INTEGRATION OF TRAVEL DEMAND MODEL AND BENEFIT-COST ANALYSIS (BCA) METHOD FOR NEW CAPACITY HIGHWAY PROJECT EVALUATION

By

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ABSTRACT

The selection of transportation projects by Metropolitan Planning Organizations (MPOs) or state Departments of Transportation (DOTs) trying to make the best use of limited financial resources is a burdensome process that often involves conflict between decision-makers representing different constituencies. This study presents a methodology to estimate benefit-cost (B/C) ratio for transportation projects using a regional travel demand model and B/C analysis. The B/C ratio can provide an objective measure for decision-makers to quantitatively evaluate the regional benefits and costs of each proposed transportation project under certain assumptions. This methodology shows the impact of one project on the entire regional transportation network. The key to this methodology is use of total vehicle hours traveled (VHT) savings resulting from each proposed project, converted into dollar benefits. The total VHT is estimated using congested travel time and trips instead of a simple summation of each link's VHT. A second key issue of this methodology is to estimate economic development benefits of the proposed transportation investments. For this process the Pikes Peak Area Council of Governments (PPACG) used TRsportation Economic Development Impact System (TREDIS) web-based software. The input that TREDIS requires for new capacity transportation projects are total VHT or vehicle miles traveled (VMT) before a project and total VHT or VMT after the project by trip purpose and travel mode. TREDIS offers default values such as economic value factors for driver and occupant time-saving benefits (dollars per VHT or VMT), vehicle cost factor for vehicle cost savings (dollar per VHT or VMT). The case study suggests that the proposed approach can be useful and effective in assessing regional transportation projects by considering their economic impacts.

INTRODUCTION

One of the principal responsibilities of MPOs is to develop long-range transportation plans and transportation improvement programs (TIP) for the region. The TIP identifies regionally significant transportation projects, such as highway expansion, that if implemented would increase the efficiency of the transportation system for local residents. However, MPOs are faced with limited financial resources with which to implement these projects. It has become increasingly important for decision-makers to evaluate and prioritize transportation projects given these budget constraints.

Different multiple criteria decision-making (MCDM) methods have been utilized for the purpose of transportation project ranking, including weighted-criteria scoring models, analytical hierarchy process (AHP), the technique for ordered preference by similarity to ideal solution (TOPSIS), etc. *(1)*. These methods typically take into consideration criteria such as volume/capacity ratio, the benefit cost (B/C) ratio, level of service, cost, environment impact, etc. These criteria are used to generate final scores for transportation project ranking. B/C ratio is generally one of most important factors considered during this process.

Transportation projects have different financial costs and different economic and environmental impacts on the region. Planners and analysts often use benefit-cost analysis (BCA) to evaluate transportation projects. BCA works by measuring the stream of benefits accrued to road users (such as travel time savings) and to society (such as reduction of pollution) against project costs, including preliminary engineering, construction cost, right-of-way acquisition, etc. This allows comparison between transportation projects using a single ratio; and results can be presented to decision-makers as one measure. BCA is an objective tool used to assess and compare transportation infrastructure investments and assist planners in determining which investments would bring the maximum net benefit to the region. Its outputs can be easily understood by decision-makers and the public.

LITERATURE REVIEW

Since 1992, the federal guidelines have strongly encouraged the use of BCA by all federal programs *(2)*. An executive order reaffirmed this in 1994, requiring federal agencies to implement comprehensive analysis of benefits and cost for all transportation projects using federal funds*(3)*. With the endorsement of the Federal Highway Administration (FHWA) Office of Policy, the Highway Economic Requirements System State Version (HERS-ST) was developed to evaluate transportation projects using life-cycle BCA methodology *(4)*. HERS-ST considers both engineering and economic concepts and principles when determining the benefits of investments. Specifically, the model estimates highway conditions and performance levels based on future traffic volume and a pavement condition decay curve; it identifies highway deficiencies in capacity, safety and pavement condition, and ranks projects by comparing life-cycle benefits to costs. Benefits include reductions in user costs (travel time savings and operating cost savings such as fuel, oil, tire, and maintenance), agency costs (savings in maintenance costs), and social costs (savings in safety costs and in emissions). However, HERS-ST is limited to assessing existing road segments; it cannot be applied to roads in new alignment- or intersection-related projects. Also, for the existing road segments, HERS-ST evaluates each individual segment independently without considering how that improvement relates to adjacent segments *(5, 6)*.

Another model recently developed by the Center for Urban Transportation Research (CUTR), the Trip Reduction Impact for Mobility Management Strategies (TRIMMS), provides a practitioner-oriented sketch planning tool for transportation demand and transit-related project evaluation *(7)*. Transportation demand management program produces a wide range of benefits by removing vehicles from roads or reducing VMT. VMT reduction results in savings in air pollution emissions, congestion, excess fuel consumption, global climate change, and health and safety costs, which are the total benefits associated with the proposed project. TRIMMS estimates the B/C ratio by dividing the total annual program benefits by the total annualized program costs. However, TRIMMS lacks the flexibility to assess highway expansion or extension projects because these projects do not necessarily reduce VMT, and in some cases they may increase VMT. For example, a high-speed highway expansion may cause road users to switch paths to this link; although traveling on this link increases travel distance (VMT), travel time is reduced, which results in travel time savings and congestion mitigation.

Travel demand forecasts are critical and indispensable to any transportation project or investment evaluation. It is recommended that induced demand, consumer surplus, and time savings on parallel facilities should be taken into account in the BCA method *(8)*. Improvements to the primary facility will most likely attract road users from parallel or competing links, which will save travel time and mitigate congestion on these links. But the definition of parallel links is not discussed in the literature and needs to be further investigated since numerous parallel links exist in a regional network.

A regional travel demand model was used to evaluate intelligent transportation system (ITS) alternatives for the Baltimore metropolitan area as a case study in the total cost analysis method *(9)*. Demand estimates were obtained from the travel demand model, and national average parameters were obtained from the Nationwide Personal Transportation Study (NHTS) when the parameters needed were not available from the travel demand model. This study compared the total cost of ITS alternatives that reduce the need for highway expansion while maintaining the same level of service.

As can be seen from the literature review above, BCA in combination with travel demand forecasts have been used for transportation project evaluation. The focus has been placed on identifying social benefits associated with VMT reduction or total VHT savings. However, most of these studies have analyzed individual segments independently without considering the impact of one segment on others; at most, the competing links are considered. Doing so ignores the region-wide or system-wide impacts of the proposed transportation projects. For example, a highway expansion or extension not only affects future traffic volume and travel time on this corridor but also has an influence on the origin-destination (OD) trip re-distribution and OD travel time. This study aims to develop a system-wide measure to capture the impact of a proposed improvement on the entire study area. It will incorporate BCA method with OD trip exchange and travel time produced from the traditional travel demand model.

MODELING APPROACH

This section presents a methodology of evaluating new or add-capacity highway projects. It is important to note that a new capacity project is distinctly different from a transportation demand management project. A transportation demand management project is designed to reduce regional VMT by removing vehicle trips from highways in a congested metropolitan area. Doing so can address congestion and emission reduction and can also produce other benefits such as reducing excessive fossil fuel consumption. A new/add capacity project is designed to reduce traffic congestion and improve accessibility, which is expected to have a positive impact on economic development. Therefore, changes in VHT by travel mode and trip purpose were chosen as a measure of evaluating new/add capacity projects in order to evaluate projects consistently.

The travel demand model is used to estimate the total VHT savings caused by new capacity transportation projects. This methodology takes into account OD trip redistribution and OD travel time associated with the new project. Using TREDIS economic software, the total VHT savings will be converted into benefits such as travel time savings and reliability, reduced environmental impacts, vehicle operation cost savings, and logistics benefits.

Savings in Total Vehicle Hours Traveled

To estimate the total VHT savings for a region, the base case VHT for the transportation system needs to be defined. When modeling regional vehicle travels between traffic analysis zones (TAZs), each TAZ serves as both origin and destination for trips. Typically, total VHT for a region is calculated by adding together the VHT on each road segment in the region. Doing so ignores the impact of intersection/node delays on vehicle travels. The proposed methodology takes into consideration the node delay when calculating OD travel time.

Let I denote the set of origin TAZs, and J denote the set of destination TAZs. The components of both set I and set J are the 753 TAZs in the study area. Let t_{ij} denote the number of trips between origin i and destination j, ($\forall i \in I$ and $\forall j \in J$); let c_{ij} denote the congested travel time between origin i and destination j, ($\forall i \in I$ and $\forall j \in J$); it can be derived after user-equilibrium traffic assignment in a regional travel demand model. User equilibrium conditions state that all used paths between each OD pair must have equal and minimum travel time, and no road user can improve his/her travel time by switching paths *(10)*. Therefore, all vehicle trips have equal travel time c_{ij} in an OD pair from i to j, ($\forall i \in I$ and $\forall j \in J$). Let *TVHT* denotes the total vehicle hours traveled in the study area. Then, the total VHT consumed by all road users can be defined as:

$$TVHT = \sum_i \sum_j t_{ij} \times c_{ij} \qquad 1$$

It is noted that in a typical travel demand model, each TAZ is connected to another by physical road networks and imaginary links (centroid connectors). In this study, the congested travel time c_{ij} excludes travel time spent on the centroid connectors, since they are imaginary links only designed for loading trips from the TAZ onto the physical road network. After new capacity is added to the region, several assumptions are made for each step of a traditional four-step travel demand in comparison with the base scenario (no action). Trip generation rates are assumed not to be affected by new-capacity projects since they are a function of socioeconomic data such as household size, income, and employment by category. The number of trips between any two TAZs (t_{ij}) will change, or trips will be redistributed over the region because of changes in congested travel time between TAZs (c_{ij}). Trip distribution is a function of OD travel time. Mode split between transit and auto will change as well since this is a function of OD travel time. Because of changes in trip distribution and mode split, assignment results will be different from the base scenario such as traffic volume and volume over capacity (V/C) ratio over the network.

Let the superscript “base” in each variable represent the variable value in the base scenario without any project completed; superscript “p” represents the variable value in the scenario with project completed; $\nabla TVHT$ denotes the total VHT savings between base scenario and project scenario. Therefore, $\nabla TVHT$ can be defined as

$$\nabla TVHT = \sum_i \sum_j t_{ij}^{base} \times c_{ij}^{base} - \sum_i \sum_j t_{ij}^{p} \times c_{ij}^{p} \quad 2$$

Both the t_{ij} and c_{ij} associated with base and project scenarios can be derived after running the base-scenario regional travel demand model and project-scenario regional travel demand model with corresponding network modification to reflect new added capacity. The total VHT can be easily derived by the summation of the product of t_{ij} and c_{ij}. The $\nabla TVHT$ is obtained by subtracting project-scenario total VHT from base-scenario total VHT. It will be analyzed by travel mode and trip purpose based on travel demand characteristics in the study region, since value of time varies by travel mode and trip purpose. The total VHT savings bring about substantial benefits for the region in terms of road user and environmental benefits, as discussed in the next section.

Benefit Estimation

Total benefits associated with a highway project are estimated by including user benefit and non-user benefit. For example, a new-capacity highway project can alleviate drivers' frustrations by reducing expected and unexpected delays and saving travel time (user benefit); it also reduces emissions (non-user benefits). The benefit estimation is achieved by using TREDIS *(11)*.

User benefits include not only all benefits accruing to drivers, passengers, and vehicle operating costs as a result of improvement in travel time, travel expense, and travel safety, but also logistics benefits. Logistics benefits are the time and shipping cost savings for industries that produce or transport commodities. TREDIS regards industries as the ultimate users of freight transportation systems. Logistics benefits emerge as shipping costs decrease, which can improve industry productivity through inventory management, production scheduling, and distributional efficiency. Road-user benefits include travel time savings for vehicle drivers and occupants, vehicle operation cost savings, and reduced accident costs. Travel time savings for drivers and occupants can be further divided into travel time savings for the crew — such as truck drivers — as a function of wage and travel time savings for passengers as a function of opportunity cost of the average passenger's time. Also travel time savings benefits include time and reliability benefits for employers; these benefits are only related to commuter trips. Vehicle operation cost savings include savings in fuel and oil consumption, tire wear, maintenance, and depreciation, which can be accomplished if transportation projects reduce VHT or VMT for vehicle trips. Reduced accident costs are expected since the proposed transportation project may lower fatalities or injury accidents for a region. It is difficult to estimate traffic accident benefits if the study area does not have a safety planning model associated with VHT, VMT, or other variables associated with highway attributes. Traffic accident benefits were not considered in this study due to lack of data from the Colorado Department of Transportation. In summary, the user benefits are the addition of four values:

$$\text{User Benefits} = \text{Value of personal time savings} + \text{Vehicle Operation Cost Savings} + \text{Travel Time Realiabity Savings (for employers)} + \text{Logistics Benefits}$$

Non-user benefits are often recognized as "external" impacts of transportation projects. They include air quality or environmental benefits commonly measured by a reduction in air pollution associated with emissions produced by motor vehicle use. Vehicles produce various harmful emissions that can cause damage to human health, visibility and agriculture *(12)*. New transportation projects generally lead to reductions in volatile organic compounds (VOC), carbon monoxide (CO), nitrogen oxide (NO_x), carbon dioxide (CO_2), and noise pollution, all of which TREDIS considers non-user benefits. . TREDIS offers default values for environmental cost such as dollars per VHT, so non-user benefits can be estimated by the product of total VHT savings and environmental cost. Non-user benefits can be determined by using the following equation:

$$\text{Non - User Benefits} = \text{Environmental Benefits} = \text{total VHT savings} \times \frac{\text{Pollutans}}{\text{VHT}} \times \frac{\text{Dollars}}{\text{Pollutant}}$$

The inputs that TREDIS requires for new-capacity transportation projects are total VHT or VMT before a project and total VHT or VMT after a project. It offers default values such as economic value factors for driver and occupant time-saving benefits (dollars per VHT or VMT), vehicle cost factors for vehicle cost savings (dollar per VHT or VMT). The economic value factors are based on value of time. Since value of time varies by different trip purposes such as commute and non-commute, TREDIS recommend specifying the input such as total VHT by trip purpose. Also, since truck drivers have a different value of time than passenger car drivers, and truck travel is associated with logistics benefits, TREDIS requires specifying total VHT by truck and car. The preparation of TREDIS input in this case study will follow this recommendation by dividing trips into commute and non-commute trips under the two categories of truck and car trips.

CASE STUDY

The proposed methodology for evaluating transportation projects is tested on the Pikes Peak Area Council of Governments (PPACG) MPO area for regional priority analysis. The MPO area includes the City of Colorado Springs, six other incorporated municipalities, and some unincorporated portions of two counties, El Paso and Teller. The regional model extent includes all of El Paso and Teller counties, covering over 2,600 square miles. In 2005, the modeling area has a population of 587,000 and 326,000 workers which including 35,000 active duty military personnel. Figure 1 shows the modeling area with its major highways and key cities.

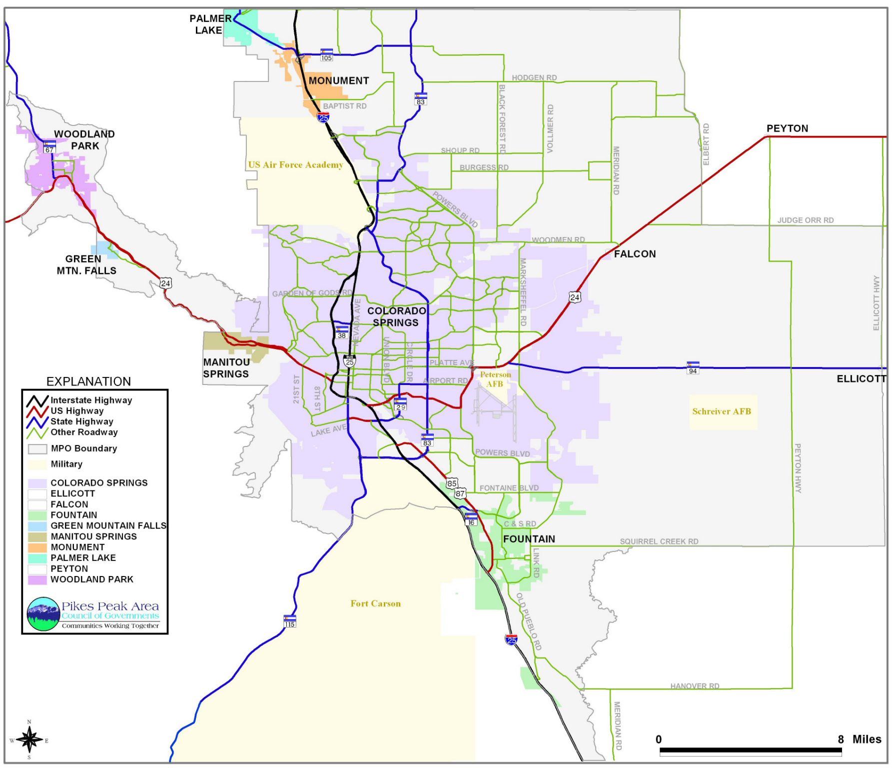

FIGURE 1 Major Highways and Key Cities in the Modeling Area.

Introduction to the PPACG Travel Demand Model

PTV America's software VISUM is used for the development and application of the PPACG model, which is a traditional four-step travel demand model. There are 737 internal TAZs and 16 external stations in the modeling area. The nine trip purposes considered in this application are Home-Based Work, Home-Based Elementary School, Home-Based High School, Home-Based College/University, Home-Based Shop, Home-Based Recreational, Home-Based Other, Work-Based Non-Home, and Non-Home Non-Work Based.

Cross-classification methods are used for the trip production and attraction models. It separates the population and employment into relatively homogenous groups based on certain socioeconomic characteristics. Trip production rates for different purposes are estimated at the most disaggregate level available based on income (five categories) and household size (five categories), resulting in 25 classifications. They are estimated according to the PPACG 2002 Household Travel Survey. Trip attraction rates are calibrated from the same data source as trip production rates using an aggregate cross-classification process. The socio-economic variables used for the trip attraction model are households, school enrollment at three levels, basic employment, retail employment, military employment, three categories of service employment, total service employment, and total employment. Special trip attraction models are developed for special generators that contain military facilities, the Colorado Springs Airport (COS), colleges and universities, and national and regional tourist destinations. Trip rates for these generators are developed based on local surveys such as traffic counts at the gates of military facilities, air passenger OD surveys, college and university enrollment, and visitor counts at major tourist destinations. The external station trip generation guiding both internal-external trips and external-external trips were obtained from annual average daily traffic (AADT) counts provided by the Colorado Department of Transportation (CDOT) and El Paso and Teller counties.

The gravity model is used to geographically distribute trips between TAZs for all but the external-external trip purpose. The travel impedance function that describes the spatial separation uses gamma, power, and exponential formulation for different trip purposes. The gravity models were calibrated by trip purpose to the observed 2002 household travel survey data. Based on calibration results, the home-based elementary and home-based college trip models use the power formulation for travel impedance function; the home-based high school trip model uses exponential formulation for travel impedance function; all other trip purpose models use the gamma formulation for travel impedance function. The congested travel time as inputs to the travel impedance function is enhanced by adding estimates of out-of-vehicle/terminal time to better represent actual travel times. The external-external trip distribution was estimated using a methodology developed by CDOT (PPACG transportation year 2010).

Binary logit models of mode choice were used to assign person-trips to auto and transit modes. The mode split models were estimated for peak and off-peak periods. The peak model has two auto modes and three transit modes: drive alone auto, shared ride auto, walk to bus, drive to express bus, and walk to express bus. The off-peak model has two auto modes and one transit mode: drive alone, shared ride, and walk to bus. All parameter estimates are consistent with the expectation of showing a reasonable difference between the estimated and the observed data. Vehicle occupancy for each trip purpose was calculated from the 2002 household travel survey. After taking vehicle occupancy into consideration, the traffic assignment was performed.

The truck OD trips were estimated separately using quick-response procedures developed by the travel model improvement program (TMIP). The truck OD trips were assigned onto the network as background traffic using an all-or-nothing traffic assignment method for three time periods: AM peak, off-peak, and PM peak. All auto trips were then assigned to the network using the user equilibrium assignment method for the same periods as the truck assignment. The state of equilibrium is reached by multi-successive iteration based on incremental assignment as a starting solution. The link performance function in the traffic assignment utilized the bureau of public road (BPR) function with different alpha and beta values based on the link functional class. Node delay functions were considered in both truck assignment and auto assignment.

Benefit Cost Analysis

Once the project list was established, cost data for each project including design, utility, right-of-way acquisition, construction and maintenance were obtained from CDOT. Four projects were selected to illustrate the procedure of benefit cost analysis, with project description and cost (dollars) listed in Table 1.

TABLE 1 Project Description and Cost

Projects	Project Description	Design Cost	Utility/Right-of-Way Acquisition/Construction Cost
Project 1	I-25 North: Widening from 4 to 6 lanes; total length: 4.52 miles	$270,000	$35,000,000
Project 2	US 24 West: Construction of a new interchange and widening from 4 to 6 lanes; total length: 0.37 mile	$700,000	$75,000,000
Project 3	US 24 East: Widening from 2 to 4 lanes; total length: 4.05 miles	$500,000	$20,500,000
Project 4	SH21 Extension: New 3.5-mile 4-lane expressway segment.	$400,000	$94,100,000

The base scenario was the existing road system, and four project scenarios were individually created in the PPACG modeling system. It was assumed that these projects would be constructed in 2014 and start operation in 2016, with a life cycle of 40 years. After each model run, the total VHT associated with each scenario was derived by summing the product of OD trips and OD travel time according to Equation 1. This calculation revealed that in PPACG's feedback model, which redistributed trips as a result of the new capacity projects, there was a significant reduction in the total VHT across the region. Figure 2 shows the V/C-ratio frequency distribution over the network associated with these projects and with a no-action scenario.

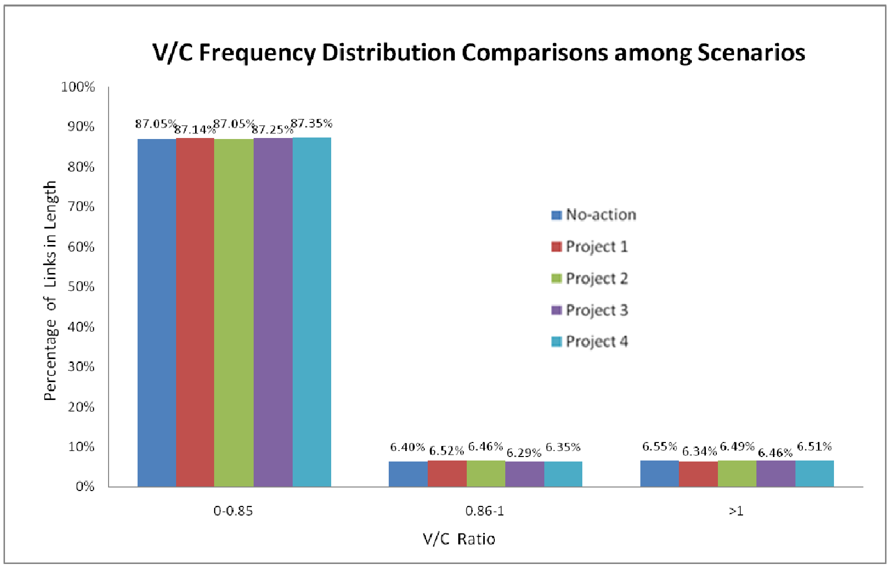

FIGURE 2 V/C Ratio Distribution over the Network from Different Scenarios.

It can be seen that each project contributes to reducing the congestion for the region in 2035 in comparison with the no-action scenario. Most notably, the percentage of roads in length with a V/C ratio of more than 1 is decreased, which indicates the project can reduce the heavily congestion. The percentage of roads with a V/C ratio of less than 0.85 is improved, indicating that each project can improve mobility for region.

The total VHT was further divided into truck and auto VHT, since a freight trip has a different value of time than an auto trip. The total auto VHT was further broken down into commute and non-commute VHT based on travel demand characteristics. For example, when converting average weekday commute VHT values to annual values, they were multiplied by 260 (52 weeks x 5 days/week). Based on the PPACG 2002 household travel survey, 17 percent of daily traffic is commute traffic with occupancy 1.12; other traffic is responsible for 83 percent of daily traffic with occupancy 1.89. Auto occupancy along with the annual truck VHT, commute VHT, and non-commute VHT were input into TREDIS for the benefit cost analysis in this study. The analysis outputs are shown in Table 2 with an analysis year of 2035 and cost savings shown in millions of dollars:

TABLE 2 Benefit Cost Analysis Output

Projects	Vehicle Operating Cost Savings	Time & Reliability Savings	Value of Personal Time Savings	Logistics Cost Savings	Environmental Benefits	Total Cost	Benefit Cost Ratio
Project 1	36.8	23.6	313.2	3.9	1.8	65.7	5.78
Project 2	0.4	0.3	3.8	0.01	0.01	78.6	0.06
Project 3	10.7	7.8	84.5	1.7	0.5	37.0	2.84
Project 4	44.2	28.4	376.6	4.7	2.1	163.5	2.79

TREDIS research shows that time and reliability benefits are split roughly between employers and workers. In the output table, time and reliability savings are brought by the commute trips only for employers. Value of personal time savings are brought by all commute trips and non-commute trips for road users due to the travel time savings created by new capacity projects. It includes both travel time and reliability savings of commute trips for workers, and travel time and reliability savings of non-commute trips for all road users.

The analysis results are consistent with expectations. Project 1, Expansion of Interstate 25, has the highest benefit cost ratio because it carries 30 percent of regional traffic; it does not have any right-of-way issues since the segments are located outside an urban area, and CDOT already owns the right-of-way. Project 2, US 24 West expansion, has the lowest benefit cost ratio partly because of the significant cost associated with right-of-way acquisition and construction of a new interchange; therefore, the 0.74-lane-mile expansion costs $75.7 million. Analysis of the benefits from this project shows significantly less travel time savings than expected. The reason for this is that there are several alternative routes with excess capacity around this location.

CONCLUSION

This paper explains a methodology that uses a combination of travel-demand-model-and benefit cost analysis as an approach to evaluate transportation projects. The approach is based on assessing the impact of a transportation improvement project with new capacity on the entire

regional network. The savings in VHT for the region is estimated for each proposed project was and then converted into dollar benefits. The methodology was demonstrated by evaluating four transportation projects in the Pikes Peak region. The results of the analysis were generally consistent with expectations. This case study suggests that the proposed approach can be useful and effective in quantitatively evaluating transportation projects.

Since most medium-sized and large MPOs have a regional travel demand model, the proposed methodology can be easily implemented by running the model and putting model results into tools such as TREDIS. The validity and accuracy of the travel demand model plays a very important role in this approach, indicating the necessity of exploring evolution and enhancements to the regional modeling system.

This methodology is only one measure that can be useful in evaluating the proposed transportation projects. Other measures should also play an important role in assessing transportation projects. The final prioritization of projects should be reached by decision makers considering the multiple goals of their regional transportation system.

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