California
Department
Of
Transportation

Cal-B/C

White Paper on BCA Approaches for New Arterial Roadway Improvements

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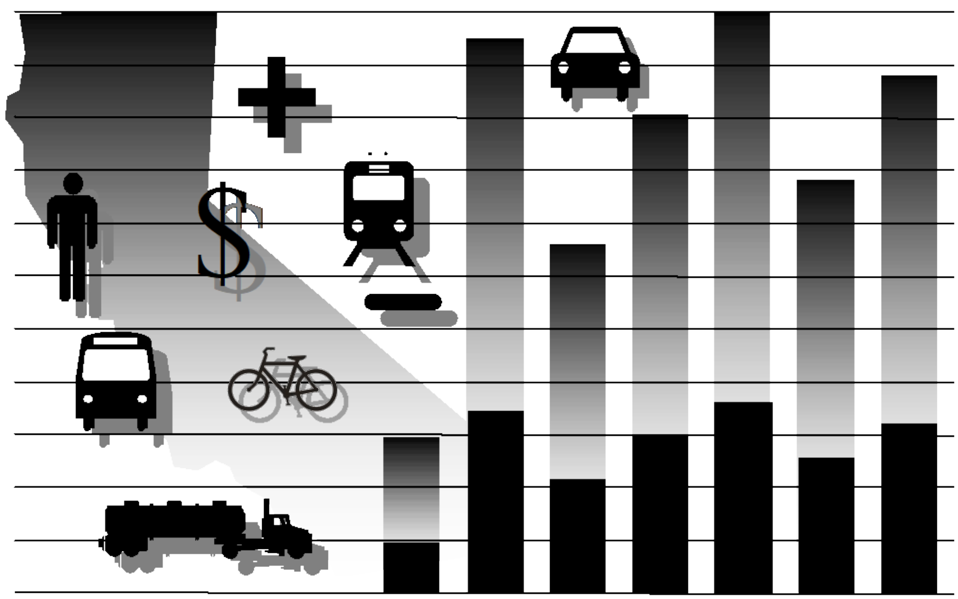

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1. Purpose

The California Life-Cycle Benefit/Cost Analysis Model (Cal-B/C) is a suite of tools developed to aid the California Department of Transportation (Caltrans or the Department) decision-makers in assessing a variety of transportation projects. The current suite of tools allows Caltrans to assess a range of projects involving highway/freeway improvements, freight transportation, active transportation, park and ride, and public transportation. While the current Cal-B/C tools cover the majority of projects previously submitted to Caltrans Headquarters or the California Transportation Commission (CTC) for evaluation, they do not include sketch planning methodologies to support the analysis of arterial and local roads, roundabouts, or other similar improvement projects. This limits the ability of decision-makers to assess the cost-effectiveness of these projects when detailed modeling data is not available from travel demand or simulation models.

This white paper provides a high-level review of Caltrans' need to evaluate arterial and local road projects. It recommends whether Cal-B/C can be revised, new tools created, or other tools leveraged to meet the Department's analytical needs. The paper identifies project evaluation gaps based on recent applications for state funding under Senate Bill 1 (SB1) and other discretionary grant programs, presents a literature review of existing tools and methodologies around the world that could help address these gaps, and outlines how these methodologies could be used to help formulate future Cal-B/C tools for similar projects. Due to the high-level nature of this review, if Caltrans chooses to develop a new Cal-B/C tool, the Department should conduct a detailed literature review and more specifically lay out the necessary methodologies.

2. Project Evaluation Gaps

Based on a review of projects that recently submitted applications for state funding under SB1 funding programs and a general scan of other discretionary grant programs like USDOT's BUILD and INFRA programs, a set of project types was identified as requiring methodologies beyond those currently offered by Cal-B/C.

The primary review was of three recent programs funded under SB1: the Trade Corridor Enhancement Program, the Solutions for Congested Corridors Program, and the Local Partnership Program. Exhibit 1 presents a description of each program and the total number of projects that had applied for funding in 2018.

Exhibit 1: Senate Bill 1 Programs Included in Project Review

Program Name	Description	Number of Projects
Trade Corridor Enhancement Program	The purpose of the Trade Corridor Enhancement Program is to provide funding for infrastructure improvements on federally designated Trade Corridors of National and Regional Significance, on the Primary Freight Network as identified in California Freight Mobility Plan, and along other corridors that have a high volume of freight movement. The Trade Corridor Enhancement Program will also support the goals of the National Highway Freight Program, the California Freight Mobility Plan, and the guiding principles in the California Sustainable Freight Action Plan.[1]	42
Solutions for Congested Corridors Program	The purpose of the Solutions for Congested Corridors Program is to provide funding to achieve a balanced set of transportation, environmental, and community access improvements to reduce congestion throughout the state.[2] This competitive program targets projects that implement specific transportation performance improvements and are part of a comprehensive corridor plan by providing more transportation choices while preserving the character of local communities and creating opportunities for neighborhood enhancement.[3]	32
Local Partnership Program	The purpose of this program is to provide local and regional transportation agencies that have passed sales tax measures, developer fees, or other imposed transportation fees with funds from the Road Maintenance and Rehabilitation Account to fund road maintenance and rehabilitation, sound walls, and other transportation improvement projects.[4]	90

The review highlighted certain project types, or project elements, that would be difficult to accurately or easily evaluate using the current version of Cal-B/C Sketch. Many of these project could be analyze in Cal-B/C Corridor if upfront planning analysis had occurred in a travel demand or simulation model. Generally, these project types fit into two categories: arterial roads and intersections. For arterial roads, the common project types included constructing new arterial roadways, adding additional lanes, widening current lanes, or adding protected turning lanes. For intersections, the project types included constructing new stop-controlled intersections, new roundabouts, intersection signalization projects, and investing in advanced traffic management systems (ATMS) or intelligent transportation systems (ITS).

As a consequence of the project review, the literature review focused on identifying tools and benefit cost analysis (BCA) methodologies that could evaluate the following project types:

- New Arterial Roads

[1] California Transportation Commission. *Trade Corridor Enhancement Program (TCEP)*. Accessed on February 26, 2020. https://catc.ca.gov/programs/sb1/trade-corridor-enhancement-program

[2] California Transportation Commission. *Solutions for Congested Corridors Program (SCCP)*. Accessed on February 26, 2020. https://catc.ca.gov/programs/sb1/solutions-for-congested-corridors-program

[3] Ibid.

[4] California Transportation Commission. *Local Partnership Program (LPP)*. Accessed on February 26, 2020. https://catc.ca.gov/programs/sb1/local-partnership-program

- New Lanes
- Lane Widening
- Turning Lanes
- Stop-Controlled Intersections
- Roundabouts
- Signalization
- Advanced Traffic Management Systems (ATMS)/Intelligent Transportation Systems (ITS).

3. Literature Review

To better understand how to address the current evaluation gaps, several sources were reviewed to assess methodologies available for measuring the impacts of improvements on arterial roads and intersections. This section lists and briefly describes the most useful sources identified, while Section 4 focuses the research on specific project types.

Some notable sources reviewed in this process included:

- Research from the Transportation Research Board (TRB)
- Publications and tools from the US DOT Federal Highway Administration (FHWA)
- Research from state DOTs and other transportation agencies within the US
- Research from transportation agencies around the world
- Various international BCA studies for roadway improvements.

Exhibit 2 highlights relevant tools and sources of methodologies reviewed, as well as the project types to which they apply. The exhibit also presents a description of the type of source reviewed and its contents. In particular, *Tools* indicates if the source is a tool, while *Case Study* represents analysis of a specific type of improvement, including some example BCA analyses. *Methodologies* identifies whether the source provides a detailed methodology or approach to assessing impacts from the improvements. *Operational Impacts* identifies whether the source helps quantify impacts to traffic flows, vehicle speed, or travel time. Meanwhile, *BCA Impacts* identifies sources that help monetize those operational impacts into economic, environmental, and social impacts.

Among the top sources, the Transportation Research Board (TRB) offers several resources that assess arterial roadway improvement BCAs, including the 6th Edition Highway Capacity Manual (HCM), and various research reports under their National Cooperative Highway Research Program (NCHRP). The HCM has a variety of technical insights in determining traffic flows and how various roadway improvements would impact those traffic flows. In turn, NCHRP research has several reports highlighting user benefits from specific improvements, particularly for roundabouts.

FHWA's research publications also included a number of relevant reports and sources that provide insights into estimating user benefits for a variety of improvements. Specifically, FHWA has studies estimating impacts from constructing dedicated left- or right-turn lanes, roundabouts, and signalized intersections. FHWA also provides a guide highlighting common methodologies for evaluating safety improvements and offers two tools for conducting BCA's for various roadway improvements (TOPS-BC and BCA.NET).

These primary sources and other useful reference materials are described in more detail below.

Exhibit 2: Applicable Methodologies / Tools by Project Type

#	Source / Methodology	Tool	Methodology	Case Study	Operational Impacts	BCA Impacts	New Arterial Road	New Lane /Widening	Turning Lanes	Stop-Controlled	Roundabout	Signalization	ATMS / ITS
							Arterial			**Intersection**			
Primary Sources													
1	TRB Highway Capacity Manual (6th Ed.)		●	●	●		●	●	●	●	●	●	
2	FHWA Guidance		●	●		●			●		●	●	
3	WSDOT BCA Tool	●	●	●	●	●		●	●	●	●		
4	TRB NCHRP Reports			●	●				●		●		
5	FHWA Tool for Operations Benefit/Cost (TOPS-BC)	●	●		●	●		●			●		●
6	BCA.NET Highway Project Benefit-Cost Analysis System	●	●		●	●	●	●	●			●	
7	Transportation Value to You (TransValU)	●	●		●	●	●	●					●
Secondary Reference Materials													
8	FHWA Research Publications			●	●	●			●	●	●	●	
9	FDOT Florida Intelligent Transportation Systems Evaluation Tool	●											●
10	FHWA ITS Deployment Analysis System (IDAS)	●			●	●							●
11	MNDOT BCA for Intersection Decision Support		●	●	●	●							●
12	Boston Transportation Dept. Benefits of Retiming/Rephasing Traffic Signals		●	●	●	●							●
13	Asset Management Committee BCA For Auxiliary Turn Lanes For New Access Connections			●		●			●				
14	Niehoff Studio Research on Roundabouts			●							●		
15	Main Roads Western Australia Guidelines for the Analysis of Roundabout Metering Signals		●		●						●	●	
16	Romanian Journal Of Transport Infrastructure Quantifying The Benefits From A Major Infrastructure Improvement		●	●	●	●					●	●	
17	Transport Research Centre, Czech Republic CBA for Roundabouts in Urban Areas		●	●	●	●					●		
General BCA Guidance													
18	VTPI Transportation CBA Techniques		●		●	●							
19	NZ Transport Agency Economic Evaluation Manual		●		●	●							
20	Queensland Government CBA Manual and CBA6		●	●	●	●							
21	DGFE Guide to Cost Benefit Analysis of Investment Project (EU)		●	●	●	●							
22	BC Ministry of Transportation BCA Guidebooks		●	●	●	●							
23	The Economic Appraisal of Investment Projects at the EIB		●	●	●	●							

TRB HIGHWAY CAPACITY MANUAL (6TH EDITION)

The *Highway Capacity Manual* (HCM) provides methodologies on quantifying roadway capacity, with a focus on traffic and operational impacts. The HCM presents techniques to evaluate roadway capacity and traffic flows for a variety of roadway and intersection projects. Specifically, the review identified 11 chapters with specific coverage of arterial roadway and intersection projects. Generally, the methodologies require information on vehicle traffic flow by lane (and potentially by hour), the number of lanes, lane capacity, and free-flow speeds. These traffic demand and roadway characteristics are combined to estimate the average travel speeds, and in turn travel time through the roadway segment. Some additional factors would need to be considered for intersection-based projects.[5] For instance, for general intersections, the HCM highlights that considerations should be made for queuing and the various types of delays at an intersection including approach delay, intersection delay, and movement control delay. For roundabouts, the HCM indicates that considerations need to be made for the change in traffic flow within the roundabouts (by lane), pedestrian impedance to vehicles, queuing, as well as both the circulating and exit flow rates.[6]

FHWA GUIDANCE

The Federal Highway Administration have various guides on understanding roadway improvements or approaches in estimating roadway impacts. These guides provide users with a standardized approach in estimating the benefits from implementing the roadway improvements. The following are some relevant guides.

Highway Safety Benefit-Cost Analysis Guide, 2018

Published by the FHWA Office of Safety, the *Highway Safety Benefit-Cost Analysis Guide* provides insights on performing highway safety benefit-cost analysis, as well as giving instructional examples on how to estimate and monetize project-related safety benefits. The guide indicates that changes to the safety performance is estimated through crash modification factors (CMFs) or safety performance functions (SPFs), where details on how to use SPFs and adjustment factors to estimate the safety performance can be found in *Highway Safety Manual Part C Predictive Method*.[7] While the guide presents a generalized methodology, it provides factors based on road types including: urban interstates/expressways, urban arterials; urban other, rural interstate/principal arterials, and other rural roadways.

The guide presents methodologies for other factors such as travel time and travel time reliability, fuel consumptions, and emissions, which are determined using factors from *The Economic and Societal Impacts of Motor Vehicle Crashes*, a National Highway Traffic

[5] Transportation Research Board. *Highway Capacity Manual 6th Edition – A Guide for Multimodal Mobility Analysis*. October 2016.
[6] Ibid.
[7] Federal Highway Administration, Office of Safety. *Highway Safety Benefit-Cost Analysis Guide*. FHWA Safety Program. February 2018.

Safety Administration (NHTSA) report.[8] Meanwhile, the guide suggests the use of Second Strategic Highway Research Program (SHRP2) C-11 Reliability Module, a model created for the TRB, to determine travel time reliability impacts, which is one of two methods previously incorporated into Cal-B/C Sketch.[9]

Signalized Intersection Informational Guide, 2013

The *Signalized Intersections Informational Guide* describes the impacts of signalized intersections. The document mainly indicates that there would be safety improvements by installing signalized intersections, where the improvements can be estimated using crash modification factors and the expected accidents of the current design. However, there are also operational impacts to consider such as additional travel time or delays from decelerating, waiting in queue, and accelerating.[10] These delays can be estimated using methodologies available within the HCM.[11]

WSDOT BCA TOOL

Washington State Department of Transportation

The Washington State Department of Transportation (WSDOT) offers a BCA tool for estimating highway improvement projects following the procedures used by the Highway Mobility Division of WSDOT.[12] Although the tool was not available on WSDOT website at the time of the review, an archived version was evaluated for future reference. The tool is able to evaluate a range of projects including roadway improvements (e.g., adding an additional lane or climbing lane), turning lanes, intersection projects, new interchanges, and park and ride projects. The tool assesses the projects mainly based on the change in vehicle travel time (or delay) and the respective safety impacts. One key component requires certain traffic inputs such as average weekly daily traffic volumes for the first or last year of the analysis.[13]

In general, the tool separates the evaluation of travel time impacts and safety. For safety, it requires users to input various safety improvements based on a pre-determined drop down list, with a maximum of five types of improvements. The selected improvements determine the reduction in accidents for all accident by severity and combined with the historical total accidents based on severity and the cost per collision, the tool presents an annual safety improvement impact, as well as the present value of the safety benefits.[14]

For travel time impacts, different projects refer to different methodologies and data points. For projects assessing two-way left turn lanes, the tool estimates impacts based on the number of

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[8] Ibid.
[9] Ibid.
[10] Federal Highway Administration, Office of Safety. *Signalized Intersections Informational Guide: Second Edition.* FHWA Safety Program. July 2013.
[11] Ibid.
[12] Dowling Associates Inc. *WSDOT Mobility Project Prioritization Process: Benefit/Cost Software User's Guide.* May 2000.
[13] Ibid.
[14] Washington State Department of Transportation. *WSDOT Mobility Project Prioritization Process Version 7/30/09*. July 30, 2009.

through lanes, median type, average access spacing, roadway's access control class, traffic volume (by vehicle type), and the split by through, right-turn, and left-turn volume per access point. For projects adding general purpose or climbing lanes, the tool determines the travel time benefits from adding the lanes. The impacts are estimates based on traffic volumes, number of lanes by direction, grade (and length of grade), capacity assumptions, posted speed, volumes (by vehicle type), and roadway type. For intersection projects, the tool assesses the change delay time at intersections for peak and off-peak traffic. To estimate this, the tool requires 24-hour traffic counts for each approach to the study intersections in addition to other inputs such as peak hour volume by share, volume growth, peak hour average delay, peak hour intersection volume-to-capacity ratio (v/c), and number of lanes. [15]

TRB National Cooperative Highway Research Program

The National Cooperative Highway Research Program (NCHRP) is a large program under the TRB that conducts research to better understand transportation issues and how to address them. Below are summarized research reports for specific arterial and local road improvements.

Roundabouts in the United States, 2007

This study published under the NCHRP assessed the safety performance of roundabouts in the United States based on crash prediction models for crashes at the intersection level and approach level. Intersection-level crashes were modeled based on the number of lanes, number of legs and the annual average daily traffic (AADT). Meanwhile, approach-level crashes were modeled based on AADT and geometric parameters. Crash prediction models for both types of accidents were modeled based on general linear models. Overall, the study compared the safety benefits from converting an existing intersection to a roundabout by comparing their respective predicted number of accidents, accident severity weights, and the dollar value for accidents (by injury type). [16]

The Dimondale Mini: America's First Mini-Roundabout, 2005

The Dimondale Mini: America's First Mini-Roundabout was a study presented to the Subcommittee on Roundabouts assessing the impacts of a mini-roundabout (i.e., a roundabout with a small diameter not exceeding 90 feet). [17] The study used a BCA methodology to assess the impacts from changing an all-way stop to a small roundabout, with a focus on the traffic delay impacts and maintenance costs. Traffic delay impacts and roadway capacity were determined using a software application version of the Highway

[15] Ibid.
[16] Lee Rodegerdts, Miranda Blogg, Elizabeth Wemple, Edward Meyers, Michael Kyte, Michael Dixon, George List, Aimee Flannery, Rod Troutbeck, Werner Brilon, Ning Wu, Bhagwant Persaud, Craig Lyon, David Harkey, and Daniel Carter. *Roundabouts in the United States.* National Cooperative Highway Research Program Report 572. 2007.
[17] Federal Highway Administration. *Mini-Roundabouts: Technical Summary.* February 2010

Capacity Manual known as the *Highway Capacity Software*.[18] The study also compared the annual crashes before and after the implementation of the mini-roundabout. However, due to the small sample, these benefits were not incorporated within the BCA.[19]

Capacity and Operational Effects of Midblock Left-Turn Lanes, 1997

This study published by the NHCRP presents a methodology for evaluating alternative midblock left-turn lanes on urban and suburban arterials. While these lanes provide access to adjacent business or other properties, they are also known to have impacts on accident rates and roadway capacities. The study assessed the operational and safety impacts of three types of midblock left-turn lanes: raised-curb median, the flush median with two-way, left-turn lane (TWLTL) delineation, and the undivided cross section. The study evaluated the two impacts using separate models created based on statistical analysis, roadway characteristics, and available data.[20]

The model used to estimate the operational impacts or vehicle delays builds upon procedures presented in the 1994 *Highway Capacity Manual* (HCM) for analyzing signalized and unsignalized intersections. The model used in the analysis focuses on assessing the operation of non-priority movements at unsignalized intersections along an arterial road and the impacts these movements have on travel time of the arterial through movements.[21] The model considers the type of midblock left-turn lane, the number of through lanes (both directions), through lane traffic flow rate (vehicles per hour per lane, vphpl), access point density for both directions (access points per mile), and the left-turn percentage.[22]

For safety, the model developed in the analysis was based on a variety of regressions and a statistical methodology that accounts for the non-constant variance associated with accident data.[23] The model focused on assessing total arterial accidents based on traffic demand, geometric conditions[24], adjacent land use[25], and the percentage of property damage only (PDO) accidents.[26]

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[18] Highway Capacity Software is a software developed by the McTrans Center that calculates operational impacts through implementing methodologies and approaches from the Highway Capacity Manual.
[19] Edmund Waddell and James Albertson. *The Dimondale Mini: America's First Mini-Roundabout*. May 2005.
[20] Ibid.
[21] Ibid.
[22] "Left-turn percentage reflects the number of vehicles making left-turns per hour over a 1,320 ft. length of roadway, divided by the total vehicle flow rate in that direction."
[23] Bonneson, James A *Capacity and Operational Effects of Midblock Left-Turn Lanes*.
[24] "Geometric conditions include provision of parallel parking and the density of access points along the major street."
[25] "Land use includes: residential, office, business, and industrial categories."
[26] Bonneson, James A *Capacity and Operational Effects of Midblock Left-Turn Lanes*.

FHWA TOOL FOR OPERATIONS BENEFIT/COST (TOPS-BC)

Federal Highway Administration, Office of Operations, 2019

The *Tool for Operations Benefit Cost Analysis* (TOPS-BC) is a planning tool created by the FHWA "with a primary purpose to help in screening multiple Transportation System Management and Operations strategies".[27] The latest version of this tool (v4.0), provides users with ability to evaluate various arterial operation projects at a high level. Examples of such projects include: arterial signal coordination, arterial transit signal priority,[28] additional lanes, roundabouts, and arterial management.[29] The related benefits assessed for arterial projects include: travel time savings, travel time reliability, reductions in fuel consumption, and safety benefits. While all the benefits are determined based on roadway characteristic changes, such as length, number of lanes, and the associated free-flow speed, certain benefits require additional assumptions. For instance, travel time reliability requires the expected reduction in crash duration, while fuel consumption and safety benefits require explicit assumptions about reduced fuel use and avoided accidents. [30]

BCA.NET HIGHWAY PROJECT BENEFIT-COST ANALYSIS SYSTEM

Federal Highway Administration

The BCA.NET Highway Project Benefit-Cost Analysis System is a web-based highway BCA tool intended to support project-level decision-making process in transportation planning.[31] The tool is able to analyze a wide range of project types including both improvements to arterial roads and intersections. Specifically, the tool compares the strategy in the base case and the alternative cases specified by the user for each roadway segment. The tool estimates the impacts of the alternative through Monte Carlo simulation, with a focus on travel time.

The analysis requires users to input a variety of information including strategies (project type), details on the project type, current characteristics of the segment, traffic distribution, and various other traffic characteristics. Details on the project type include target goals such as free-flow speed, maximum flow rate, and number of lanes among other goals. Characteristics of the segment refer to the forecasted traffic volumes (by vehicle type), free-flow speed, number of lanes, maximum flow rate, segment length, crash rate, and operating costs. Characteristics of the segment could also include signal characteristics for intersection-based projects. Other traffic characteristics refer to the vehicle occupancy factor by vehicle type, uncertainty factor for traffic, percent of autos, a minimum speed during peak hours, and

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[27] Federal Highway Administration, Office of Operations. *Tool for Operations Benefit Cost Analysis (TOPS-BC).* Last modified April 16, 2019. https://ops.fhwa.dot.gov/plan4ops/topsbctool/index.htm

[28] Federal Highway Administration, Office of Operations. *Operations Benefit/Cost Analysis TOPS-BC User's Manual: Providing Guidance to Practitioners in the Analysis of Benefits and Costs of Management and Operations Project*. June 2013.

[29] Federal Highway Administration, Office of Operations. *Transportation Systems Management and Operations Benefit-Cost Analysis Compendium*. September 2015.

[30] Federal Highway Administration, Office of Operations. *TOPS-BC Tool Version 4.0.* 2013

[31] Federal Highway Administration. *BCA.NET – Highway Project Benefit-Cost Analysis System: User's Manual*. April 2011.

an annualization factor. The tool allows users to edit various social costs, oil prices, fuel taxation, and project cost assumptions.[32]

TRANSPORTATION VALUE TO YOU (TRANSVALU)

The *Transportation Value to You (TransValU)* is a tool provided by the Florida Department of Transportation designed to assess the impacts of implementing transportation system management and operation (TSMO) improvement strategies in Florida. Incorporated within the tool is the ability to conduct a BCA on implementing a specific TSMO strategies. The BCA reports both user and societal impacts such as travel time, roadway safety, vehicle operational costs split by fuel and non-fuel costs, and emissions. For travel time, the tool estimates impacts from recurrent delays and delays due to accidents. Though both impacts are a function of traffic volume, number of lanes, and lane capacity, recurrent delays also factor in free-flow speeds, while accident related delays consider accident rates. Safety improvements are evaluated using historical accident rates and the expected reduction due to the proposed strategy. Meanwhile, vehicle operation and emission impacts are determined based on vehicle-miles travelled and average speeds. The tool also provides a methodology for determining travel time impacts from "implementing strategies that inform travelers of traffic delays, alternative routes, or other roadway performance information, or which directly manage roadway demand in an effort to allow users to avoid delay."[33]

FHWA RESEARCH PUBLICATIONS

The Federal Highway Administration provides a variety of research sources to highlight roadway issues and potential solutions. Much of the available research and documentation provides insights on how to estimate impacts from roadway improvement projects. The following are some relevant FHWA publications.

Proven Safety Countermeasures, 2017

The FHWA's *Proven Safety Countermeasures* portal highlights various infrastructure-orientated safety treatments that were chosen for their proven effectiveness and benefits.[34] Two countermeasures included on this list are dedicated left- or right-turn lanes and roundabouts. Both measures were highlighted as countermeasures expected to reduce the number of crashes. For dedicated turn lanes, FHWA cites that adding left-turn lanes would result in a 28% to 48% reduction in crashes, while adding right-turn lanes

[32] Federal Highway Administration. *BCA.NET Highway Project Benefit-Cost Analysis System*. Accessed: February 21, 2020. Accessed from: https://hwbca.net/BaseLogin/LoginReg3.aspx
[33] Florida Department of Transportation, District 5. *TransValU: Transportation Value to You User Guide – TSM&O Module*. July 2019.
[34] Federal Highway Administration, Office of Safety. *Proven Safety Countermeasures Last* modified January 24, 2020. https://safety.fhwa.dot.gov/provencountermeasures/

would reduce crashes by 14% to 16%.[35] For roundabouts, the report indicates that converting a two-way stop controlled intersection would reduce crashes by 82%, while converting a signalized intersection would reduce crashes by 78%.[36]

Advantages of the Split Intersections, 2000

This study, presented in the FHWA *Public Roads* publication in May/June 2000, compares the impacts from converting a major road intersection to either a split intersection or a diamond interchange. The split intersection would require the major road to be separated into two one-way roads and would facilitate smoother traffic flows with less delay, and improved safety through reduced congestion and by separating the opposing directions of traffic".[37] The study used the Corridor Simulation (CORSIM) micro-simulation model to determine the difference in traffic delay between the two alignments, and reported the annual net benefits after including some cost assumptions.[38]

Safety Effectiveness of Intersection Left- and Right-Turn Lanes, 2002

The *Safety Effectiveness of Intersection Left- and Right-Turn Lanes* was a study sponsored by the FHWA to evaluate the safety impacts of left- and right-turn lanes for at-grade intersections. This study compared a variety of components for 280 improved intersections and 300 intersections without improvements. The components included the geometric design, traffic control, traffic volume, and traffic accidents. To evaluate the before-after impacts on traffic safety, the study leveraged three approaches: yoked comparison or match-pair approach, the comparison group approach, and the Empirical Bayes approach.[39] The analysis assessed the impacts by area (urban or rural), traffic control, and project type. The analysis was also conducted based on various subgroups to account for the project-related characteristics (e.g., type of turn lanes, area type, etc.) and the type of accident (overall or fatal and injury). These statistical analyses informed the accident modification factors (AMFs) for a variety of turn-lane projects. The AMFs were then used to estimate the reduced number of accidents, which were monetized and reported as the avoided accident costs.[40]

Safety Evaluation of Offset Improvements for Left-Turn Lanes, 2009

The *Safety Evaluation of Offset Improvements for Left-Turn Lanes* is a document published by the FHWA assessing the impacts from improving offset left-turn lanes. Offset

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[35] Federal Highway Administration, Office of Safety. *Proven Safety Countermeasures: Left and Right Turn Lanes at Two-Way Stop-Controlled Intersections.* Last modified October 17, 2017. https://safety.fhwa.dot.gov/provencountermeasures/left_right_turn_lanes/
[36] Federal Highway Administration, Office of Safety. *Proven Safety Countermeasures: Roundabouts.* Last modified October 17, 2017. https://safety.fhwa.dot.gov/provencountermeasures/roundabouts/
[37] Ibid.
[38] Ibid.
[39] Federal Highway Administration, Office of Safety Research and Development. *Safety Effectiveness of Intersection Left- and Right-Turn Lanes.* July 2002.
[40] Ibid.

left-turn lanes refer to the positioning of the left-turn lanes for two-way traffic, which impacts the sight distance for vehicles turning left. Three types of left-turn lanes were consider in the analysis: negative offset, no offset, and positive offset. [41] Negative offset refers to opposing left-turn lanes that are shifted rightwards, reducing the sight distance for vehicles turning left. No offset refers to turning left-lanes directly across from one another and have improved sight distance relative to the negative offset. Finally, positive offset refers to opposing left-turn lanes that are shifted leftward.

The analysis used data for various intersections in Florida, Nebraska, and Wisconsin. The study compared the before and after impacts of offset left-turn lane improvements, which were estimated using Empirical Bayes and regression modeling. This change determined the crash reduction factor for installing offset left-turn lanes for overall crashes, injury-related crashes, left-turn based crashes, and rear-end incidents. The study monetized the reduction in accidents using the FHWA mean comprehensive cost per crash for signalized intersections with speeds less than 45 mph. [42]

Florida Intelligent Transportation Systems (FITS) Evaluation Tool

Florida Department of Transportation, 2015

The *FITS Evaluation Tool* was developed for the Florida Department of Transportation (FDOT) to aid in the evaluation of different ITS deployments. The tool considers a variety of ITS deployments for arterial roads like signal control, emergency vehicle signal priority, and transit priority systems. [43]

The tool assesses performance based on a variety of factors such as vehicle-miles of travel, vehicle-hours of travel, average speed, number of accidents (by severity), fuel consumption, monetary benefits to users or the agency, and emissions. The tool differentiates the performance of the alternatives based on their respective benefit-cost ratios. The costs for each alternative includes the initial cost, operation and maintenance cost, estimated interest rates, and lifetime equipment amortization. [44]

FHWA ITS Deployment Analysis System (IDAS)

The *ITS Deployment Analysis System* is a modeling software developed for FHWA with capability to estimate impacts of implementing a range of ITS programs. In particular, the tool assesses the impacts that an ITS program has on travel time, energy consumption, emissions, noise, and safety. These impacts are determined by using information or outputs from travel models, as well

[41] Federal Highway Administration, Research, Development, and Technology. ***Safety Evaluation of Offset Improvements for Left-Turn Lanes***. Tech Brief. June 2009.
[42] Ibid.
[43] Florida Department of Transportation. *Evaluation Tools to Support ITS Planning Process: Development of a Sketch Planning Tool in FSUTMS/Cube Environment.* December 15, 2008.
[44] Ibid.

as data on "deployment of ITS strategies by type and location on the transportation network." [45] IDAS was reviewed as part of developing Cal-B/C Sketch.

BCA FOR INTERSECTION DECISION SUPPORT

Minnesota Department of Transportation, 2007

This 2007 report from the Minnesota Department of Transportation (MNDOT) outlined the potential impacts of incorporating an Intersection Decision Support (IDS) system through a BCA. The IDS system is an ITS "designed to assist drivers on stop-controlled low-volume rural roads choosing gaps when confronted with busy multiple lane-divided highways, without affecting traffic on the high-volume road." [46] The study not only assesses the potential impacts from installing an IDS system, but it also compares the results to alternative roadway design solutions. While most of the analysis relies upon simulation data, both solutions are projected to reduce vehicle delays and crashes. [47]

BENEFITS OF RETIMING/REPHASING TRAFFIC SIGNALS

Boston Transportation Department, 2010

This 2010 BCA study conducted for the Boston Transportation Department assessed the implications of improving traffic signal operations. While the analysis relied upon simulation data from Synchro, the results indicated that the project is expected to reduce vehicle hours of delay and likelihood of crashes. The reduction in delay translated to travel time savings, emission reductions, and fuel cost savings. [48]

BCA FOR AUXILIARY TURN LANES FOR NEW ACCESS CONNECTIONS

Vergil G Stover and Phillip B. Demostrenes, 2017

Using Benefit/Cost Analysis for Auxiliary Turn Lanes for New Access Connection is a study assessing the impacts from constructing auxiliary turn lanes. The study determined that auxiliary turn lanes are expected to reduce crashes, fuel consumption, vehicle emissions, travel delay, and a variety of other impacts. The study only considered the impacts of reduced crashes, and it did not identify the specific methodology used to identify the cost of crashes with and without the auxiliary turn lanes. [49]

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[45] Federal Highway Administration, Office of Planning, Environment, & Realty (HEP). *A Sampling of Emissions Analysis Techniques for Transportation Control Measures: ITS Deployment Analysis System (IDAS)*. Last modified May 17, 2017. https://www.fhwa.dot.gov/ENVIRonment/air_quality/conformity/research/transportation_control_measures/emissions_analysis_techniques/descriptions_idas.cfm

[46] Michael Corbett, David Levinson, and Xi Zou. *Benefit-Cost Analysis for Intersection Decision Support*. October 2007.

[47] Ibid.

[48] Boston Transportation Department. *The Benefits of Retiming/Rephasing Traffic Signals in the Back Bay*. March 2010.

[49] Vergil G. Stover and Philip B. Demosthenes. *Using Benefit/Cost Analysis for Auxiliary Turn Lanes for New Access Connections*. 2017.

RESEARCH ON ROUNDABOUTS

Victoria Fromme, Niehoff Studio, 2010

Research on Roundabouts is a report discussing the merits of roundabouts and their impacts on traffic operations, with a focus on safety. While the main impacts from roundabouts are safety related, the document highlights the potential of emissions and fuel consumption impacts, as well as the reduction in operation and maintenance costs. The study also presents case studies demonstrating the impacts from roundabouts installed in the Greater Cincinnati Area and Vail, Colorado. Both case studies showed a general reduction in accidents. [50]

GUIDELINES FOR THE ANALYSIS OF ROUNDABOUT METERING SIGNALS

Main Roads Western Australia, Traffic Engineering Branch, 2015

Guidelines for Analysis of Roundabout Metering Signals is a guide created by Main Roads Western Australia's Road and Traffic Engineering Branch. The guide highlights the potential impacts from adding signalization or metering to roundabouts. Estimating impacts from metering roundabouts require forecasted traffic volumes, degree of saturation [51] (e.g., capacity factor), and traffic modeling programs (SIDRA Intersection), where the forecasted traffic volumes can be obtained from the Main Roads ROM Model (Traffic modeling Section of the Asset and Network Information Branch). [52] The guide highlights that in a previous study for metering a single-lane roundabout, there was an optimal range in which the metering would be beneficial. This range depends on traffic volume on the approach and within the roundabout. The guide indicates that justification for installing roundabout metering signals should include data on the degree of saturation, average delay, level of service, queue length, and number of vehicles per queue for the existing roundabouts and the model of proposed roundabouts. [53]

QUANTIFYING THE BENEFITS FROM A MAJOR INFRASTRUCTURE IMPROVEMENT

Marios D. Miltiadou and Efstathios Bouhouras, 2015

Quantifying the Benefits from a Major Infrastructure Improvement: The Case of Thessaloniki Western Ring Road Upgrade to Eliminate At Grade Signalised Intersections is a study demonstrating that eliminating signalized intersections may result in an overall improvement to users. This study looked at eliminating signalized intersections through grade separation and thereby reducing vehicle delays at the intersections, their associated operational costs, and likelihood of accidents. The vehicle delay was calculated based on the percentage of vehicles affected, the time spent at the intersection in addition to braking time, evacuation time for the last

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[50] Victoria Fromme. *Research on Roundabouts.* Winter 2010. Retrieved from: https://www.uc.edu/cdc/niehoff_studio/programs/great_streets/w10/reports/roundabout_report.pdf

[51] "The Degree of Saturation (DOS) gives an indication of the available reserve capacity of the roundabout. A DOS of 1.0 indicates that the roundabout is at capacity. A DOS > 1.0 indicates that the demand traffic volumes exceed the roundabout capacity."

[52] Main Roads Western Australia, Road and Traffic Engineering Branch. *Guidelines for the Analysis of Roundabout Metering Signals*. October 2015.

[53] Ibid.

vehicle passing the intersection, and the acceleration time for the first vehicle passing through the intersection. The vehicle delay time not only reflected the travel time costs, but also a key component in the operational costs (e.g., fuel consumption). The study also assessed the number of accidents reduced based on the traffic violations at the various intersections. [54]

CBA FOR ROUNDABOUTS IN URBAN AREAS

Petr Pokorny, 2011

This study, conducted by the Transportation Research Centre in the Czech Republic, compared the safety impacts from implementing roundabouts in various cities of the Czech Republic. The analysis compared the number of crashes before and after installing roundabouts to identify the safety benefits. This was done through combining the target locations with improvements and a control group of sites, which were similar in most characteristics to the treatment sites (i.e., locations with roundabout improvements).[55] The evaluation of the treatment effect at each site was determined based on the odds-ratio[56] with the comparison group, combined with a weighting methodology.[57] The accidents avoided were calculated over 20 years and monetized using an average cost per accident.[58]

4. Project-Specific BCA Methodologies

This section focuses on the project types identified in the review of SB1 project types and highlights relevant tools and methodologies from the literature review for estimating operational and economic impacts for each project type. These methodologies can generally be leveraged to add new project evaluation capabilities in Cal-B/C tools.

ARTERIAL ROADS

New Arterial Road

Projects that construct new road extensions or improve network fluidity by acting as arterial connectors seek to improve traffic flow and avoid intersection-related accidents.

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[54] Marios D. Militiadou and Efstathios Bouhouras. *Quantifying the Benefits from a Major Infrastructure Improvement: The Case of Thessaloniki Western Ring Road Upgrade to Eliminate At Grade Signalised Intersections*. Romanian Journal of Transport Infrastructure. Vol. 3. Issue 1. February 6, 2015.

[55] Petr Pokorny. *Cost-Benefit Analysis for the Implementation of Four-arm Roundabouts in Urban Area.* Transactions on Transport Sciences. Vol. 4. April 2011.

[56] "An odds ratio is a measure of association between an exposure and an outcome. The odds ratio represents the odds that an outcome will occur given a particular exposure, compared to the odds of the outcome occurring in the absence of that exposure." Szumilias, Magdalena. *Explaining Odds Ratios*. Journal of the Canadian Academy of Child and Adolescent Psychiatry. 19(3). August 2010.

[57] Ibid.

[58] Ibid.

The HCM 6th Edition is a particularly useful source as it contains methodologies for assessing traffic flow based on lane capacities, free-flow speeds, traffic volumes, and other factors for a variety of roadway types. Improvements, such as grade separation or new arterial connections, can leverage HCM methodologies in assessing vehicle travel times or delays with and without intersections.

Relevant Operational Performance Analysis from the Highway Capacity Manual

HCM Chapter 15: Two-Lane Highways

User Inputs

- Highway class (I, II, III)
- Terrain type (level, rolling, specific grade)
- Passing lane length (mi)
- Hourly demand volume (veh/h)
- Directional volume split (%)

Default Values (Modifiable by User)

- Lane width (ft)
- Shoulder width (ft)
- Access point density - both sides (access points/mi)
- Percent no-passing zone (%)
- Free-flow speed (mi/h)
- Analysis period length (min)
- Peak hour factor (decimal)
- Heavy vehicle percentage (%)

Performance Outputs for BCA

- Average travel speed (mi/h)

New Lane / Widening

The general concept of new lanes or lane widening projects is to help increase roadway capacity and traffic flow, as well as to improve the safety conditions on the road. This may have different impacts on peak and off-peak traffic as adding an additional lane will have minimal impact in some cases due to low traffic volumes during the off-peak period.

Changes in travel times can be quantified and monetized using methodologies from the TOPS-BC and WSDOT tools. These tools rely on user inputs for traffic volumes, roadway capacity, free-flow speed, and the number of lanes to quantify travel time savings while relying on standardized industry BCA parameters to generate benefit estimates.

Meanwhile, the *Highway Safety Benefit-Cost Analysis Guide* provides a methodology to estimate safety benefits by using historical accident rates by severity and applying crash modification factors as determined by the proposed improvements.

Relevant Operational Performance Analysis from the Highway Capacity Manual

HCM Chapter 15: Two-Lane Highway

User Inputs

- Highway class (I, II, III)
- Terrain type (level, rolling, specific grade)
- Hourly demand volume (veh/h)
- Directional volume split (%)
- Length upstream of the new lane (mi)
- Length downstream of the new beyond its effective length (mi)
- Total length of the analysis segment (mi)
- New lane length (mi)

Default Values (Modifiable by User)

- Lane width (ft)
- Shoulder width (ft)
- Access point density - both sides (access points/mi)
- Percent no-passing zone (%)
- Free-flow speed (mi/h)
- Analysis period length (min)
- Peak hour factor (decimal)
- Heavy vehicle percentage (%)
- Adjustment factor for the effect of a new on ATS (%)

Performance Outputs for BCA

- Average travel speed (mi/h)

Turning Lanes

Turning lane projects involve new dedicated turning lanes along the roadway. The addition of a dedicated turning lane has the potential to improve throughput traffic by separating those waiting for turn versus those wanting to drive through. In addition, the addition of dedicated turning lanes is expected to reduce the number of crashes. For instance, FHWA's *Proven Countermeasures* resources indicate that at a two-way, stop-controlled intersection installing a left-turn lane is expected to reduce crashes by 28% to 48%, while installing a right-turn lane is expected to reduce crashes by 14% to 16%.

While the overall travel time implications from installing dedicated turn lanes may vary depending on the structure and location (e.g., intersection or midblock), the HCM provides evaluation approaches to estimate the impacts. Despite referencing an older version of the HCM, *Capacity and Operational Effects of Midblock Left-Turn Lanes* indicated that HCM procedures for analyzing unsignalized and signalized intersections can provide the basis for determining traffic flow impacts for midblock left-turn lanes. Meanwhile for intersection turning lanes, the HCM 6th Edition has methodologies in place to estimate the travel time impacts of including dedicated turn lanes based on their impacts to through lane capacities and intersection types. Safety impacts can be estimated using accident reduction factors, or crash modification factors, and applying them to historical accident rates.

Relevant Operational Performance Analysis from the Highway Capacity Manual

HCM Chapter 18 and Supplementary Material: Urban Street Segments

User Inputs

- Segment length (ft)
- Restrictive median length (ft)
- Speed limit (mi/h)
- Midsegment volume (veh/h/ln)
- Percent share of left and right turn traffic (%)

Default Values (Modifiable by User)

- Number of lanes at access points
- Analysis period duration (h)
- Number of through lanes (ln)

Performance Outputs for BCA

- Through delay (s/veh)
- Travel speed of through vehicles for the segment (mi/h)

INTERSECTIONS

Stop-Controlled Intersection

Stop-controlled intersection projects involve the creation of new interaction points between two or more roadways using stop signs. As a new intersection connects two or more roads together, it can reduce travel distances for motorists, reduce congestion, and improve traffic flow on other nearby roads.

The operational/delay impacts from creating a new intersection can be estimated using methodologies available in the HCM. Specifically, Chapters 20 and 21 in the HCM 6th Edition provide an approach to assess traffic flows and delays for two-way, stop-controlled intersections and all-way, stop-controlled intersections, respectively. These intersection approaches, combined with methodologies to assess vehicle traffic flow for roadways, provide the basis to determine the travel time impacts from constructing a new intersection.

Relevant Operational Performance Analysis from the Highway Capacity Manual

HCM Chapter 20: Two-Way Stop-Controlled Intersections

User Inputs

- Number and configuration of lanes of each approach
- Special geometric factors such as
  - Unique channelization aspects
  - Existence of a two-way left-turn lane or raised or striped median storage (or both)
  - Existence of flared approaches on the minor street
  - Existence of upstream signals
- Hourly turning-movement demand volume (veh/h) AND peak hour factor
- OR Hourly turning-movement demand flow rate (veh/h)

Default Values (Modifiable by User)

- Approach grades
- Analysis period length (min)
- Peak hour factor (decimal)
- Heavy-vehicle percentage (%)
- Saturation flow rate for major-street through movement (for analysis of shared or short major-street, left-turn lanes)
- Saturation flow rate for major-street, right-turn movement (for analysis of shared or short major-street, left-turn lanes)

Performance Outputs for BCA

- Average control delay (s/veh)

HCM Chapter 21: All-Way Stop-Controlled Intersections

User Inputs

- Number and configuration of lanes of each approach
- Hourly turning movement demand volume (veh/h) AND peak hour factor
- OR Hourly turning movement demand flow rate (veh/h)

Default Values (Modifiable by User)

- Analysis period length (min)
- Peak hour factor (decimal)

- Heavy-vehicle percentage (%)

Performance Outputs for BCA

- Average control delay (s/veh)

Roundabouts

Roundabout projects involve modifying intersections from either stop-controlled or signalized intersections to roundabouts. These improvements are expected to reduce vehicle delays at intersections. In addition, studies have shown that converting intersections to roundabouts can reduce the number of crashes. For example, FHWA's Proven Countermeasure found that converting two-way stop controlled intersections to roundabouts could reduce crashes by 82%, while converting signalized intersections to roundabouts could reduce crashes by 78%.

Chapter 22 in the HCM 6th Edition provides a computational methodology to assess travel time or delays associated with roundabouts. Using geometric information, such as the number and configuration of lanes on each approach, and demand data, the HCM methodology is able to estimate delay impacts. Meanwhile, safety impacts can be assessed using the methodology within the WSDOT BCA Tool, which applies historical accident data and applying accident reduction factors by severity.

Relevant Operational Performance Analysis from the Highway Capacity Manual

HCM Chapter 22: Roundabouts

User Inputs

- Number and configuration of lanes on each approach
- Hourly turning movement demand volume (veh/h) AND peak hour factor
- OR Hourly turning movement demand flow rate (veh/h)

Default Values (Modifiable by User)

- Analysis period length (min)
- Peak hour factor (decimal)
- Heavy-vehicle percentage (%)
- Lane utilization

Performance Outputs for BCA

- Average control delay (s/veh)

Signalized Intersections

Signalization projects convert stop-controlled intersections to signalized intersections. The upgrade to signalized intersections impacts both vehicle queuing time and safety.

As highlighted in the *Signalized Intersection Informational Guide,* the HCM provides procedures and methodologies to estimate operational impacts, such as vehicle delays. In HCM 6th Edition, these methodologies are found in Chapter 19 and require information such as traffic characteristics, geometric design, and signal control.

For safety impacts, the *Signalized Intersection Informational Guide* recommends applying crash modification factors to historical accident rates to assess improvements from the signalized intersection.

Relevant Operational Performance Analysis from the Highway Capacity Manual

HCM Chapter 19: Signalized intersections

User Inputs

- Demand flow rate (veh/h)
- Initial queue (veh)
- Pedestrian flow rate (p/h)
- Bicycle flow rate (bicycles/h)
- Number of lanes (ln)
- Number of receiving lanes (ln)
- Turn bay length (ft)
- Presence of on-street parking
- Type of signal control
- Phase sequence
- Left-turn operational mode
- Right-turn overlap with the complementary left-turn phase.
- Speed limit (mi/h) and detection mode (if actuated)
- Area type (CBD, non-CBD)

Default Values (Modifiable by User)

- Right-turn-on-red flow rate (Percentage heavy vehicles (%)
- Peak hour factor (decimal)
- Upstream filtering adjustment (decimal)
- Base saturation flow rate (pc/h/ln)
- Local bus stopping rate (buses/h)
- Approach grade (%)
- Passage time (s) (if actuated)
- Maximum green (s) (if actuated)
- Green duration (s) (if pretimed)
- Minimum green (s)
- Yellow change + red clearance
- Walk (s)
- Pedestrian clear (s)
- Phase recall (if actuated)
- Dual entry (if actuated)
- Simultaneous gap-out (if actuated)
- Analysis period duration (h)
- Stop-line detector length (ft)
- Average lane width (ft)
- Platoon ratio (decimal)
- Lane utilization adjustment factor (decimal)
- On-street parking maneuver (veh/h)
- Unsignalized movement delay (s)
- Cycle length (if pretimed)
- Cycle length (s)
- Phase splits (s) (if actuated)
- Offset (s)
- Offset reference point (s)
- Force mode (if actuated)

Performance Outputs for BCA

- Average control delay (s/veh)

Advanced Traffic Management Systems (ATMS) / Intelligent Transportation Systems (ITS)

Advanced Traffic Management Systems (ATMS) or Intelligent Transportation Systems (ITS) are intended to improve traffic flow and potentially enhance safety. The inclusion of these technologies aims to reduce potential traffic delay not only at a specific intersection, but multiple intersections along an arterial road or across a local network.

The HCM states that as its methodologies are “generally limited to the evaluation of strategies that have a fixed geometry, lane assignment, and traffic control plan during the analysis time frame,”[59] and thus would not have approaches in assessing various dynamic projects, including

[59] Transportation Research Board. *Highway Capacity Manual 6th Edition – A Guide for Multimodal Mobility Analysis*.

certain ATMS/ITS solutions. Moreover, the literature for ATMS/ITS projects recommends using simulation tools and outputs to estimate operational impacts. For example, the BCA analysis conducted by the Boston Transportation Department used traffic micro-simulation outputs to assess the impacts of ATMS/ITS investments. The study applied simulation output information to estimate travel time delay, emissions, and fuel consumption, while safety impacts were assessed using historical accident information and a crash modification factor.

Despite the recommendation to use simulation data, methodologies do exist for assessing ATMS/ITS technologies without simulation model runs. For instance the *TransValU* tool provides benefit estimates from the deployment of ATMS/ITS solutions such as traffic signal coordination, traffic incident management, demand management approaches, and traveler information systems. These improvements are assessed based on expected changes to speeds, capacity, number of lanes, crash rate, accident duration, and some other variables requiring user input.

5. Summary

The current set of Cal-B/C tools do not include sketch planning methodologies to support the analysis of arterial and local roads, roundabouts, or other similar improvement projects. Through our review, we have identified several potential ways to address the current gaps in project evaluation. While the literature review demonstrates that there are several ways to address current project evaluation gaps, none are fully comprehensive, standardized, or as user-friendly and transferrable as the Cal-B/C tools. The use of different tools for different improvement projects could result in fundamental differences in user assumptions and methodologies that would lead to inaccuracies in evaluating and comparing projects. The variability and relative abundance of methodologies creates a similar concern, requiring consolidation and standardization for reliable and equitable BCA result comparisons.

In terms of leveraging existing BCA tools, *BCA.NET Highway Project Benefit-Cost Analysis*, *TOPS-BC*, and the *WSDOT BCA Tool* offer the best coverage across the various project types. The *BCA.NET* tool focuses more on arterial projects such as new arterial roads and turning lanes, but can also assess intersection signalization projects. In addition to new lanes, the *WSDOT BCA Tool* helps assess turning lane and intersection projects, specifically stop-controlled intersections and roundabouts. Meanwhile, *TOPS-BC* covers new lanes, roundabouts, and ATMS/ITS projects.

Of the three tools, *BCA.NET* provides the most comprehensive analysis, especially for arterial projects, as it allows users to estimate impacts for multiple segments at once, as well as applying simulations to account for uncertainty. However, the exact methodologies used in *BCA.NET* are not explicitly described, unlike the *WSDOT BCA Tool* and *TOPS-BC*. The *WSDOT BCA Tool* in particular provides explicit and transparent calculation methodologies that the user can review.

Beyond these tools, the literature review identified several methodologies that could be leveraged in developing new Cal-B/C modules. The HCM was commonly referenced as a key source for assessing operational impacts of various roadway or intersection improvements. For instance, the *Capacity and Operational Effects of Midblock Left-Turn Lanes* study developed a model assessing operational impacts based in HCM methodologies.[60] As well, both *TOPS-BC* and the *WSDOT BCA Tool* use HCM's approach for speed and traffic flow in their approach to assess travel time impacts.[61, 62]

The latest HCM (i.e., *HCM 6th Edition*) contains a comprehensive set of methodologies for determining operational impacts of various improvements. The relevant operational outputs are primarily changes in travel time and speed, which can be leveraged to estimate changes in economic benefits like travel time, emissions, and vehicle operating costs. For changes in safety, the general consensus from the literature is to assess the improvements based on historical accident rates and crash modification factors (CMFs). While the majority of CMFs can be obtained through the FHWA CMF Clearinghouse[63], alternative CMFs could be obtained through statistical analysis of comparable improvements as presented in numerous before-after analyses and case studies. Accident rate groups may also be available from Caltrans sources.

While the HCM provides approaches to help assess the operational impacts for a variety of improvements, there are some more specialized measures requiring additional analysis. Specifically, the HCM cites its capabilities as "limited to the evaluation of strategies that have a fixed geometry, lane assignment, and traffic control plan during the analysis time frame."[64] Thus, operational impacts from ATMS/ITS projects involving dynamic solutions may not be properly estimated using HCM methods. Moreover, most sources recommend the use of simulation modeling to estimate the operational impacts from ATMS/ITS measures. In turn, safety impacts hinge on the relevance and reliability of specific CMFs. The issue becomes even more prevalent for projects with multiple simultaneous improvements that require additional analysis and an understanding of the applicability of multiple CMFs.

Based on the review of project types and available methodologies, there are three possible paths forward for the benefit-cost analysis of arterial and local roads, roundabouts, or other similar improvement projects:

1. Planners or engineers could conduct detailed micro-simulation modeling to derive outputs that can be used as inputs to Cal-B/C Corridor for conducting BCAs.
2. Planners or engineers could use HCM methods to estimate impacts for entry into Cal-B/C Corridor to estimate the BCA impacts.
3. A new Cal-B/C sketch planning tool could be developed to assess arterial and local road projects - through the HCM methodology and supplemented by other research. The project types that a new Cal-B/C model would evaluate include:
    - New arterial roads

[60] Bonneson, James A *Capacity and Operational Effects of Midblock Left-Turn Lanes*.
[61] Federal Highway Administration, Office of Operations. *Operations Benefit/Cost Analysis TOPS-BC User's Manual: Providing Guidance to Practitioners in the Analysis of Benefits and Costs of Management and Operations Project*.
[62] Dowling Associates Inc. *WSDOT Mobility Project Prioritization Process: Benefit/Cost Software User's Guide.*
[63] Federal Highway Administration. Crash Modification Factors Clearinghouse. Last modified December 7, 2019. http://www.cmfclearinghouse.org/
[64] Transportation Research Board. *Highway Capacity Manual 6th Edition – A Guide for Multimodal Mobility Analysis*.

- New lanes lane widening
- Turning lanes
- Stop-controlled intersections
- Roundabouts
- Signalized intersections.

The project types listed above were selected due to methodologies to assess their operational impacts being readily available within the *HCM 6th Edition*. Meanwhile, the safety impacts from these project types can be estimated using CMFs. For ATMS/ITS projects, the literature tends to highlight evaluation methodologies that leverage simulation approaches. Thus, creating a Cal-B/C module that incorporates these projects may not be feasible. However, a high-level approach similar to *TOPS-BC* and *TransValU* could be taken, where improvements are assessed based on a percentage change relative to the baseline.

Although a new Cal-B/C tool could be developed, some project types could be addressed by expanding the current Cal-B/C Sketch tool. Cal-B/C Sketch has the capabilities to assess capacity expansion projects for highways and intersections, as well as queuing projects. The project types that could be most readily incorporated are new arterial road and new lane/widening projects. Intersection and roundabout projects would require substantial changes to incorporate a more detailed approach in assessing travel time impacts per the HCM and CMFs for safety impacts.

Overall, while the high-level assessment and review detailed in this white paper determined that Caltrans would benefit from a new comprehensive tool that leverages methodologies like those in TRB's Highway Capacity Manual, the scope of the review was limited to assessing the existence of such methodologies. Prior to developing new tools, a more thorough analysis and compilation of specific methodologies should be used to develop a blueprint of the new tool and confirm its realistic scope and limitations.

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