for induced demand is the change in consumer surplus and the ROH amounts to linearization of the travel demand function. This method has been applied to user costs and travel time savings in the context of transportation benefit cost analysis for many years and is established practice (9).

The benefit calculator includes matrix-based calculation of the ROH using mode choice production-to-attraction (P-A) demand matrices and network level-of-service skims from the travel model to estimate travel time savings, including changes in consumer surplus. Calculations are implemented by mode:

- Auto: Auto travel time and parking cost by purpose and income in P-A format
- Walk transit: In-vehicle time, initial wait time, transfer wait time, walk time, boardings, and fare by purpose and income in P-A format
- Drive transit: In-vehicle time, initial wait time, transfer wait time, walk time, boardings, and fare for all transit trips in OD format since the P-A format data is not easily output.

Walk and bike travel time savings are not calculated in this benefit since there is significant overlap with the health benefits of physical activity calculated later.

After calculating the travel time and cost savings between the build and base scenario, US DOT guidance on the valuation of travel time savings (19) is used for monetization. This guidance recommends against using separate values of time for different travelers, in part to ensure economic analyses do not favor projects or policies beneficial to higher income citizens over those beneficial to lower income citizens. Therefore, one regionally relevant value of time was used to monetize all travel time savings.

Travel Time Reliability

Travel time reliability is a measure of variable or unexpected delay. At Metro, travel time reliability is defined as a day-to-day measure. Considerable federal research has been done on travel time reliability in recent years and several methods for estimating travel time reliability and its value have now been demonstrated. Two of the primary approaches are the SHRP2 C04 (20) method demonstrated by San Diego Association of Governments and the SHRP2 L11 (21) method demonstrated by Puget Sound Regional Council.

The SHRP2 C04 method was selected since it is an OD level measurement and therefore better integrates with the upstream demand models. The SHRP2 C04 method measures the standard deviation of travel time at the OD level by calculating a link reliability measure that is included in the assignment volume-delay functions, skimmed just like travel time, and then the skim is fed back to the upstream demand model to inform revised utility equations. The reliability measure is a function of link volume to capacity (V/C), but also other attributes such as speed, intersection control, and distance to the nearest interchange. After being skimmed, the square root of the travel time variance measure is taken to convert the values to the standard deviation of travel time. Standard deviation measures variability within a group of values and in this instance, represents the amount of deviation expected in each OD travel time. The travel time reliability difference between the build and base are monetized using the same methods as the travel time savings benefit.

The SHRP2 C04 reliability measure and skim were applied only as a model post-process for the estimation of reliability benefits for the MCE toolkit. This was done to avoid making significant revisions to the regional model for the purposes of toolkit development at this time although reliability may be incorporated in the demand model in the future.

Vehicle Ownership Costs

The valuation of annual auto ownership costs is intended to capture all the aspects of auto ownership not captured by the valuation of operating costs. These costs would include factors such as purchase and depreciation, financing and insurance. Reductions in vehicle ownership are considered to be a net benefit or savings. For example, if transit services improve, this may induce households to own fewer vehicles thus saving them associated ownership costs. The vehicle ownership benefit was implemented at the zone level since the auto ownership model also operates at the zone level. The monetization of the vehicle ownership benefit was done based on costs from AAA (22).

Physical Activity

Physical activity benefits represent health care cost savings and improved productivity associated with physical activity. It also includes the safety benefit for pedestrians and cyclists for motor vehicle–related fatal and nonfatal injuries in terms of medical care and lost productivity. Recently, several agencies including Oregon Department of Transportation, Oregon Health Authority, Central Lane (Eugene-Springfield, Oregon) MPO, and others have engaged in efforts to conduct health impact assessments of regional health impacts and related cost savings from alternative transportation futures.

These efforts have made use of the Integrated Transport and Health Modeling (ITHIM) (18) tool developed at the Centre for Diet and Activity Research, Cambridge Institute of Public Health and first implemented in the U.S. by the State of California Department of Public Health and in Oregon by the Oregon Health Authority. The ITHIM model offers some advantages over alternative methods for quantifying public health benefits of physical activity (23) such as the World Health Organization's Health Economic Assessment Tool (HEAT) (15). While both the ITHIM and HEAT tools estimate mortality related reductions, the ITHIM model also quantifies benefits of reduced morbidity, thereby providing a more comprehensive measure of physical activity benefits. In addition, the HEAT model operates at the individual level, thereby making it a better fit for an activity-based model, whereas the ITHIM model is an aggregate model, thereby making it a better fit for a trip-based model. ITHIM also includes a traffic safety benefit for pedestrians and cyclists. Due in large part to the existing regional interest in ITHIM, the Metro benefit calculator uses ITHIM derived benefit estimates.

The physical activity benefit is an OD level benefit measure and uses the mode choice walk and bike demand matrices, along with the walk and bike network distance matrices, and an assumed walk and bike travel speed, to calculate daily estimates of mean walking and biking time by age and sex. ITHIM also requires a Global Burden of Disease (24) input file that describes the health of the regional population and was provided by Oregon Health Authority. The ITHIM R (25) package was used to calculate the difference in disability adjusted life years (DALYs) between the build and base scenarios. The monetization of the DALYs was done using an estimate of the value of a DALY from the Central Lane MPO study (26).

Travel Options

The travel options (or choices) benefit measures the availability of alternative modes or destinations (accessibility) and its value to the region's travelers. While it is widely recognized that the availability of alternative modes or destinations (accessibility) itself constitutes a key benefit of transportation infrastructure and services, until recently, analytic methods have not been available to quantify and monetize the options value of additional modes or destinations as part of a systematic evaluation of transportation benefits. However, recent research for FHWA (2) on new methods for BCA using activity-based models has helped push these ideas into practice. This research demonstrates how accessibility measures from destination choice logsums (including expected welfare from mode choice) can be used to quantify and monetize these benefits.

Since Metro's trip-based model includes joint destination and mode choice models like those in activity-based models, this new method was implemented in the benefit calculator using the outputs of the regional model. For regions without joint mode and destination choice models, this benefit could be estimated by borrowing the utility functions from another region. This new method developed for FHWA is a more comprehensive alternative to travel time and vehicle operating cost savings. Therefore, in order to avoid double-counting and identify the additional benefit of travel options apart from travel time savings, etc., these benefits are calculated by subtracting travel time and vehicle operating cost savings from the estimate of benefits based on the model's destination choice logsums, identifying any remainder as the benefit from new or improved travel options.

The destination choice logsums by purpose by production zone are input to the benefit calculator. The tool applies the rule of half, using the logsums rather than trip costs/time. The resulting logsum changes are converted to dollars using the mode choice model's in-vehicle time cost coefficients by trip purpose. The travel options benefit is a zone level benefit measure and can therefore be summarized by equity group.

Crashes

The crash benefit monetizes the impact of motor vehicle crashes in the region. Bicycle and pedestrian safety benefits are a component of the ITHIM model and are therefore not included in this benefit in order to avoid double-counting. Methods from the *Highway Safety Manual (HSM)* (27) were used for estimating safety benefits. The methods used are those implemented in FHWA's Interactive Highway Safety Design Model (28) and documented in the Engineer's Manuals included in the tool's help files. In general, the method predicts the number of crashes using Safety Performance Functions (SPFs) for roadway segments (links) and intersections (nodes) together with Crash Modification Factors (CMFs).

The benefit calculation is implemented as a series of link and node calculations, using the following model network attributes: volume, length, lanes, facility type, speed, intersection control, and median (which was added for this benefit). The monetary value of fatality and injury collisions was calculated based on recent US DOT Guidance (29), whereas the value of property damage only collisions was estimated using guidance from insurance claims data (30).

Emissions

The valuation of emissions is intended to capture the benefits and costs associated with changes in emissions by pollutant type. Like most MPOs with mobile source emissions models, Metro runs EPA's MOVES (31) model to estimate motor vehicle emissions for air quality analysis, producing emissions rate tables by facility type, speed bin, pollutant, and year. Metro uses MOVES to estimate emissions rates for a variety of pollutants including greenhouse gases (carbon dioxide equivalents or CO2e), fine particulate matter (PM2.5), particulate matter (PM10), oxides of nitrogen (NOx), and volatile organic compounds (VOCs). The benefit calculator reads in the rates table from MOVES and applies these VMT-based rates to the link VMTs to estimate emissions costs. The unit costs for pollutants other than PM10 are borrowed from work done by the Bay Area Air Quality Management District (32). The PM10 unit cost was borrowed from work done by Caltrans (33).

Surface Water

Transportation can significantly impact water quality through, for instance, the deposit of rubber particles, oil, and other pollutants on roads which are washed into storm water when it rains. The purpose of this benefit is to monetize these impacts. Quantifying the impacts of transportation on surface water and assigning them monetary value is challenging. However, impacts are generally accepted to be a function of link level auto VMT and a basic method of estimating the value of these impacts has been developed by the Victoria Transport Policy Institute (34). The surface water impacts benefit calculation is implemented as a link calculation. Monetizing surface water impacts in this way does not account for mitigation of these impacts which may be a part of some projects. Therefore, the calculator includes a link scaling factor for evaluation of projects for which impacts have been mitigated.

Noise

A variety of factors affect the noise impacts of transportation including setting, speed, facility type, vehicle type, and barriers. Not all of these can be fully accounted for in the benefit calculator, but a valuation of noise impacts as a function of VMT by facility type and vehicle type is done based on research by Delucchi and Hsu (35). The noise impacts benefit calculation is implemented as a link calculation. As with surface water impacts, it is important to acknowledge that monetizing noise impacts in this way does not account for mitigation of these impacts, such as sound walls, which may be a part of some projects. Therefore, the calculator includes a link scaling factor for evaluation of projects for which impacts have been mitigated.

Vehicle Operating Costs

Vehicle operating costs represent the variable cost associated with operating a vehicle, such as fuel costs and maintenance. As noted earlier, Metro runs MOVES to estimate motor vehicle emissions for air quality analysis. In the process of estimating vehicle emissions, the MOVES model also estimates fuel consumption rates (as pollutant ID 92). These rates vary by facility type, speed bin, and year, and are output by MOVES in the emissions rate table. The benefit calculator reads in this VMT based rate table and applies these rates to the link assignment results to estimate fuel consumption costs.

Monetization is done separately for fuel and non-fuel costs. Assumed fuel prices per gallon by vehicle type (auto and truck) are described in detail in the original benefits design memo (17). Automobile operating costs do not include fixed costs that are separately accounted for as vehicle ownership costs, such as purchase, financing, and insurance costs. Automobile operating costs are therefore composed only of maintenance and tire costs. However, truck ownership costs are not separately accounted for and therefore include the costs of truck/trailer lease/purchase, insurance premiums, and permits and licenses in addition to maintenance and tire costs. Non-fuel automobile operating costs are based on AAA (22) data, where as non-fuel operating costs for trucks are taken from the American Transportation Research Institute (ATRI) (36).

INTEGRATING THE BENEFITS CALCULATOR WITH THE TRAVEL MODEL

Before running the benefits calculator, a series of data export scripts are run to produce the inputs for the calculator. These export scripts are responsible for transforming the data from the model implementation platform, which in this case is a trip-based model implemented in R and EMME, to the benefits calculator platform, which is independent of model design. The data export routines consist of:

- R scripts that export to CSV format the zone data, including land use data, auto ownership model results, and destination choice logsums
- R scripts that export to OMX (37) format the mode choice P-A matrices
- R scripts that export to CSV and OMX format the walk and bike mode choice P-A matrices and the land use data in order to run the R ITHIM package
- EMME Modeller Python scripts that export to OMX format the skim matrices
- EMME Modeller Python scripts that calculate the network reliability measure and export to OMX format the reliability skims
- EMME Modeller Python scripts that export to CSV format the link data.

Metro's benefits calculator makes use of the open source BCA calculator (6) initially developed as part of FHWA research on BCA with activity-based models (2). The BCA calculator is a general framework for aggregate (matrix), disaggregate (table), and link-based calculations and is implemented entirely with open source Python libraries for scientific computing, most notably Numpy (38) for matrices and Pandas (39) for data tables. The BCA calculator is implemented with the same technology as ActivitySim (40), the next generation activity-based modeling platform sponsored by a consortium of transportation planning agencies.

The calculator takes as input a series of open data format travel model output files for a base and build scenario and runs a series of processors to produce the benefits estimates. The calculator has processors for zones, OD pairs, households, persons, trips, and links, which provides sufficient flexibility to specify the range of benefit calculations. An extremely powerful and flexible core component of the BCA calculator is the ability to specify custom Python expressions for calculations. An example series of expressions is presented in Table 6 below.

The example expressions illustrate the calculation of the travel options benefit for home-based other trips using the zones processor. The "zones.base_hboprl" expression in the Expressions column is the "hboprl" (home-based other production low income) column on the base scenario version of the zones inputs table. This column is added to the other two columns in the Expression field to create the "base_prod_hbo" column, which is the total productions for home-based other for the base scenario by zone. After getting some additional inputs, the calculation of the travel options benefit for home-based other is done in the expression that results in the "access_benefit_hbo" column. The final expression adds up the access benefit by trip purpose to get the total access benefit. Note that the calculation of the other trip purposes is not shown. The final output of the benefits calculator is a summary of benefit dollars by equity group and for the total population (Table 7).

TABLE 6 Custom Expressions in the Benefits Calculator

Description	Target	Expression
#zone-based inputs		
hbo productions in base scenario	base_prod_hbo	zones.base_hboprl + zones.base_hboprm + zones.base_hboprh
hbo productions in build scenario	build_prod_hbo	zones.build_hboprl + zones.build_hboprm + zones.build_hboprh
hbo logsum in base scenario	base_ls_hbo	zones.base_hbodcls
hbo logsum in build scenario	build_ls_hbo	zones.build_hbodcls
#calculate travel options benefit by zone		
access benefit hbo	access_benefit_hbo	(0.5 * (base_prod_hbo + build_prod_hbo) * (build_ls_hbo - base_ls_hbo) / UPM_HBO) * (VOT_HBO / 60) * DISCOUNT_RATE * ANNUALIZATION_FACTOR
travel options benefit	travel_options_benefit	access_benefit_hbo + access_benefit_hbr + access_benefit_hbs + access_benefit_hbw + access_benefit_nhbnw + access_benefit_nhbw

TABLE 7 Example Benefits Summary

Processor	Description	Minority	Low English proficiency	Age <18 or 65+	Low income	Total Population
zone	travel options	$19,983	$3,171	$91,803	$20,128	$159,680
zone	vehicle ownership	$3,836	$440	$7,081	$8,179	$24,455
od	physical activity	$(1,045)	$(197)	$(3,443)	$(1,130)	$(6,548)
od	travel time reliability	$24,017	$4,515	$78,183	$22,673	$139,961
od	travel time	$123,161	$18,628	$469,767	$148,972	$847,134
link	vehicle operating					$(327,808)
link	emissions					$(103,654)
link	noise					$(8,935)
link	surface water					$(26,199)
link	crashes					$(59,352)

ANALYSIS OF RESULTS

To test and verify the entire workflow, including the travel model runs, the data export routines, and the benefits calculation, the tool chain was run through a test scenario. The test scenario included a base scenario and a build scenario, and the differences between them are monetized to estimate benefits. The base scenario includes 2040 land use and network improvement projects that are included in a financially constrained forecast (i.e. programmed and budgeted for). The build scenario adds approximately 13 miles of an additional lane to Interstate 205 in the Southeast of the region. The build alternative is an illustrative network improvement project without recognized or committed funding to date.

The initial iteration of the benefits application (as illustrated in Table 7 above) showed that the additional lane on the Interstate had a positive impact on travel options, travel time savings, travel time reliability, little impact on vehicle ownership and physical activity, and a negative impact on vehicle operating costs, emissions, noise, surface water runoff, and crashes, due largely to the increase in VMT in the build scenario. Generally speaking, these results were expected and so the exercise then turned to auditing/verifying each benefit calculation to ensure everything was working correctly.

Unfortunately, or maybe fortunately, the initial iteration also revealed a couple of issues in the regional travel demand model. First, the model scenarios used for the test were from the previous version of the trip-based model since they were readily available. This turned out to be problematic since the previous version of the model included a polynomial transformation on the mode choice logsum term in the destination choice model. This polynomial transformation resulted in some unexpected results in the travel options benefit when mapped and compared to the travel time savings benefit (which makes up most of the travel options benefit in this scenario). In addition, the test scenarios were not sufficiently converged, both in terms of highway assignment and overall model feedback. This was verified by tracing travel time skims for select OD pairs that had higher or lower benefits than expected. Insufficient convergence also resulted in unexpected benefits for zones far from the project and in significantly negative benefits for some zones, which did not seem right for this project. Some level of noise is to be expected in the travel model outputs, but when the difference in the scenario results were monetized and mapped, they simply did not make sense.

During the same time that the benefits calculator was being constructed, Metro was finalizing revisions to their trip-based model, including a new specification for destination and mode choice, which did not include the polynomial transformation on the logsum, and a tighter overall model convergence. The base and build test scenarios were run through this new version of the model, and the scenarios were checked for sufficient convergence. The scenarios were then re-run through the benefits calculator, and the resulting travel time and travel options benefit looked much better. The travel options benefit is shown in Figure 1 below, and the location of the project corresponds with the area with the most benefit. The map shows the annual benefit dollars for the zone.

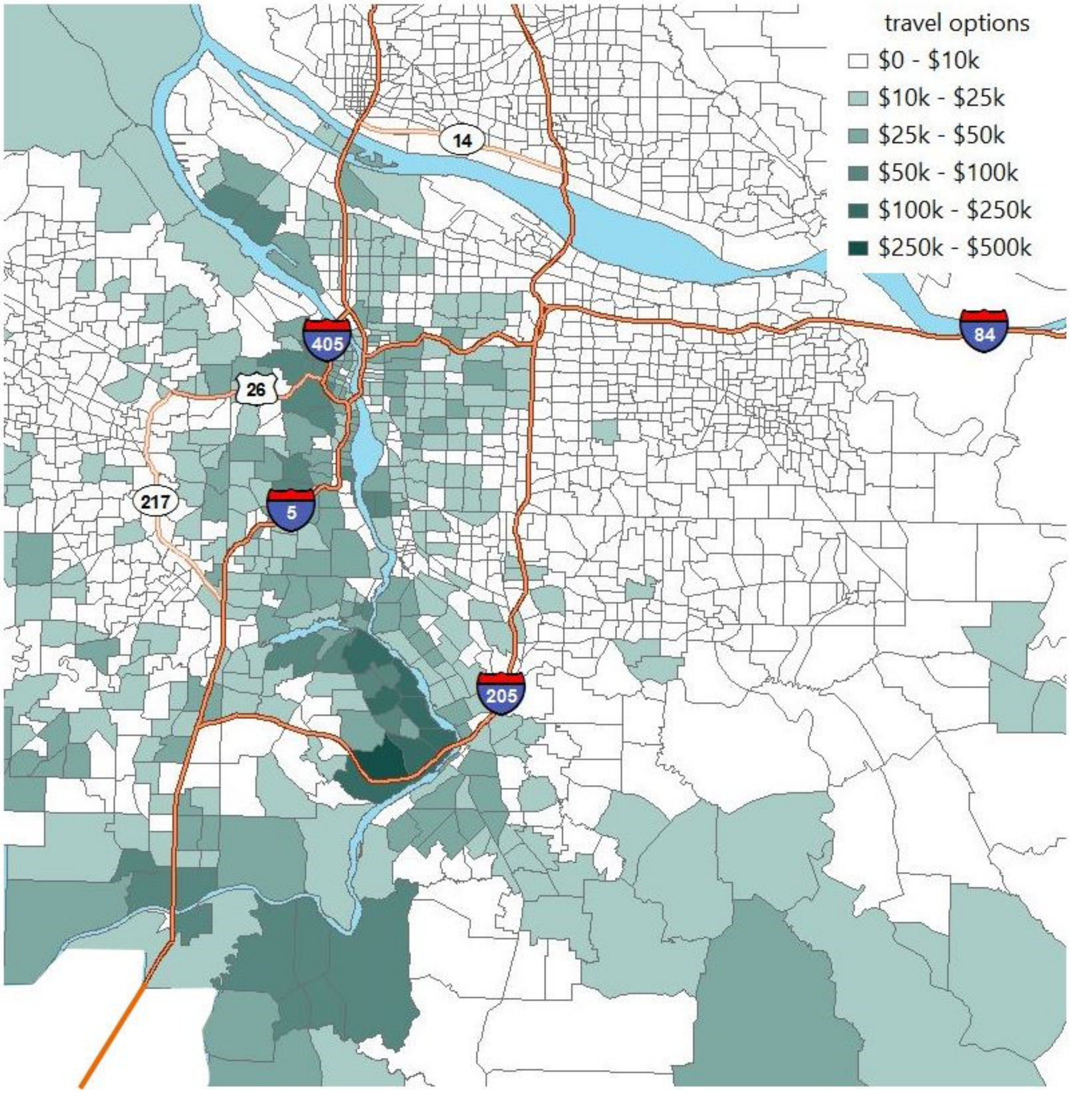

FIGURE 1 Example Travel Options Benefit

CONCLUSIONS

Oregon Metro is looking forward to utilizing the benefits calculator, as part of the overall MCE toolkit, in its transportation and land use planning activities. The triple-bottom-line set of measures that has been developed is a big step forward in the agency's ability to estimate the benefit of transportation investment scenarios. Especially important to Metro is the ability to quantify the new types of benefits, including travel time reliability, the health benefits of physical activity, and travel options / accessibility. These features, in conjunction with the ability to report benefits by equity group, are key to satisfying the objectives of the initiative.

One of the main lessons learned as part of this effort is the usefulness of the benefits calculator in auditing the travel model results. The benefits calculator provides a tremendous amount of useful information that is converted into easily understandable units such as minutes and dollars, and therefore helps to shine a light on model system components and their sensitivities that are not often analyzed in day-to-day applications. Based on this experience, the authors believe it should be standard practice in our industry for travel model development and application efforts to be run through a comprehensive benefits analysis as well. This would help ensure travel forecasts are correct and reasonable, much in the same manner that FTA's New Starts and Users Benefits program has done for transit forecasts (41). It was also very helpful that the FHWA BCA calculator uses user-defined expressions as opposed to hard coded benefit calculations in scripts (or source code), since this flexibility allowed changes to expressions and segmentation, and the addition of expressions for debugging purposes, etc.

While some questions remain about how best to "roll-up" (i.e. weight / prioritize) the benefits when compared to costs as part of the overall MCE toolkit, the benefits tool on its own provides a wealth of information to assist Metro and its stakeholders in transportation planning alternatives analysis. As the Oregon Metro region gets more familiar with the tool, the authors hope it to be used in ways that were unanticipated. For example, components of the travel options benefit are likely to be used for the transportation cost component of Metro's upcoming housing and transportation cost burden analysis.

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