Prioritizing Highway Construction: Benefits Analysis

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Abstract—The Virginia Department of Transportation began last year to implement a quantitative methodology as an aid to prioritizing highway construction improvements. The methodology adopts fifteen quantitative metrics used to evaluate the candidate projects. The results of the methodology are used by executive review teams to negotiate, interpret, and support decisions regarding the selection of construction improvements for funding in a $1.8B per year construction program. The agency is exploring how the methodology can provide transparency of project selection to the public, agency staff, legislators, and the Commonwealth Transportation Board. The existing metrics need further modeling and aggregation to be meaningful. This effort will describe an effort to extend the current prioritization methodology via modeling and uncertainty analysis of the aggregated risk reductions, benefits, and costs associated with the candidate construction improvements. The team developed monetized estimates of benefits in several categories including crashes avoided, travel time saved, fuel uses avoided, and emission avoided. The estimates of benefits were then compared to estimates of project costs, representing the uncertainty of the results as numerical intervals. The developed methodology is demonstrated with project data from nine districts with roughly four hundred candidate projects ranging in cost from $150K to over $100M. The results with our aggregated measures were compared to the results of the prioritization methodology that is currently in use. We conferred regularly with a project steering committee of metropolitan planning organizations, planning district commissions, agency engineers, planners, executives, and others.

I. INTRODUCTION

In order to effectively allocate resources for construction improvements, choices must be made as to which projects are most important. Although this process of prioritization could be conducted through subjective means, objective analysis guarantees fair and unbiased decision making. Past efforts have explored multiobjective comparison of highway and other transportation projects.[1,2,3,4,5,6,7,8] Full benefit-cost analysis would allow construction costs to be compared to benefits accrued from factors such as decreased traffic congestion and reduced accident rates.

This effort proceeded under the auspices of the Virginia Department of Transportation (VDOT) and the Virginia Transportation Research Council (VTRC), and centered on prioritizing state highway construction plans. The effort’s objectives are: to evaluate and monetize metrics currently utilized by VDOT to prioritize plans and to create a benefit-cost model that analyzes the various factors which come together in a transportation construction improvement. This system will be a tool to aid decision-makers in selecting road improvements. The benefit-cost analysis identifies projects which make effective use of resources.

The current prioritization system in place for VDOT identifies five areas of evaluation: mobility and connectivity, safety and security, economic development, environmental preservation, and system management and preservation. Each proposed construction improvement is evaluated in the five areas: safety, mobility, environmental protection, economic development, and system wide efficiency. This effort will describe our progress to monetize metrics for: crashes-avoided, travel time avoided, reduced fuel consumption, reduced vehicle emissions, and different methods for treating the cost assumptions. At the conclusion, we identify needs for future work.

II. CRASHES AVOIDED ANALYSIS

A. Methods

The purpose of this analysis is to estimate the annual savings from avoided crashes for each of the candidate projects. This first section describes the method of developing the model. The National Cooperative Highway Research Program (NCHRP) developed a program called StratBENCOST which provides a financial analysis for transportation projects. They found the cost of crashes to be:

\[
\text{Accident Costs} = \text{Accident Rate} \times (\text{AADT} \times \text{Project Length}) \times \text{Accident Costs}
\]

where:

- Accident Costs = total annual accident costs ($)
- Accident Rate = accident rate by period and type
- AADT = average annual daily traffic
- Project Length = actual length of the project (miles)

However, the benefit of the crashes avoided must be found and not just the cost of crashes. To find the benefit, the crash reduction rate is incorporated. The candidate projects will decrease the amount of projects by a factor of the crash reduction rate, which is the amount of crashes avoided per crash. By incorporating the crash reduction rate, this analysis will essentially find the annual savings from avoided crashes after the projects have been implemented.

The benefit-cost ratio represents one year and it is understood that the lifetime of each project is 25 years. For each project, a lower, mid, and upper value of the benefit-cost ratio is calculated to represent the uncertainty involved with some of the input parameters.

The following is the model used to represent the benefit-cost ratio:

\[
\text{Benefit-Cost Ratio} = \frac{\text{Benefits}}{\text{Costs}}
\]
**B/C** = \( \frac{\text{Crash Rate} \times \text{VMT} \times \text{cost($)/crash} \times \text{Crash Reduction Rate}}{\text{Cost of Project per Year}} \)

where:

\[
\text{VMT} = \frac{\text{length(miles)} \times 2004 \text{AADT}(\text{vehicles/day}) \times 365(\text{days/year})}{100e6}
\]

\[
\text{VMT} = 100e6 \text{ vehicle miles traveled per year}
\]

\[
\text{Crash rate} = \text{crashes/VMT}
\]

\[
\text{Crash reduction rate} = \frac{\text{crashes avoided}}{\text{crash}}
\]

\[
\text{length} = \text{length of project in miles}
\]

\[
2004 \text{ AADT} = \text{average annual daily traffic in 2004}
\]

**B. Results**

The benefit-cost ratio calculation was applied to the data for Northern Virginia. There are 56 total candidate projects for this area. The input parameters are Length, 2004 AADT, VMT per year, crash rate, total cost, and life time of project. The uncertain parameters are the cost of each type of crash (fatal, injury, or property), the frequency of each type of crash, and the crash reduction rate.

The graphs used to analyze the data are a floating bar chart, a stock chart, and a three variable bubble chart. Each bar in the bar chart starts at the lower value of benefit-cost ratio and ends at the upper value. The bar chart is shown in figure 1.

**Figure 1: Benefit Cost Ratios for Crashes Avoided in Northern Virginia**

The stock chart essentially shows the same thing except it also marks the mid value. Using these charts, the user can see which projects have the highest benefit-cost ratio. In the bubble chart, the projects closer to the top right have more crashes per year and the size of the bubble corresponds to the benefit-cost ratio value. A noticed trend is that the projects in the lower left have a smaller benefit-cost ratio. Therefore, there is a correlation between crashes per year and benefit-cost ratio (in this specific analysis).

The top five candidates using the scores (current methodology) are: 2090083, 2090020, 2090002, 2090029, and 2090047. Using benefit-cost ratios for crash avoidance, the top five candidates are: N3, 2090069, 2090016, 2090047, and 2090007. When ranking the projects according to crash rate, the top five scores are: 2090077, 2090016, 2090011, 2090015, and 2090029. The notable projects are 2090047, 2090016, and 2090029 because they are in the top five of at least two of the sets.

**III. TRAVEL-TIME ANALYSIS**

**A. Method**

This section establishes an equation to estimate the annual benefit in travel time savings from peak from capacity enhancement. The equation models benefit as a reduction in annual vehicle hours during peak compared to levels before capacity enhancement. The reduction in vehicle hours can be multiplied by the value of vehicle operating time to determine a monetary benefit for direct comparison to project cost.

\[
VAL \times B = VH_o - VH_a
\]

where

\[
B = \text{the benefit (vehicle hours)}
\]

\[
VH_o = \text{the peak vehicle hours prior to capacity enhancement (vehicles*hours)}
\]

\[
VH_a = \text{the peak vehicle hours after capacity enhancement (vehicles*hours)}
\]

\[
VAL = \text{the value of vehicle operating time [9]}
\]

A BPR curve adopted from current Virginia Department of Transportation methodology is used to estimate travel time. Free flow travel times are derived from free flow speeds adopted from National Cooperative Highway Research Program methodology [10]. This value is multiplied by the length of influence of a project.

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

where

\[
T_c = \text{the travel time under peak V/C (hours)}
\]

\[
T_o = \text{the free flow travel time (hours)}
\]

\[
\text{Volume} = \text{current peak flow rate (vehicles/lane/hour)}
\]

\[
\text{Practical Capacity} = \text{the capacity (vehicles/lane/hour)}
\]

**B. Results**

This section establishes the conditions of the demonstration of this methodology on Hampton Roads 2005 candidate projects. Peak hour volumes and capacities are derived from existing data on peak hour flow rate and volume to capacity ratio (V/C). It is considered for this demonstration that the length of the influence of a project is 10 times the project length, that 25% of the AADT will experience peak volume to capacity, that every project will be widened by one lane in the peak direction, and that each project will take ten years to complete.

The benefit to cost (B/C) ratio of each candidate project is estimated and plotted with corresponding project ID (figure 2). A low and high estimate of the annual benefit results
from the low and high estimate of travel-time cost [9].

Three candidate projects were in the top five for both current and risk-cost-benefit methodologies. Significant overlap should be expected because the risk-cost-benefit methodology models benefit as the product of travel time reduction and traffic volume during peak which is closely related to flow rate. The two new candidate projects that the risk-cost-benefit methodology places in the top five, 2050063 and 2050063, are rural projects which due to less traffic had received low scores under existing methodology. These projects have low costs and could greatly improve congestion without excluding as many other projects due to budget constraints.

The risk-cost-benefit methodology identifies three candidate projects with costs and can be justified solely based on travel-time benefits. Of the top five projects under existing methodology, only two can be justified based entirely on travel time benefits.

IV. REDUCED FUEL CONSUMPTION ANALYSIS

A. Methods

An important cost for consideration in construction decisions are those costs associated with operating the vehicles that utilize the proposed construction improvement. Operating costs can be broken down into five categories, which include: fuel consumption, lubricating oil consumption, wear on tires, maintenance and repair costs, and depreciation of the vehicles value. Research on behalf of the National Cooperative Highway Research Program shows that these costs depend on several variables related to a vehicle’s performance; these include: vehicle type (truck, car, or bus), pavement condition, road grade, constant speed, changing speeds, time idling, and curvature of the roadway segment. To estimate the total consumption on a roadway segment all of these factors must be taken into account. Therefore, for each class of vehicle and each component type an appropriate rate of consumption must be found. This consumption rate is a function of two look-up tables, the first relates the V/C ratios given by VDOT to speed for given road grades[10]. The second look-up table relates speed to the consumption rate of the component (fuel, oil, etc.) for specific vehicle types. This information must be combined with the total vehicle miles traveled on a roadway segment during a specified period of time to find the consumption associated with uniform speeds. Then a measure of consumption under excess conditions, such as speed cycling and idling, must be included. After combining these two measures the result can be multiplied by the unit component costs and adjusted for the effects of pavement [9]. The NCHRP model allows for additional simplification in accordance with the level of precision required by the planner. The simplified model used in this analysis is as follows:

\[
\text{Gas Cost} = \text{Gallons} \times \text{Rate} \times \text{Cost/Day} \times \text{Day/Year} \times \text{Length} \times \text{Time} \times \text{Cost per Gallon}
\]

The above model gives an estimation of the costs associated with a specific roadway segment given three inputs: segment length, segment volume to capacity ratio, and average annual daily traffic on the segment. In order to convert this cost estimate into an estimate of benefits, the costs must be calculated for three scenarios: the current state of the roadway segment, an optimistic view of the roadway segment after the project, and a pessimistic view of the roadway segment after the project. This method allows the planner to focus on the value of a single variable, the volume to capacity ratio, and a projects effect on it, in order to make an estimate of the range of values for the benefits associated with a project.

Several additional factors must be taken into account in order to account for lack of data. The primarily concern is with the volume-to-capacity ratios provided by VDOT. These V/C ratios are provided for the current state of each project during the peak traffic period. In order to effectively calculate the costs associated with operating a vehicle on each section of roadway under consideration, a value is needed for the number of vehicles experiencing the peak level of congestion. For the purpose of this analysis and arbitrary proportion of the given AADT was used to calculate the number of vehicles experiencing the peak level of congestion. This proportion was set equal to 75% of the given AADT.

The final estimated variable necessary for demonstrating the process is the change in the volume to capacity ratio that will result from completing the project. The pessimistic estimate is a reduction of 10% and the optimistic estimate is
a reduction of 35%.

The results of this approach will be an interval for the values of the benefit-cost ratio associated with each project, which is calculated by dividing each estimate of benefits by the cost of the project. The cost was divided by 25 years in order to estimate the annual project cost. So the annual BC ratios are simply each benefit estimate respectively divided by the annual cost.

B. Results

The results of applying these techniques to the data for the Culpeper district are presented in figure 3. The figure shows the benefit-cost ratio intervals for the proposed projects in the Culpeper district. As the figure shows, the vast majority of the proposed projects have intervals with maximum values much less than one, the BC ratio at which the project breaks even. Indeed, some of the projects have intervals that fall into negative territory, implying that the project would produce increases in gasoline consumption and the associated costs. The figure also shows that several projects have very long intervals for their benefit-cost ratios. This is due to a limitation in the lookup tables provided by the TRB, specifically the lookup table used to estimate average speed only includes V/C ratios up to 1.05 [10]. Those projects with long intervals have V/C ratios above 1.05, which means that the 10% reduction did not change the V/C ratio enough to go below 1.05 and register a savings in gasoline consumption. Better data is needed in order to fix this problem.

The reason that many intervals cross into the negative region is that the lowest gasoline consumption rate occurs around 45 mph. Therefore, for projects that already have average speeds around 45 mph during the peak period, reducing the V/C ratio will actually increase the speed above 45 mph and increase the gasoline consumed on the roadway segment, thereby increasing the costs associated with gasoline consumption.

V. REDUCED VEHICLE EMISSIONS ANALYSIS

A. Method

This section discusses the methodology for estimating the savings resulting from reduced emissions costs on the road segment under consideration. Emissions can be broken down into three types: hydrocarbons (HC), carbon monoxide (CO), and nitrous oxide (NOx). The negative effects of pollution are due to not only the amount produced, but also to the types of pollutants emitted. There are lookup tables for small vehicles, buses, and trucks by each emission type. The model uses these tables to obtain emission rates at speeds surrounding the average vehicle speed, and then interpolates between these two rates, yielding a single emission rate [9].

The analysis applies only to the period associated with peak volume on the roadway. The following metrics provided by VDOT are used in this analysis: 2004 average annual daily traffic (AADT), project length in miles, and total project cost. For the purposes of simplicity, we consider that 89% of the traffic is cars, and that 75% of the traffic occurs during the peak travel period. We also consider that the impact − improved vehicle speed − occurs both before and after the actual project equal to its length; therefore, the impact zone is three times the project length. Finally, because this analysis is annual, we consider that the project cost in a given year is 1/20th of the total project cost.

This section describes the specific model used. For the purposes of the modeling equation, variables are needed which were not provided in the data from VDOT. These are: vehicle speed before the project, improvement in speed due to the project, and emissions costs. We will assume that the average vehicle speed before the project is thirty miles per hour. In order to capture the uncertainty of the variables, we will assume both a low estimate and a high estimate for improvement in vehicle speed due to the road work. The low estimate is 10%, and the high estimate is 80%. To estimate emissions costs per ton, we use the data provided by StratBENCOST, which is based on vehicle type (car, truck, or bus) and emission type (hydrocarbons, carbon monoxide, and nitrous oxide) [10].

Emission rates were calculated using the emission rate lookup table from StratBENCOST [10]. Using the emission rate (ER), we can now calculate the annual emissions costs (AEC) as follows:

$$AEC = ER \times (\text{Traffic Volume} \times \text{Project Length}) \times \text{Emission Costs}$$

Emission rate units were tons of emission per vehicle, traffic volume was vehicles per mile, project length was in miles, and emission costs were dollars per ton of emissions.

This calculation of annual emission cost was performed three times. First, a base case for emission cost was calculated using the emission rate before the road improvement. The calculation was then performed for after the road improvement using an emission rate with the low estimate of improved vehicle speed, and again using the emission rate from the high estimate of improved vehicle speed.
speed. Each of the annual costs for after the road improvement was subtracted from the base case, resulting in two estimates of emission cost benefits. The final step in calculating the benefit-cost ratios is to divide each estimate of benefits by the cost of the project. The cost was arbitrarily divided by twenty years in order to estimate the annual project cost. So the annual BC ratios are simply each benefit estimate respectively divided by the annual cost.

B. Results

This section discusses the results of the preliminary data analysis applied to the Fredericksburg district data.

The results of applying these techniques to the data for the Fredericksburg district are presented in figure 4. The figure shows the benefit-cost ratio intervals for the proposed road improvements. As the figure shows, all of the proposed road improvements have intervals with maximum values much less than one, the break-even value.

![Figure 4: Benefit-cost ratios for Fredericksburg](image)

These results suggest that a road improvement cannot be justified on the merits of reduced emission costs alone. Other factors must aid in the decision of which projects are more beneficial.

It is important to note that VDOT currently grants project an environmental score in prioritization. Emissions-reduced rankings are not intended to replace that score, as there are many of aspects of environmental concerns other than emissions. None of the road improvements ranked in the top five by B/C ratio was found in the top five when ranked by environmental score.

VI. COST ESTIMATES ANALYSIS

A. Method

This part of the project focuses on the extension of the current cost estimation methodology. A widely accepted tool that was found is called StratBENCOST and will be considered a good basis for implementing this extension. More specifically, this section discusses the implementation of ongoing costs and discounting into the cost estimation model to determine if cost is a driving uncertainty for benefit-cost ratios, and if maintenance costs are significant.

Each project has a cost assigned to it, but these costs only include initial construction, right-of-way, and other fixed costs. They do not include ongoing costs like repaving and maintenance over a set period of analysis, or discounted costs since the costs are assumed to be paid over time [10].

The cost model is imperative in the implementation of benefit-cost ratios which are used in the StratBENCOST model. Some parameters are optional, like resurfacing, but may be incorporated into the model if the data is given [9]. Since the data for these ongoing costs is not given initially, estimates are made. Using StratBENCOST methodology, values are found for the analysis period (25 years) and discount rate (4%); and ranges for project duration (4-5years), annual repaving costs (1/120 – 1/80 of the project cost), and annual maintenance costs (1/800 – 1/250 of the project cost) are found [11].

The discounting model requires more than just plugging in the discount rate. An accepted calculation of discounted cost for the capital is used with some basic considerations:

\[
\text{Present Value Capital Cost} = \frac{C}{n} + (\frac{C}{n}) \times (1+\frac{i}{100}) \times (\frac{1}{1+i})
\]

\[
C = \text{Capital Cost ($)}
\]

\[
n = \text{Project Duration (years)}
\]

\[
i = \text{Discount Rate (%)}
\]

This equation considers that payments occur at the beginning of each year, start immediately, and have a constant burn rate of capital over the project duration [12]. The discounted ongoing costs like maintenance and resurfacing use a similar equation which takes into account the costs starting in the future, after the construction is finished:

\[
\text{Present Value of Ongoing Cost} = \frac{(M/(N-n))}{n} + (\frac{M/(N-n)}{n}) \times (\frac{1}{1+i}) \times (\frac{1}{1+i}) - (\frac{M/(N-n)}{n}) \times (\frac{1}{1+i}) \times (\frac{1}{1+i})
\]

\[
M = \text{Total Ongoing Cost over the Analysis Period ($)}
\]

\[
N = \text{Analysis Period (years)}
\]

\[
n = \text{Project Duration (years)}
\]

\[
i = \text{Discount Rate (%)}
\]

This equation considers that payments occur at the beginning of the year, start after the project is complete, and have a constant burn rate of capital until the end of the Analysis Period [12].

B. Results

The resulting rankings of projects by cost including maintenance, resurfacing, and discounting were the same as those ranked using the original tool. This is expected since the maintenance costs were not given. The estimated range for ongoing costs is significant if these costs are given, but the project must go in another direction since these values are not available.

The deviations between the high and low ends of the range for the maintenance and construction cost estimate is 2.8%, which is much lower than the 18.6% deviation found associated with the resurfacing and construction cost estimate. The addition of both of the components to the
construction cost results in a 20% deviation. Discounted cost estimation produces a deviation of 11.7%. Therefore, resurfacing is the most important inclusion in the cost formula if the data is available per project. Also, if maintenance and resurfacing are considered to be a single cost estimate, as it is in some states, the combination of this ongoing cost and the fixed construction cost provides the greatest deviation for a single component.

Looking at the total maintenance and resurfacing costs, and comparing them to the original construction costs, it can be shown that maintenance adds between 3 and 8% to the construction cost, and resurfacing adds between 17 and 67%. This considers that the analysis period is 25 years and that the cost of maintenance and resurfacing stays constant. When both are added to the cost the range of addition is between 19 and 78%. This represents a large amount of cost that is not figured into the existing methodology. This is certainly enough to reorder many projects considering not only the percentage that can be added, but the range in percentages, as well. If this data is available, or can be estimated accurately, this can be important in standardizing the costs for use in the benefit-cost methodology.

VII. CONCLUSION

This effort has tested methodologies for monetary benefit estimation of crash reduction, travel time savings, emissions reduction, and fuel savings resulting from highway improvement projects. Methodologies for the estimation of maintenance costs are also established in the model. These factors were demonstrated significant when the methodologies were applied to candidate projects in Virginia from 2005. These methodologies have two aspects not present in existing VDOT prioritization criteria. The first is that they yield results in monetary terms instead of a score. The second is that they are forward-looking. Existing metrics base prioritization on the current state of a road.

This effort provides VDOT with a recommendation of which projects will provide the most benefit and it is up to the decision makers to take a closer look at these projects to decide whether or not they should be chosen. If this analysis is shown helpful, decision makers can use the benefit-cost ratio equations for future candidate projects.

The Steering committee composed of representatives from the Virginia Department of Transportation, the Virginia Transportation Research Council, and regional planning organizations have made recommendations for future improvements to the methodology presented in this paper. These recommendations include simplification of equations, the addition of benefit estimates for more factors, and non-monetized benefit estimates. The team has begun research into estimating benefits for economic development, multimodal transportation, and STRAHNET access.

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