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BENEFITS ESTIMATES OF HIGHWAY CAPITAL IMPROVEMENTS WITH UNCERTAIN PARAMETERS

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16. Abstract

This report warrants consideration in the development of goals, performance measures, and standard cost-benefit methodology required of transportation agencies by the Virginia 2006 Appropriations Act. The Virginia Department of Transportation has begun to implement a quantitative methodology as an aid to prioritizing highway construction projects in four categories: interstate, primary, urban, and rural.

The methodology adopts fifteen quantitative metrics including level of service (LOS), volume-to-capacity ratio, traffic flow, intermodal access, crash rate, emergency route access, heavy truck usage, unemployment rate, environmental issues, right-of-way use, use of alternative transportation modes, bridge sufficiency rating, and cost-effectiveness. The results of the methodology are used by executive review teams to negotiate, interpret, and support decisions regarding the selection of construction projects for funding in a $1.8 billion construction program.

This report describes an effort to extend the current prioritization methodology via modeling and uncertainty analysis of the risk reductions, benefits, and costs that are expected of candidate construction projects. The report (1) develops monetized estimates of benefits in several categories including crashes avoided, travel time saved, fuel uses avoided, and emissions avoided; (2) compares the estimates of benefits to the estimates of project costs, representing the uncertainty of the results as numerical intervals; and (3) compares the results to the results of the prioritization methodology that is currently in use. The major contribution of the report is the assembly of existing and new methods of benefits assessment via an interval analysis of uncertainty that enables a prioritization to proceed with sparse data on a large number of potential projects. With the interval analysis of uncertainty, a decision maker is provided with a sound basis to recommend that more data are needed or that existing available data are sufficient to distinguish among the potential projects. The developed methodology is demonstrated with project data from VDOT's Northern Virginia District using a database of performance criteria of 53 candidate projects ranging in cost from $2 million to $130 million. A prototype of a prioritization software was developed along with the report for the support of future analyses.

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NOTICE

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Each contract report is peer reviewed and accepted for publication by Research Council staff with expertise in related technical areas. Final editing and proofreading of the report are performed by the contractor.

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ABSTRACT

This report warrants consideration in the development of goals, performance measures, and standard cost-benefit methodology required of transportation agencies by the Virginia 2006 Appropriations Act. The Virginia Department of Transportation has begun to implement a quantitative methodology as an aid to prioritizing highway construction projects in four categories: interstate, primary, urban, and rural.

The methodology adopts fifteen quantitative metrics including level of service (LOS), volume-to-capacity ratio, traffic flow, intermodal access, crash rate, emergency route access, heavy truck usage, unemployment rate, environmental issues, right-of-way use, use of alternative transportation modes, bridge sufficiency rating, and cost-effectiveness. The results of the methodology are used by executive review teams to negotiate, interpret, and support decisions regarding the selection of construction projects for funding in a $1.8 billion construction program.

This report describes an effort to extend the current prioritization methodology via modeling and uncertainty analysis of the risk reductions, benefits, and costs that are expected of candidate construction projects. The report (1) develops monetized estimates of benefits in several categories including crashes avoided, travel time saved, fuel uses avoided, and emissions avoided; (2) compares the estimates of benefits to the estimates of project costs, representing the uncertainty of the results as numerical intervals; and (3) compares the results to the results of the prioritization methodology that is currently in use. The major contribution of the report is the assembly of existing and new methods of benefits assessment via an interval analysis of uncertainty that enables a prioritization to proceed with sparse data on a large number of potential projects. With the interval analysis of uncertainty, a decision maker is provided with a sound basis to recommend that more data are needed or that existing available data are sufficient to distinguish among the potential projects. The developed methodology is demonstrated with project data from VDOT’s Northern Virginia District using a database of performance criteria of 53 candidate projects ranging in cost from $2 million to $130 million. A prototype of a prioritization software was developed along with the report for the support of future analyses.

INTRODUCTION

This report identifies and recommends methodology and tools for enhancing the current method that identifies priority projects in the Statewide Transportation Plan pursuant to § 33.1-23.03 of the Code of Virginia. The report also relates to and warrants consideration in the coordinated development of goals, performance measures, and standard cost-benefit methodology required by the Virginia 2006 Appropriations Act (Items 427(I)(1) and (2) and 442(A)(3)(b), Chapter 3, Special Session I, 2006 Acts of Assembly), which became effective July 1, 2006. This law directs state transportation agencies in cooperation with regional authorities and organizations, and representatives of local government to develop transportation goals and performance measures as well as a standard cost-benefit methodology for evaluating projects. The goals and performance measures are required to be quantifiable and achievable, and relate to "congestion reduction and safety, transit and HOV usage, job/housing ratios, job and housing access to transit and pedestrian facilities, air quality, and/or per-capita vehicle miles traveled." In addition, the specific performance measures are to include, but not be limited to, "improvements related to safety, connectivity, economic development, improved air quality and traffic mitigation."

The Virginia Department of Transportation (VDOT) recently began to implement a quantitative methodology as an aid to prioritizing highway construction projects in four categories: interstate, primary, urban, and rural. The first two categories comprise the State Highway Plan. The methodology adopts fifteen quantitative metrics including level of service (LOS), volume-to-capacity ratio, traffic flow, intermodal access, crash rate, emergency route access, heavy truck usage, unemployment rate, environmental issues, right-of-way use, use of alternative transportation modes, bridge sufficiency rating, and cost-effectiveness.

The results of the methodology are used by executive review teams to negotiate, interpret, and support decisions regarding the selection of construction projects for funding in a $1.8 billion per year construction program. The agency is considering how the methodology can assist with the transparency of project selection to the public, agency staff, legislators, and the Commonwealth Transportation Board. The agency tested the methodology in nine districts for the interstate system and found that the existing metrics need additional aggregation.

This report describes an effort to support and extend the current prioritization methodology via modeling and uncertainty analysis of the risk reductions, benefits, and costs that are expected of the candidate construction projects. The foundations of this report are the theory and methodology of cost-benefit analysis, multi-objective decision-making, and risk analysis.

We conferred regularly with a project steering committee of metropolitan planning organizations, planning district commissions, agency engineers, planners, executives, and other relevant parties.

PURPOSE AND SCOPE

The purpose of this report was to extend and complement an existing multiobjective methodology for prioritizing highway capital improvements via an assessment of the forecasted benefits of individual projects.

In particular, the report:

- Adopts and modifies as appropriate existing methodologies of benefits analysis from the practice and the literature.
- Uses the existing databases and capabilities for data collection of a highway agency appropriate to the planning phase of construction projects.
- Identifies and develops the relevant assumptions and formulae for estimation of aggregated risk reductions and benefits and costs.
- Identifies the exogenous parameters with their associated uncertainties.
- Develops non-monetized and monetized estimates of benefits in several categories including crashes avoided, travel time saved, fuel uses avoided, and emission avoided.
- Compares the estimates of benefits to the estimates of project costs, representing the uncertainty of the results as numerical intervals.
- Compares the results of the benefits-based assessments to the results of a multiobjective prioritization methodology that is currently in use.

The developed methodology is demonstrated with project data from VDOT's Northern Virginia (NOVA) District using a database of performance criteria of 53 candidate projects ranging in cost from $2 million to $130 million. A prototype prioritization software is provided along with the report for future analysis. The software and database are available for download at www.virginia.edu/crmes/prioritization.

REVIEW OF LITERATURE

The literature yields several alternative approaches to prioritization methods employed by transportation agencies in different states.

The Ohio Department of Transportation classifies candidate projects into three levels: minimal, minor, and major based on their complexity, i.e., the number of steps it takes to complete each project. The projects in the three classes are analyzed separately (ODOT, 2005).

The Illinois Department of Transportation (IDOT) divides its projects into categories and distributes a certain percentage of their funds to each category. The categories include preservation, interstate reconstruction, major bridge modernization, traffic and safety improvements, new roads for economic development, and new bridges for alleviating urban congestion. For example, IDOT (2002) estimates that total funding needs would range from

$12.1 to 20.3 billion during the period of 2004-2009 in order to be able to make significant improvements in all the six categories mentioned.

The Massachusetts Department of Transportation considers the following factors when prioritizing candidate projects: environmental regulation compliance, alignment and structural code adherence, utility and right-of-way considerations, and budget constraints (MHD 2006).

In addition, there are different approaches to benefit-cost analysis for highway projects.

Cervero and Aschauer (1998) describe a three-step process to conduct benefit-cost analysis. The first step in the process is to define the economic life of the project while the second is to choose a proper discount rate that reflects society's time value of money. The third step is to measure benefits associated with the project. Some important benefits of transit investments are travel time savings that accrue over the life of the project, reduced accidents and reduced air pollution. All these benefits are monetized. Cervero and Aschauer (1998) describe how an improved transportation system will assist with economic growth. Benefits of a growing economy and improved transportation include user benefits (e.g., reduced travel time), regional employment and income growth, and job accessibility benefits.

Lambert et al. (2005) developed a methodology to coordinate and prioritize multimodal investment networks. Lambert et al. (2003) and Haimes (2004) describe multiobjective decision aids that can be useful for project evaluation by bringing forth available relevant information and encouraging transparency in decision-making.

Several aspects of risk-cost-benefit analysis for prioritizing transportation projects have been addressed by Frohwein et al. (1999), Baker and Lambert (2001) and Lambert et al. (2002). Risk-based methodologies for resource allocation are studied by Lambert et al. (2006), Lambert and Turley (2005), and Lambert et al. (2003).

The National Cooperative Highway Research Program (NCHRP-A 1999) describes a cost estimation methodology entitled StratBENCOST. StratBENCOST provides analyses for several categories of monetized benefits of highway construction, including environment, safety, and travel time. Related methodology for assessing the social and economic impacts of transportation projects is described by NCHRP (2004) and NCHRP (2001). These latter two methods are oriented to situations where data across projects are uniformly available, and they thus require data that may not yet be available on highway projects that are in the early stages of planning.

The literature provides foundations on which we will proceed to assemble several existing and new methods of benefits assessment of highway projects.

METHODOLOGY

Overview

This section describes the methodology that is adopted, developed and modified for the estimation of the anticipated benefits and costs of highway construction in several categories: crashes avoided, travel time savings, reduced vehicle operating costs, emissions avoided, economic development measured by heavy truck traffic, and highway project life-cycle costs.

Crashes Avoided

Highway crashes are broadly classified into three types: fatal crash, injury crash, and property damage only crash. The annual cost of crashes can be estimated using the following formula:

$$\text{annual cost of crashes} = r_{CR} * \left(p_F c_F + p_I c_I + p_{PD} c_{PD} \right) * M$$

where

r_{CR} is the crash rate in crashes per 100 million VMT
p_F is the percentage of fatal crashes
c_F is the cost associated with a fatal crash
p_I is the percentage of injury crashes
c_I is the cost associated with an injury crash
p_{PD} is the percentage of property damage only crashes
c_{PD} is the cost associated with a property damage only crash
M is 100 million vehicle miles traveled per year and it is estimated as follows:

$$M = \frac{l * AADT * 365}{100{,}000{,}000}$$

where

$AADT$ is average annual daily traffic at the project location
l is the roadway length (miles) influenced by the project and
365 is the number of days in a year.

The implementation of a candidate project will reduce, or even potentially increase, the crash rate at the project location by a specified percentage. We did not encounter in this study any potential projects that are forecast to increase the crash rate. Such an assessment of an increase in crash rate would, however, propagate straightforwardly in the ranking analysis as a benefit that is negative in sign. We incorporate a crash reduction factor that is useful in estimating the annual savings from crashes avoided after the project has been implemented. For example, a crash reduction factor of 0.1 indicates a 10% reduction in crashes. Thus, for each project, the monetized benefits from crashes avoided are given as follows:

$$\begin{aligned} B_{CR} &= \text{annual cost of crashes} * \text{ crash reduction factor} \\ &= r_{CR} * \left(p_F c_F + p_I c_I + p_{PD} c_{PD}\right) * M * \text{crash reduction factor} \end{aligned}$$

and the benefit-cost ratio is given by:

$$\text{benefit - cost ratio of crashes avoided} = \frac{B_{CR}}{C_c / N}$$

where

C_c is the capital cost of the project, and

N is project lifetime in years.

The benefits are estimated on a yearly basis, and thus the total cost of the project is amortized over the lifetime of the project to obtain an equivalent annual cost of the project.

A non-monetized version of the benefit-cost analysis, known as cost-effectiveness ratio is described by:

$$\begin{aligned} \text{cost} - \text{effectiveness ratio} &= \frac{\text{number of crashes avoided per year}}{\text{cost of project/project lifetime}} \\ &= \frac{r_{CR} * M * \text{crash reduction factor}}{C_c / N} \end{aligned}$$

Net benefits, or the difference of benefits and costs, can be generated as well from the data that are supporting the calculation of the benefit-cost ratio. In this regard, we note that a high-cost project with a relatively lower benefit-to-cost ratio might be preferred to a low-cost project with a relatively higher benefit-to-cost ratio and that an opportunity to invest more in order to achieve more benefits can be masked by presentation of the benefit-to-cost ratio alone. The benefit-to-cost ratio should not be used alone and independent of project cost to prioritize projects. Similarly, a measure of net benefits cannot be used alone since, for example, it does not take into account that there may be a constraint on how much investment can be made in the program. In this report, we favor neither benefit-to-cost ratio nor net benefits; rather, we suggest presentation of the benefits in their natural units (e.g., crashes avoided, travel time savings, emissions avoided, fuel savings) for screening of the projects.

The AADT, crash rate, capital cost of project, roadway length influenced by the project and project lifetime are considered to be the deterministic parameters in the model. Uncertain parameters in the model are the cost and the frequency (percentage) of occurrence associated with each type of crash, and the crash reduction factor (crashes avoided per crash). The uncertainty is addressed using interval analysis of the low and high bounds on the value of each uncertain parameter.

The costs associated with each of the three types of crash are provided in Table 1. These estimates are adopted from NCHRP-A (1999). An analyst can change these values in the prototype software.

Table 1. Highway Accident Costs by Accident Type (1996 dollars/accident)

Accident Type	Median Estimate	Lower Estimate	Upper Estimate
Fatal Accident	$3,521,359	$809,054	$8,097,408
Injury Accident	$83,848	$14,946	$216,698
Property Damage Only Accident	$5,806	$1,442	$11,720

Source: NCHRP-A (1999).

The crash frequencies are provided in Table 2. These percentages were found through a statistical study (Einstein Law 2004) of 6,289,000 reported auto crashes, 3,200,000 injuries related to auto crashes, and 41,345 deaths due to auto crashes in 1999:

Table 2. Frequencies of Each Type of Crash

Type of Crash	Proportion
Fatal Accident	0.01
Injury Accident	0.51
Property Damage	0.48

Source: Einstein Law (2004).

Awaiting additional data on the projects, the crash reduction factor is considered uniformly for all projects to lie in the range provided in Table 3. An analyst can change these values in the global variables section of the prototype prioritization software. For each project, a lower, median, and upper estimate value of the benefit-cost ratio as well as the cost-effectiveness ratio is calculated to represent the uncertainty.

Table 3. Crash Reduction Factor

Median Estimate	Lower Estimate	Upper Estimate
0.1	0.05	0.15

Travel Time Savings

It is reasonable to assume that, by relieving congestion during peak hours through capacity enhancement, the reduction of vehicle operating time and associated reduction in vehicle operating costs could be significant.

The annual peak vehicle hours VH for each project location is derived by the following formula:

$$VH = T_c * k * AADT * 365$$

where

k is the proportion of traffic that experiences peak period congestion

T_c is the travel time in hours under peak volume-to-capacity ratio and is estimated by a traditional BPR (the United States Bureau of Public Roads) curve and related BPR equation adopted from a current VDOT methodology:

$$T_c = T_o\left[1 + 0.15\left(\frac{Volume}{Capacity}\right)^4\right] \times 0.87$$

where

T_o is the free flow travel time (hours)

The free flow travel times, T_o is given by:

$$T_o = \frac{l}{s_f}$$

where

l is the roadway length influenced by the project

s_f is the free flow speed.

The free flow speeds for different road types are adopted from NCHRP-B (1999) and are provided in Table 4. It is assumed that the implementation of a candidate project results in a reduced volume to capacity ratio at a project location. A global uniform range for reduced volume to capacity ratio is fixed for all the projects. Annual peak hours before capacity enhancement are estimated for each project using the above equations and the current volume to capacity ratio. Similarly, lower and higher values of the annual peak hours after a capacity enhancement are estimated for each project using the lower and higher values of reduced volume to capacity ratio respectively. The difference between the before implementation and after implementation values is the annual benefit in travel time savings during peak hours attributable to the implementation of the project. The benefit is divided by an equivalent annual project cost to obtain a cost-effectiveness measure as travel time saved per dollar invested.

$$\text{travel time saved per dollar} = \frac{VH_{before} - VH_{after}}{C_c / N}$$

where

VH_{before} is the annual peak vehicle hours prior to capacity enhancement

VH_{after} is the annual peak vehicle hours after capacity enhancement

For each project, low, high and median estimates of the cost-effectiveness measure are calculated using above formulation.

Reduced Vehicle Operating Costs

Operating costs are typically analyzed via five components: fuel consumption, lubricating oil consumption, wear on tires, maintenance and repair costs, and depreciation of the vehicle's value. NCHRP-A (1999) shows that these costs depend on several parameters including vehicle type (truck, automobile, or bus), pavement condition, road grade, constant speed, changing speeds, time idling, and curvature of the roadway segment.

The current effort addresses only the fuel consumption costs. Our simplified model for fuel consumption costs is based on NCHRP-A (1999) and uses two different parameters: vehicle speed and road type. The other parameters are held constant. In particular, the estimation proceeds with the following assumptions: (i) The pavement adjustment factor is set to one; (ii) All roads are considered to have a 0% grade; (iii) The vehicle type is restricted to automobiles.

Thus, the annual fuel consumption cost during peak hours, FC is given by the following equation:

$$FC = \left(\frac{AADT * l * k * 365}{1000} \right) * f_c * C_{fuel}$$

where

f_c is fuel consumption rate in gallons per thousand vehicle-miles

C_{fuel} is the cost of fuel in dollars per gallon.

The fuel consumption rate depends on the vehicle's speed, which in turn depends on the volume to capacity ratio of the project location and the road type. Thus, the fuel consumption rate can be estimated for each project location based on its volume to capacity ratio and road type. Two lookup tables are adopted from NCHRP-B (1999) to estimate fuel consumption rate. Table 4 shows the relationship of vehicle speed to the V-C ratio and road type. One limitation of Table 4 is that it has V-C ratios only up to 1.05. In reality, some project locations can have V-C ratio higher than 1.05. Currently, we treat V-C ratio of all such locations to be 1.05.

Implementation of project enhances the capacity of the roadway segment under consideration and thus reduces the V-C ratio, which in turn allows increased vehicle speeds for highway users as shown in Table 4. As mentioned above, a global uniform range for change in V-C ratio is fixed for all the projects bounded by low value and high value. This range can be easily changed in the global variables section of the prototype prioritization software.

Table 4. Relation of Vehicle Speed to Volume-to-Capacity Ratio and Road Type (Source: NCHRP-B (1999))

Vehicle Speed		Volume-to-capacity ratio											
(MPH)		**0**	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**	**1**	**1.05**
Road Type	**R2**	60	56	52	51	50	49	48	47.5	47	46.5	46	12
	R4	60	57.2	55.6	53.1	50	47.3	43.8	39.7	12.5	15	15	15
	R4D	60	57.4	56	54.2	51.4	49	46	43.1	39.2	12	12	12
	R6D	60	57.4	56	54.2	51.4	49	46	43.1	39.2	12	12	12
	U2	35	32.7	30.3	29.8	29.2	28.6	28	27.7	27.4	27.1	26.8	7
	U3	35	32.7	30.3	29.8	29.2	28.6	28	27.7	27.4	27.1	26.8	7
	U4	48	45.9	44.9	43.7	41.6	39.6	37.7	35.3	32.7	21.1	12	12
	U4D	48	46	45	44	42	40	38.5	36	34	31	10	12
	U6D	60	58	57	56	54.5	53	50	48.5	46	42	32	12
	U8D	60	58	57	56	54.5	53	50	48.5	46	42	32	12

Table 5 shows the relationship between vehicle speed and the fuel consumption rate. The annual fuel consumption costs during peak hours are calculated for three scenarios: consumption costs before project implementation, consumption costs after project implementation under low V-C ratio change assumption, and consumption costs after project implementation under high V-C ratio change assumption. It is interesting to note that the relationship between vehicle speed and fuel consumption rate as shown in Table 5 is neither strictly increasing nor decreasing. The lowest consumption rate occurs around 45 mph. Therefore, for project locations that already have average speeds around 45 mph during the peak period, implementation of the project would reduce the V-C ratio and in turn allow increased vehicle speeds above 45 mph for highway users. This can actually result in estimating increased fuel consumption and thus negative benefits of the project in the present category. Our calculations below will be based on rational behavior of the highway users. We will consider that the users drive at optimal speeds for reduction of fuel consumption. In the few situations that might lead us to negative benefits, we replace the negative benefits with zero benefits. Furthermore, whenever a potential project allows speeds more than 45 mph, we consider that the project has no impact on the roadway segment.

The benefit can be divided by an equivalent annual project cost to obtain benefit-to-cost ratio:

$$\text{benefit} - \text{cost ratio of fuel savings} = \frac{FC_{before} - FC_{after}}{C_c / N}$$

Table 5. Relation between Vehicle Speed and Fuel Consumption Rate (Source: NCHRP-B (1999))

Speed (mph)	Fuel consumption rate (gallons per 1000 miles)
5	74.02
10	56.89
15	45.29
20	37.33
25	31.87
30	28.17
35	25.80
40	24.46
45	24.02
50	24.42
55	25.72
60	28.06
65	31.69
70	37.07

where

FC_{before} is the annual fuel consumption cost during peak hours before capacity enhancement

FC_{after} is the annual fuel consumption cost during peak hours after capacity enhancement

For each project, low, high and median estimates of benefit-to-cost ratio of fuel savings are calculated using the above formulation.

Emissions-Avoided

Emissions can be classified into three types: hydrocarbons (HC), carbon monoxide (CO), and nitrous oxide (NOx). An emission rate lookup table for each emission type is given in NCHRP-B (1999). The model uses this table to obtain emission rates at the average vehicle speed.

The analysis applies only to the period associated with peak volume on the roadway. In the current formulation, the vehicle type is restricted to automobiles, and the emissions type is restricted to hydrocarbons.

The average vehicle speed before the implementation of the project, and the improvement in speed due to the project are not known with certainty. The current formulation assumes that that the average vehicle speed during peak hours before the project implementation is 30 miles per hour. Emission rates depend on vehicle speed and are estimated using Table 6. The annual emission costs are calculated using the emission rates as follows:

$$\text{Annual emission cost} = \left(\frac{k * AADT * l}{1000}\right) * \frac{r_E}{2000} * C_E * 365$$

where

r_E is the emission rate in pounds of hydrocarbons per thousand vehicle miles of travel

C_E is the emission cost in dollars per ton of hydrocarbon

Table 6. Emission Rates in Pounds of Pollutants per Thousand Vehicle Miles

Vehicle Speed MPH	Auto			Bus			Truck		
	HC	**CO**	**Nox**	**HC**	**CO**	**Nox**	**HC**	**CO**	**Nox**
5	7.46	151.00	2.32	1.31	5.56	32.00	1.31	5.56	32.00
10	3.28	61.40	1.15	1.37	5.80	33.20	1.37	5.80	33.20
15	1.93	33.20	1.38	1.44	6.12	35.20	1.44	6.12	35.20
20	1.30	20.60	1.96	1.55	6.56	37.60	1.55	6.56	37.60
25	0.95	14.12	2.68	1.67	7.10	40.80	1.67	7.10	40.80
30	0.75	10.74	3.46	1.82	7.74	44.40	1.82	7.74	44.40
35	0.62	9.10	4.30	2.00	8.48	48.80	2.00	8.48	48.80
40	0.55	8.58	5.14	2.20	9.32	53.60	2.20	9.32	53.60
45	0.51	8.78	6.02	2.42	10.28	59.00	2.42	10.28	59.00
50	0.49	9.50	6.90	2.68	11.34	65.00	2.68	11.34	65.00
55	0.49	10.58	7.80	2.94	12.50	71.80	2.94	12.50	71.80
60	0.51	11.96	8.68	3.24	13.74	79.00	3.24	13.74	79.00
65	0.53	13.54	9.58	3.56	15.12	86.80	3.56	15.12	86.80
70	0.57	15.30	10.50	3.92	16.58	95.20	3.92	16.58	95.20

Source: NCHRP-B (1999).

A global uniform range is fixed for improvement in speed due to the project to address uncertainty in the model. Four different calculations of annual emission cost are performed. First, a base case for emission cost is calculated using the emission rate prior to the project implementation. Second, a calculation is performed for *after the project implementation* case using the low estimate of improved vehicle speed. Third, a calculation is performed for *after the* *project implementation* case using the high estimate of improved vehicle speed. Finally, a fourth calculation is performed for *after the project implementation* case using the median estimate of improved vehicle speed. Lower, higher and median estimates of annual emission costs after the project implementation are subtracted from the base case respectively, resulting in low, high and median estimates of emissions-avoided benefits. The annual benefits are divided by annualized costs of the projects to obtain relevant benefit-cost ratios.

Heavy Truck Traffic

Heavy truck traffic is an important economic development indicator. We estimate the ratio of annual heavy truck miles (supported by a project) at the project location to the annual cost of the project. The heavy truck miles per dollar is given by the following formula:

$$\text{heavy truck miles per dollar} = \frac{n_{ht} * x * l * 365}{C_c / N}$$

where

n_{ht} is number of heavy trucks per day at project location before project implementation

x represents percentage increase in truck traffic due to project implementation.

A global uniform range is fixed for x bounded by low and high value to represent uncertainty. Heavy truck miles per dollar is calculated in an interval analysis of uncertainty for two cases: for a low value of x and for a high value of x.

Extension of Cost Estimation

The current effort divides project capital cost by project life time to obtain annual project cost, which is then used to develop estimates of benefit-cost ratios in several categories as discussed above. An extension of the cost estimation model includes maintenance and other life-cycle costs and the concept of discounting. This extension of cost estimation can be used in future research related to cost-benefit estimation, project prioritization, and capital budgeting.

In agency databases, each project has a capital cost that includes only initial construction costs, right-of-way costs, and other fixed costs. It does not include maintenance and other life-cycle costs, or discounted costs since the costs are assumed to be paid over time. Since the data for several recurring costs are not known with precision, interval analysis is used to account for uncertainty of the important parameters. Table 7 gives the low and high values of these parameters. The values can be easily modified if required in global variable section of the prototype prioritization software. These values are used for total discounted cost calculations and they represent the basis for sensitivity analysis.

Table 7. Input Parameters for the Cost Estimation

Parameter	Low	High
Discount rate (*i*)	4%	4%
Project life (*N*)	25	25
Project construction time (*n*)	5	4
Maintenance costs (proportion of capital cost)	1/800	1/250
Other life-cycle costs (proportion of capital cost)	1/120	1/30

The present value of capital construction cost is given by the following formula:

$$\text{PV of capital cost} = \frac{C_c}{n}\left[\frac{1-(1+i)^{-n}}{i}\right]*(1+i)$$

where

n is project construction time in years,
i is discount rate

The above equation assumes that payments occur at the beginning of each year, start immediately, and have a constant rate of capital over the project construction duration. Estimating present value of ongoing costs (maintenance and other life-cycle costs) uses a similar equation that takes into account the costs starting in the future period after the construction is completed. The following equation thus assumes that payments occur at the beginning of the year, start after the project is complete, and have a constant rate of capital until the end of the project life.

$$\text{PV of ongoing cost} = C_{ongoing} * \left[\frac{(1+i)^{-n} - (1+i)^{-N}}{i}\right]*(1+i)$$

where

$C_{ongoing}$ is the annual ongoing cost over the project life ($)

The present value of the total cost associated with any project is the sum of the present value of project capital cost and the present value of project ongoing costs.

Table 8 shows the inputs for a sample of projects from the Northern Virginia district. The inputs include the project ID number, the jurisdiction and the project construction cost.

Table 8. Sample Input Data for NOVA District Projects

Project ID	Jurisdiction	Construction cost (thousand $)
2090001	Arlington	14,000
2090002	Arlington	18,000
2090003	Arlington	11,000
2090005	Arlington	18,000

The lower and higher values of maintenance cost and other lifecycle costs over the project life are estimated for each project using the input data and input parameters. For example, Table 9 shows the undiscounted and discounted values of the life-cycle cost for the sample of projects shown in Table 8.

The low and high estimates of the present value of the capital cost are developed for each project. The range associated with the present value of the project capital costs depends on the range of construction time associated with that project. Table 10 shows lower and higher estimates of an undiscounted combination of capital, maintenance and other life-cycle cost for the sample of projects shown in Table 8.

Table 9. Undiscounted and Discounted Life-Cycle Costs for the NOVA District Projects

Project ID	Undiscounted Life-Cycle Cost		Discounted Life-Cycle Cost	
	Low	High	Low	High
2090001	$2,333,333	$9,800,000	$1,355,325	$5,820,207
2090002	$3,000,000	$12,600,000	$1,742,560	$7,483,123
2090003	$1,833,333	$7,700,000	$1,064,898	$4,573,020
2090005	$3,000,000	$12,600,000	$1,742,560	$7,483,123

Table 10. Total Cost Estimates for the NOVA District Projects

Project ID	Capital + maintenance +other life-cycle costs	
	Low	High
2090001	$16,683,333	$24,976,000
2090002	$21,450,000	$32,112,000
2090003	$13,108,333	$19,624,000
2090005	$21,450,000	$32,112,000

Overall, the cost estimation model can provide a systematic approach for incorporating life-cycle cost estimates to the cost-benefit analysis of road improvements and can be used in future research.

RESULTS

Overview

A case study of the Northern Virginia district demonstrates an application of above methodology and provides results in several sections: crashes avoided, travel time savings, reduced vehicle operating costs, emissions avoided, and heavy truck traffic.

There are 53 total candidate projects for Northern Virginia district with costs ranging from $2 million to $130 million. The input data collected for this district are shown in Table 11. Each project is labeled by its ID number. The input parameters shown in the table are road type, length of the project, 2004 volume-to-capacity ratio during peak period, 2004 AADT, crash rate, number of heavy trucks per day and total cost of the project.

In interpreting the results, it is important to note some common assumptions on which results are based. For example, the lifetime of each project is considered to be 25 years. It is assumed that project implementation will cause reduction in volume-to-capacity ratio in a uniform range between 10% and 50%. Roadway length influenced by the project, l is considered to be five times the length of the project. The proportion of traffic that occurs during the peak period, k is fixed at 25% of AADT. These values can be changed as required in the prototype prioritization software.

Table 11. Northern Virginia Input Data

ID	Road type	Project length (miles)	2004 V/C ratio	2004 AADT	Crashes per 100 million VMT	# Heavy trucks per day	Total Cost (thousand $)
2090001	U6D	0.91	1.24	76,213	88.92	1,451	14,000
2090002	U6D	1.37	1.64	70,000	101.48	1,400	18,000
2090003	U6D	0.40	0.6	27,220	541.37	272	11,000
2090005	U6D	1.08	1.22	32,073	255.54	321	18,000
2090007	U6D	0.64	1.41	66,326	313.1	663	7,000
2090009	U6D	0.47	1.1	74,976	135.19	1,500	10,000
2090011	U6D	0.83	0.94	34,878	703.35	1,046	13,000
2090012	U6D	0.22	0.8	29,675	578	890	4,000
2090013	U4	0.40	0.98	14,564	232.81	146	5,000
2090014	U4	1.99	0.62	16,225	385.66	487	20,000
2090015	U4D	0.07	1.66	26,228	652.8	525	2,000
2090016	U4D	1.72	1.04	33,500	808.07	1,005	16,400
2090018	U4D	0.23	0.96	33,500	481.12	1,005	5,000
2090019	U4D	1.02	1.15	14,000	391.28	467	14,000
2090020	U4D	1.17	0.72	15,355	468.61	461	12,000
2090025	U6D	8.80	1.56	61,082	184.73	1,222	130,000
2090026	U8D	2.23	1.22	68,460	532.61	3,423	54,000
2090027	U6D	1.92	1.04	36,840	458	1,105	20,000
2090028	U8D	0.52	0.89	50,694	574.67	2,535	10,000
2090029	U6D	1.38	1.33	50,655	585.41	2,533	22,000
2090030	U6D	2.67	1.75	60,697	286.9	3,035	28,500
2090032	R4D	0.70	0.57	15,451	57	310	12,000
2090033	U6D	5.53	1.12	39,181	245.13	1,567	65,000
2090036	U8D	0.82	2.05	69,679	184.54	2,090	14,000
2090037	U6D	3.27	1.15	58,615	282.93	1,758	40,000
2090040	U6D	12.57	1.2	37,828	182.89	1,135	130,000
2090045	U6D	3.09	2.02	61,000	198.29	1,725	40,000
2090046	U6D	0.87	1.04	53,000	294.85	530	15,000
2090047	U8D	0.87	1.6	77,094	552.82	771	15,000
2090048	U6D	4.96	1.4	47,541	243.37	475	60,000
2090049	U4	0.81	1.23	30,507	84.22	305	8,000
2090053	U6D	7.27	1.59	54,000	427.72	1,620	90,000
2090055	U4	0.50	1.28	35,000	300	700	4,000
2090056	U6D	2.36	0.98	36,222	555.45	1,811	30,000
2090057	U4D	2.35	1.8	25,605	190.04	768	23,000
2090100	U6D	5.05	0.97	39,116	305.17	391	65,000
2090069	U6D	12.00	1.23	36,500	457	933	32,600
2090070	U6D	8.00	1.23	36,500	227	2,190	80,000
2090072	R4D	4.20	0.46	15,670	127.9	940	30,000
2090073	U6D	3.50	1.32	29,112	297.75	2,329	28,000
2090074	U6D	2.13	1.64	50,000	303.64	2,500	40,000
2090076	U6D	0.80	1.32	59,000	513	4,720	125,000
2090077	U4D	0.64	0.26	7,173	855	645	8,000
2090083	U6D	1.78	1.32	33,573	446.48	2,016	28,200
2090085	U6D	1.28	0.32	5,550	185	500	12,000
2090062	R6D	2.38	1.09	48,000	78	2,400	50,000
2090XXX	R6D	2.87	0.83	62,000	279	3,100	50,000

ID	Road type	Project length (miles)	2004 V/C ratio	2004 AADT	Crashes per 100 million VMT	# Heavy trucks per day	Total Cost (thousand $)
2090101	R6D	5.29	0.58	39,278	117.9	3,142	130,000
2090102	U8D	5.61	1.07	61,004	137.99	1,220	100,000
N1	R4D	4.25	1.64	50,000	156.74	1,500	115,000
N2	R4D	5.60	1.62	85,107	156.74	851	60,000
N3	R4D	4.00	1.54	95,182	156.74	3,807	7,000
N4	R4D	5.30	1.54	95,182	156.74	3,807	50,000

Crashes Avoided

Lower, higher and median values of benefit-cost ratio due to crashes avoided are calculated. Figure 1 provides graphical presentation of the results from the analysis of the benefits of crashes avoided. Each horizontal bar in the graph starts at the lower value of benefit-cost ratio and ends at the higher value. The vertical mark on each bar represents median estimate. The bars are labeled by their associated project ID. The graph highlights which projects have the highest benefit-cost ratio, where the monetized benefits are based upon the anticipated crashes avoided.

Figure 2 is a comparison of the number of crashes to the benefit-cost ratio. The projects located toward the top right of the figure have more crashes per year and higher vehicle miles traveled. The size of the bubble corresponds to the median estimate of benefit-cost ratio. In general, the projects in the lower left tend to have smaller benefit-cost ratios as compared to the projects located in the upper right.

Figure 3 shows the results of the cost-effectiveness calculation of crashes avoided per dollar. This graph is related to Figure 1 in that the ordering of the candidate projects is the same.

Table 12 provides the top five candidate projects using two different prioritization rules: the benefit-cost ratios for crash avoidance, and the current crash rate based scoring rule associated with safety goal used by VDOT. The project 2090016 is the only common project among the top five projects generated by both the prioritization rules.

Travel Time Savings

The travel time savings benefit of each candidate project is estimated and compared with its equivalent annual cost. Figure 4 provides a measure of the cost-effectiveness as the hours of travel time saved per dollar invested.

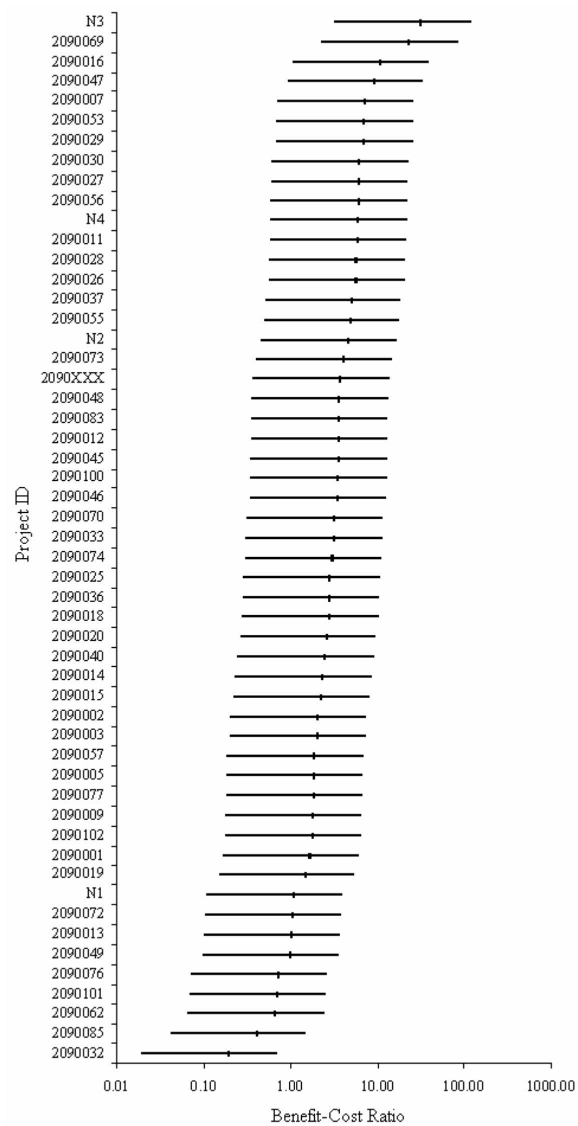

Figure 1. Benefit-Cost Ratio for the Crashes Avoided

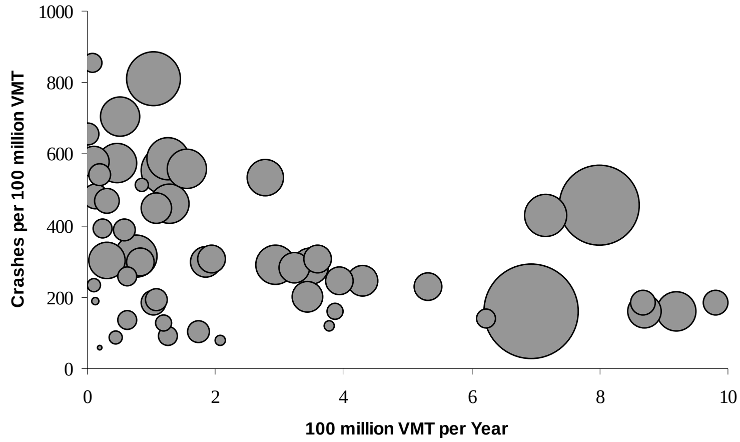

Figure 2. Comparison of Number of Crashes to the Benefit-Cost Ratio

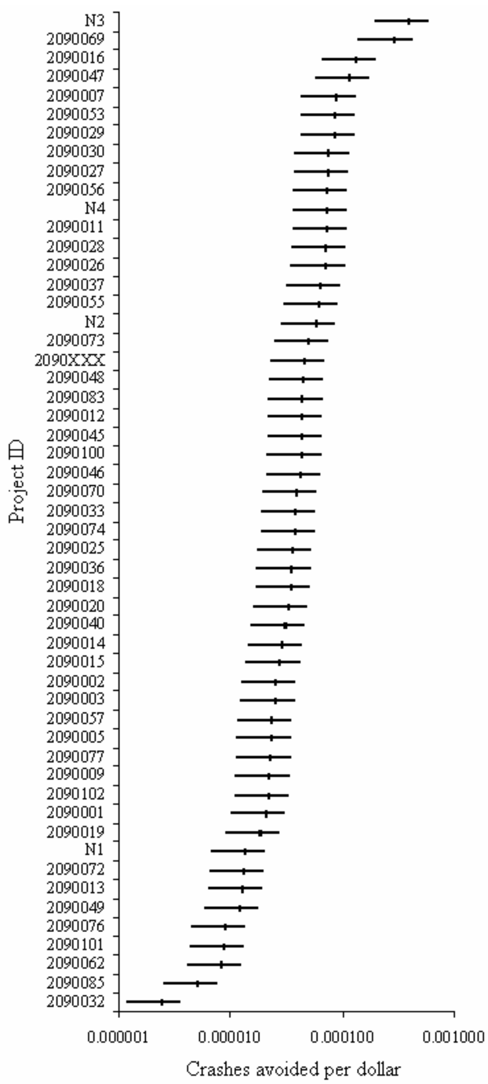

Figure 3. Cost-effectiveness Analysis for the Crashes Avoided

Table 12. Top Five Projects in the Crashes-Avoided Analysis Using Different Prioritization Methods

Benefit-Cost Ratio Prioritization		Crash-Rate Prioritization	
Rank	**Project ID**	**Rank**	**Project ID**
1	N3	1	2090077
2	2090069	2	2090016
3	2090016	3	2090011
4	2090047	4	2090015
5	2090007	5	2090029

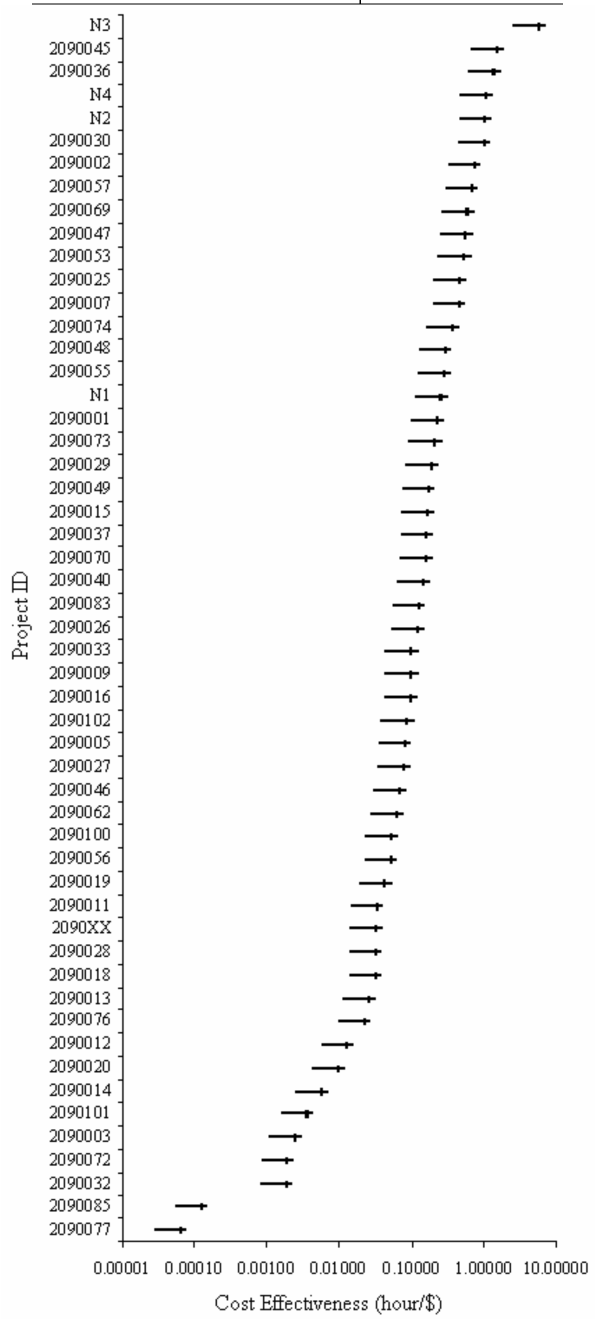

Figure 4. Estimation of the Benefits of Travel Time Savings

Reduced Vehicle Operating Costs

Figure 5 shows the benefit-to-cost ratio intervals of candidate projects based on reduction in fuel consumption costs. Fuel cost is assumed to be $2.3 per gallon for all the calculations. This value can be easily changed in the global variable section of prototype prioritization software for any future analysis. From the figure, it is evident that many projects have intervals with maximum values of the benefit to cost ratio much less than one.

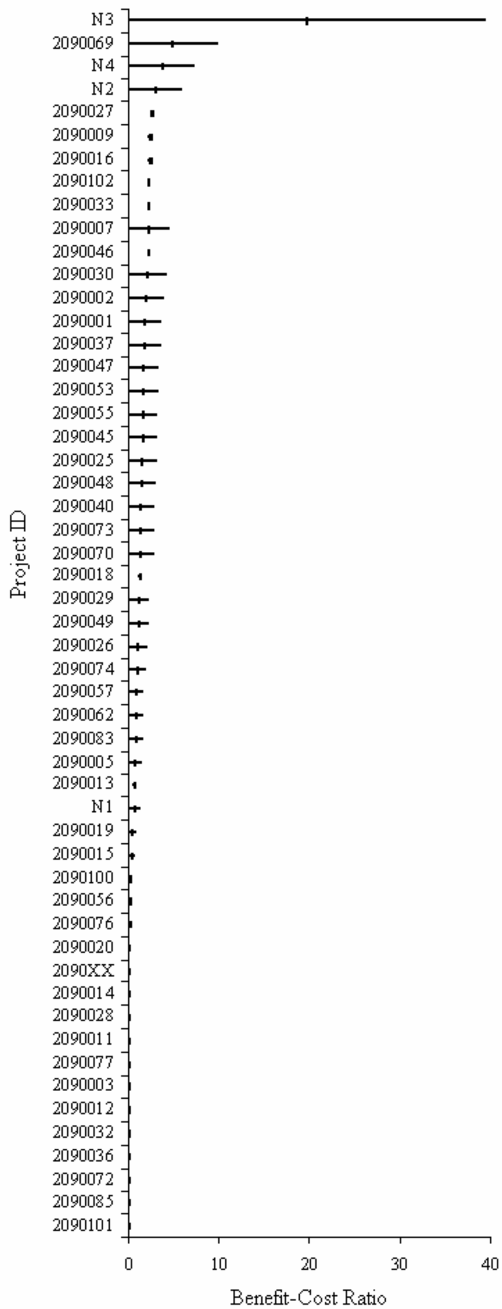

Figure 5. Benefit-Cost Ratio due to Reduced Vehicle Operating Costs

Emissions-Avoided

In an overview of the projects from Table 11, Figure 6 shows the average annual daily traffic contrasted with the lengths of the projects and the project costs. The more costly projects (larger circles) tend to be those with longer project lengths and higher traffic volumes. Because all three of these variables are used in the calculation of emissions reduction, it is important to understand this relationship.

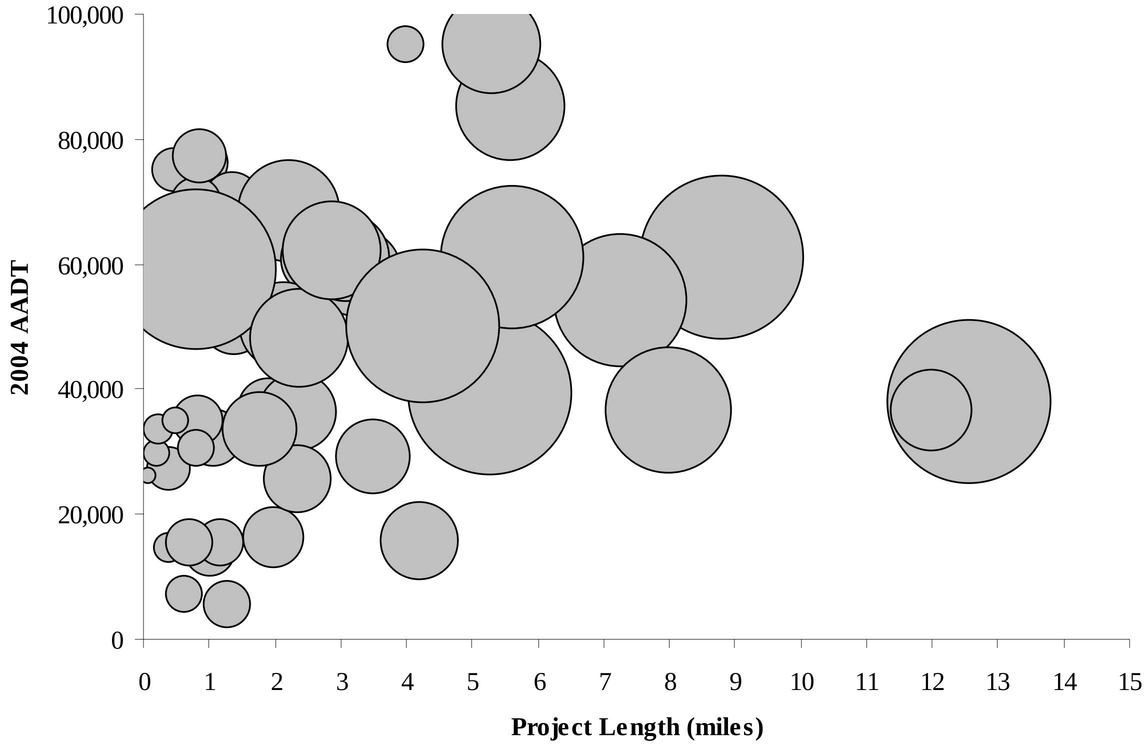

Figure 6. Cost vs. Project Length vs. AADT for Northern Virginia Projects

Figure 7 shows the uncertainty intervals of the benefit-cost ratio due to emissions avoided. We use a low estimate of 10%, a high estimate of 80% and a median estimate of 45% for improvement in vehicle speed due to the project. We also use a median estimate, $3,045 for emission cost in dollars per ton of hydrocarbon. All the candidate projects have intervals with maximum values of the benefit-to-cost ratio much less than one, the break-even value.

The results suggest that a road improvement cannot be justified on the merits of reduced emission costs alone. It is important to note that VDOT awards candidate projects an “environmental” score in its current prioritization methodology. Emissions-reduced rankings are not viable to substitute for that score, as there are other aspects of environmental concerns than emissions.

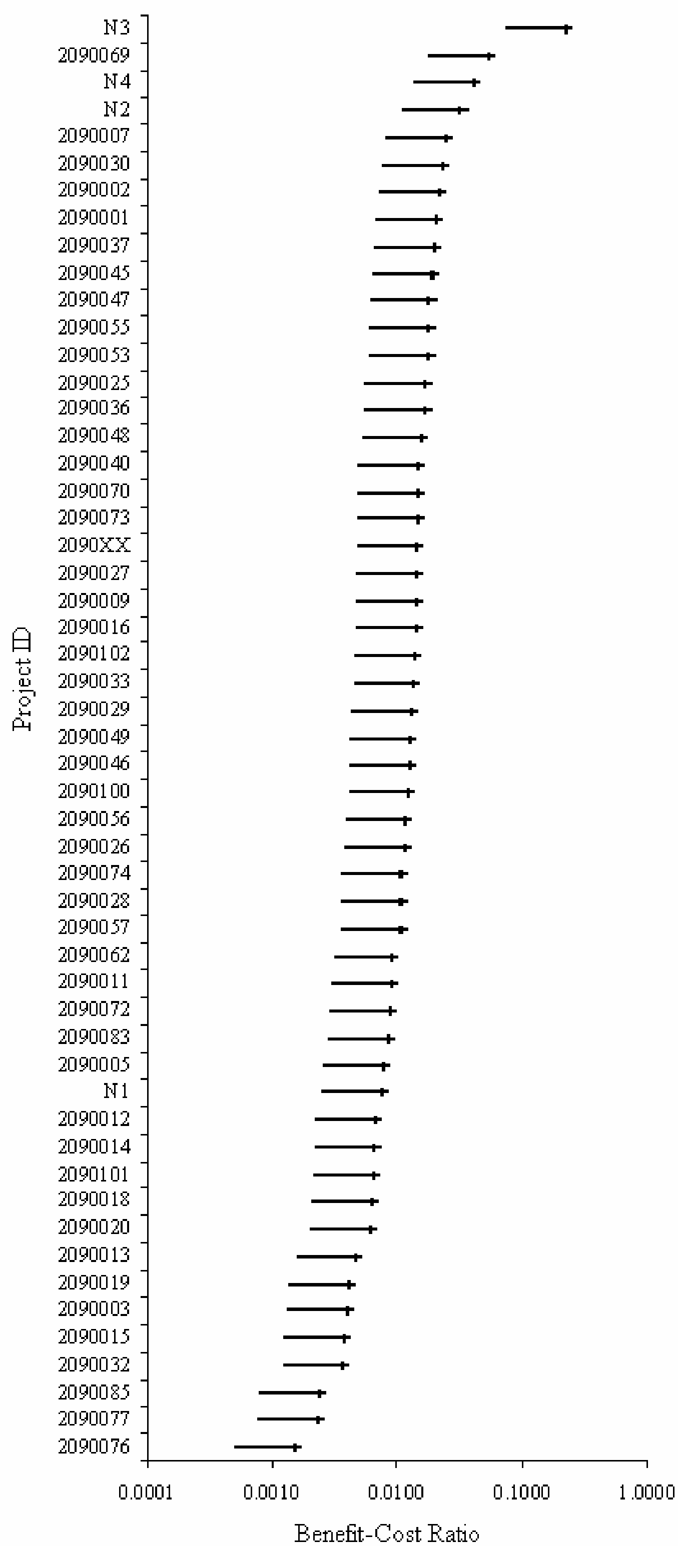

Figure 7. Benefit-Cost Ratio Intervals of Emissions Avoided

Heavy Truck Traffic

This section describes the results of applying the metric of truck traffic to the candidate projects. The results are compared with the project rankings based on truck traffic in the current prioritization methodology of VDOT.

Figure 8 provides uncertainty intervals and the rankings using the metric of heavy truck miles served per unit cost of the project. The top five projects are N3, N4, 2090069, 2090073 and 2090030 respectively. Using the heavy trucks per day measurement in the current prioritization methodology of VDOT, the top five ranked projects are 2090076, N3, N4, 2090026, and 2090101. Projects N3 and N4 are in the top five lists of both the rankings. The new metric and the existing metric are useful in promoting projects with high truck traffic. The new metric accounts not only for truck traffic volume but also for the length of the road section influenced by the project and the annual equivalent project cost.

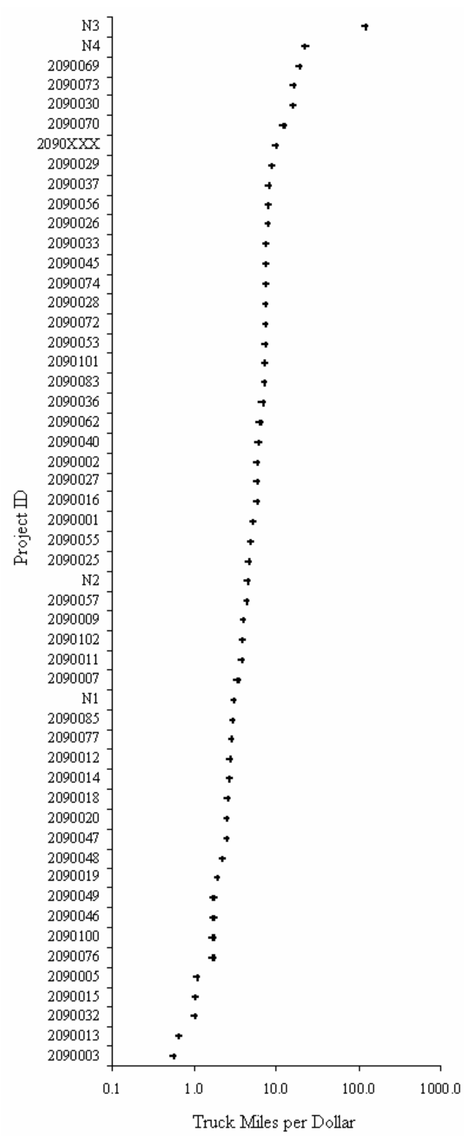

Figure 8. Heavy Truck Miles per Dollar

DISCUSSION

Table 13 shows the top five projects under each of the five benefits criteria: crashes avoided, travel time savings, savings in fuel consumption cost, emissions avoided, and heavy truck traffic metric. Project N3 appears in the top five across all the five criteria. Several other projects are common across at least two criteria. It is important to note that the various benefit indicators are not independent of one another since they have some common underlying parameters. For example, a significant reduction in travel time may also result in significant reductions in emissions and reduced operating costs. On saturated corridors, a reduction in crashes might result in an improvement in travel time, etc. The interdependence of the several benefits indicators is not explored in the current effort.

Table 13. Top Five Projects in Each of the Five Benefits Criteria

Crashes avoided	Travel time savings	Reduced vehicle operating costs	Emissions avoided	Heavy truck traffic
N3	N3	N3	N3	N3
2090069	2090045	2090069	2090069	N4
2090016	2090036	N4	N4	2090069
2090047	N4	N2	N2	2090073
2090007	N2	2090027	2090007	2090030

In the current effort, we calculate annualized benefits in each criterion and then these benefits are divided by annualized project costs to obtain the respective benefit-cost ratios. Project costs are annualized by dividing project capital cost by the lifetime of the project. Another way to calculate the benefit-cost ratios is to add the benefits of a project over its entire lifetime. This requires developing annual estimates of the expected growth in traffic, annual estimates of reduction in crash rates and estimates of many other such parameters on yearly basis over the entire lifetime of the project. Discounted total costs (capital cost and ongoing costs) can be calculated for each project using the extension of cost estimation model discussed in the methodology section. Finally, one can generate benefit-to-cost ratios by dividing the present value of all the benefits over the project lifetime by present value of the total cost of the project over its lifetime. The estimates of travel-time savings, emissions, and operating costs might significantly change under such a procedure, which might in turn yield a different ranking of projects. The formulae could be made more self-consistent in future implementations if they considered both the fiscal discount rate and a traffic growth rate.

CONCLUSIONS

This effort has demonstrated an assembly of methodologies for the estimation of the benefits of crash reduction, travel time savings, emissions reduction, fuel savings, and service of heavy trucks that are anticipated from road improvement projects. The methodologies have been applied to 53 candidate projects from the Northern Virginia district from 2005 and the results have been compared to those of a prioritization methodology that is currently implemented by VDOT.

The report and the developed prototype software provide the highway agency with additional methodology for benefits estimation, which the agency can use to distinguish among candidate projects. The methodology for benefits estimation is complementary to the multiobjective scoring method currently implemented by VDOT.

Use of interval analysis for uncertainties of the parameters, such as the crash reduction factor, the value of travel time savings, the reduction in volume-to-capacity ratio, etc., allows the estimation of benefits to proceed in a situation of sparse or uneven data about the candidate projects. The interval analysis can highlight situations where data are sufficient for prioritization, or situations where additional data are needed.

Monetization of benefits may be less preferred than keeping the benefits in their natural units, such as crashes avoided, travel time hours, tons of emissions, heavy trucks served, and amount of fuel consumption.

The methodology for the estimation of maintenance and other life-cycle costs has also been reviewed. The review suggests that maintenance and other life-cycle costs may be a constant proportion of the equivalent annual capital costs, and furthermore may be considered to be uniform across the candidate projects absent additional project-specific information. That is, this assumption could be justified either if (1) all projects are the same type - e.g., lane widening as opposed to transit improvements or signal coordination, both of which should have higher proportions of maintenance costs; or (2) the data are sufficiently lacking that it is needed to use a uniform factor/assumption to estimate maintenance costs.

RECOMMENDATIONS

The following are recommendations for the deployment of the methodology for benefits estimation that is developed and demonstrated in this report. These recommendations should be considered in the light of the Virginia 2006 Appropriation Act, which requires the coordination of transportation agencies in the development of goals, performance measures, and standard methodology of cost-benefit analysis.

1. The highway agency can complement its existing score-based prioritization system with methodologies for the estimation of the anticipated benefits of candidate projects.

2. The benefits can be estimated in several categories, e.g., safety, congestion, environment, and economic development. The benefits should not necessarily be added across categories due to the assumptions and data availability that vary from category to category.

3. The benefits can be monetized, but it may be preferable to keep them in their natural units, and/or to present the monetized and non-monetized benefits side by side.

4. A straightforward interval-type presentation of parameter uncertainties should be used to enable assessments of benefits to proceed when critical information about particular projects is awaited. Eventually, the default values of uncertain global parameters (e.g., improvement in vehicle speed, k-factor for percentage of traffic in the peak period, reduction in volume-to-capacity ratio) should be reconsidered in favor of calculated values for each project or category of project.

5. The assumptions and data inputs used in the estimation of project benefits should as much as possible be transparent to decision-makers, engineers, agency executives, legislators, and members of the public.

6. Consideration of additional categories of benefits, e.g., variance of travel times, emergency and evacuation, intermodal efficiencies, economic development, environmental protection, and quality of life, should proceed as the state of the practice of benefits estimation evolves.

7. The additional benefit category of the "avoided cost of a lost or missed opportunity," such as a failure to purchase a right of way where development is imminent, should be explored.

8. The methodology should be considered for use in prioritizing the allocation of resources within dedicated funds for smaller projects of particular types, e.g., signal and timing improvements, grade crossing safety, the Congestion Mitigation and Air Quality (CMAQ, which are projects such as turn lanes and signals, based largely on reductions in emissions volume), Regional Surface Transportation Program (RSTP), the National Highway System Funds (largely interstate), and the Urban Programs (prerogative of localities). In this vein, the MPOs have a quantification method for RSTP funds, similar to methods illustrated in this report. For NHS programs, there is no such methodology—some factors are quantified and some are not, and judgment is used to combine them. The urban funding is decided within the cities. The purveyors of the disparate funding programs identified above should be exposed to the methods of this report and encouraged to adopt the features (interval analysis where assumptions of parameter values should be nonspecific, monetized versus non-monetized, disaggregation of benefits, etc.) that may be appropriate programs.

9. Prioritization methodology with which to support the removal of already selected or ongoing projects from a construction program should be considered.

10. Validation of the anticipated benefits against what benefits are actually realized from completed projects should proceed with the help of the methodologies that are explored in this report.

11. MPOs and localities (cities) have their own existing methodologies for quantifying the performance of projects and prioritizing them. The MPOs and localities should be exposed to the methods developed in this report and encouraged to select what features and sophistication that are most appropriate to their circumstances. There is

at present a variety of degrees of rigor and sophistication in such methods across Virginia MPOs and localities.

COSTS AND BENEFITS ASSESSMENT

The methodology developed in this project supports the identification of cost-effective highway project investments. The potential benefits of the methodology include:

- Identification of highway projects with the highest value-to-cost ratios in several categories.
- Enabling of benefits assessments and prioritization to proceed while awaiting additional data about the projects.
- Uncertainty analysis highlighting the potential value of additional knowledge of particular projects.
- Education of the agency and the public about the criteria for the assessment and selection of projects.
- Harmonization of the assumptions and databases that are used from district to district for prioritization and selection of projects.
- Increased accountability of the highway agency for the allocation of limited resources for road improvements.

The costs of implementing the methodology developed in this study include:

- Resources for the one-time training of staff of the highway agency in the application of the methodology demonstrated in the current study.
- Resources to improve the benefits estimation capabilities of the highway agency with the advantage of using the existing project databases.
- Resources to prepare and present the additional information to the public at public meetings in planning and programming.

The prototype software is implemented in an Excel workbook, which itself is a set of related worksheets. Given that the workbook is based on existing available data of the agency, it would take approximately one additional hour per district for VDOT staff to perform future analyses using this software.

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