Oregon Transportation Benefit-Cost Analysis
Mode-Based Benefit-Cost Analysis Calculator
PART 1 – Literature and Best Practices Review

Final Report
November 2026

Authors

Jenny H. Liu, Ph.D. | jenny.liu@pdx.edu
Eunjun Choi
Hyeoncheol Kim

Center for Urban Studies
Toulan School of Urban Studies & Planning
Portland State University

ODOT Lead
Sylvan Hoover, ODOT Climate Office

Technical Advisory Committee
Sam Bell, Oregon State University
Alex Bettinardi, ODOT TPAU
Anne Brown, University of Oregon
Evan Rogers, ODOT Finance & Budget
Thor Morris, ODOT TPAU

Project sponsored by
Oregon Department of Transportation
Climate Office
555 13th St. NE, Ste 2
Salem, OR 97301-6867

Abstract

This document is **Part 1 of the Oregon Transportation Benefit-Cost Analysis - Mode-Based Benefit-Cost Analysis Calculator** project, which details the literature and best practices review that was conducted to inform the development of the Oregon benefit-cost analysis (BCA) framework and mode-based BCA calculator. Additional information can be found in the companion documents of this project – Part 2 - Benefit-Cost Analysis Framework and Part 3 - Oregon Mode-Based BCA Calculator Technical Documentation.

Portland State UNIVERSITY

Table of Contents

1 Transportation Benefit-Cost Analysis (BCA) Literature Review 1
1.1 Overview and Background 1
1.2 Review Process 2
1.3 Parameters 3
1.3.1 Environment 4
1.3.2 Travel time and vehicle operation 8
1.3.3 Health, accidents and perceived comfort 10
1.3.4 Quality of Life, Branding and Tourism 12
1.3.5 Other Parameters 13
1.4 Sensitivity Analysis 15
1.5 Equity and Distributional Considerations 16
1.6 Alternative Methods 19
1.6.1 Multi-Criteria Decision Analysis (MCDA) 19
1.6.2 Economic Impact Analysis (EIA) 19
1.6.3 Cost Effectiveness Analysis (CEA) 20
2 Transportation BCA Best Practices Review 21
2.1 United State Context 21
2.1.1 Framework Rules 22
2.1.2 Contents of the BCA Frameworks 22
2.1.3 Best Practices 36
2.2 Oregon Context 48
2.2.1 Mosaic Framework 49
2.2.2 VisionEval 52
2.3 International Context 55
2.3.1 Framework Rules 55
2.3.2 Basic Principles and Target Subjects 56
2.4 Comparisons between U.S. and International Practices 63
3 BCA Workshops 69
4 Lessons from the Literature and Best Practices Reviews 70
5 Bibliography 73

1 Transportation Benefit-Cost Analysis (BCA) Literature Review

1.1 Overview and Background

Benefit-Cost Analysis (BCA) is a widely used economic analysis method globally (Browne & Ryan, 2011; Weisbrod & Duncan, 2016; Lawrence et al., 2018; Chi & Bunker, 2021; De Rus et al., 2022). BCA is used to evaluate the costs and benefits that both users and society derive from transportation projects, programs, or policies (Lawrence et al., 2018; De Rus et al., 2022). This method quantifies costs and benefits in monetary terms, helping analysts and decision-makers to determine if a project is economically efficient when the total benefits exceed the total costs (Weisbrod & Duncan, 2016; Lawrence et al., 2018; De Rus et al., 2022).

BCA requires the setting of several default values before analysis can commence. The first is the **discount rate**, which accounts for the time value of money and includes the effects of expected inflation (Browne & Ryan, 2011). This rate is used to convert the future costs and benefits of transportation projects or policies to their present value. Secondly, a suitable **project lifetime** must be established to ensure meaningful analysis (Lawrence et al., 2018). The FHWA recommends that the analysis timeframe should include not only the initial construction phase but also at least one subsequent rehabilitation activity (Lawrence et al., 2018). Lastly, the indicators for analyzing results, primarily the **Benefit-Cost Ratio (BCR)** and the **Net Present Value (NPV),** should be determined. The NPV is the difference between the Present Value of Benefits (PVB) and the Present Value of Costs (PVC), used for comparing the magnitude of net benefits among alternatives. Conversely, the BCR, which is the ratio of PVB to PVC, is used when the costs and benefits are relatively minor or the difference between them is narrow (Lawrence et al., 2018). Furthermore, because the BCR is calculated by dividing benefits by costs, the classification of outcomes as benefits or costs significantly affects the BCR value. The USDOT (2023a) recommends that negative outcomes be categorized as "disbenefits" and subtracted from the total benefits (the numerator), rather than added to the costs (the denominator).

BCA offers the advantage of promoting efficient use of limited resources by assessing the various benefits and costs associated with transportation investments (Damart & Roy, 2009; Jones et al., 2014). This approach enhances the planning process and positively impacts decision-making (Beukers et al., 2012; Chi & Bunker, 2021). Moreover, it incorporates diverse and broad perspectives—including those of users, non-users, and institutional stakeholders—on the impact of infrastructure investments, which sets it apart from other analytical tools (Salling & Leleur, 2011; Chi & Bunker, 2021).

BCA is widely applied in decision-making for various transportation projects, programs, and policies across different modes. This includes initiatives to construct, expand, or enhance infrastructure, such as highway expansions, transit lane additions, and bike path installations, as well as policies like toll systems, emissions regulations, and safety standards. In practice, BCA is used to compare multiple alternatives during the initial planning phase and is also conducted when applying for grants or federal funding (Koopmans & Mouter, 2020; USDOT, 2023b).

For example, the New Jersey Department of Transportation conducted a BCA to secure funding

from the U.S. Department of Transportation (USDOT) for the construction of Route 18/Hoes Lane, a connector road to the highway (RITS, 2010). The BCA compared two scenarios: a no-build scenario and a build scenario over a 25-year project timeline. The results revealed a favorable BCR of 138.06, with a substantial net benefit compared to the no-build scenario. A sensitivity analysis, adjusting for key variables like road capacity and value of time, yielded a BCR range between 107.65 and 206.69, reinforcing the project's positive projected impact. Based on these findings, the project successfully received grant funding and was implemented in 2011.

The California High-Speed Rail (CAHSR) project also conducted a BCA to support a federal grant application (Parsons Brinckerhoff, 2014). This BCA focused on Phase 1 construction, which connects San Francisco to Anaheim. Given the relatively long lifespan of high-speed rail infrastructure, the analysis period was extended to cover over 50 years, from 2013 to 2071. The BCR was calculated for a no-build scenario and three different phase scenarios, each of which yielded a positive BCR exceeding 2. Following this analysis, CAHSR began construction in 2015, and is currently ongoing. Additional examples, applications and analysis are detailed in the BCA Best Practices section of this report.

Despite these advantages, BCA has certain limitations. First, impacts that are difficult to convert into monetary values or quantify are often excluded or underestimated (Beukers et al., 2012; Jones et al., 2014; Chi & Bunker, 2021). Second, by aggregating the value of costs and benefits, traditional BCA tends to ignore distributional effects—failing to account for who receives the benefits and who bears the costs (Beukers et al., 2012; Van Wee, 2012; Martens & Di Ciommo, 2017). These two limitations are commonly highlighted in various studies. In addition to these, other issues include simplified assumptions, methodological limitations in measuring impacts, and inadequate handling of uncertainties (Beukers et al., 2012).

1.2 Review Process

To investigate the literature on the BCA framework, we conducted backward and forward searches for BCA-related articles using five different search engines: Web of Science, Google Scholar, TRID (Transportation Research International Documentation), the Federal Highway Administration (FHWA), and the Transportation Research Board (TRB). We focused on literature published within the last 20 years, except for the most-cited or theory-based papers, which could be older. The search keywords included “BCA,” “CBA,” “Cost-Benefit Analysis,” “Benefit-Cost Analysis,” “Costs and Benefits,” and “transport infrastructure investment.”

Initially, we identified 74 pieces of literature and selected relevant ones based on their titles, abstracts, and citation counts. Additional literature was included as it was discovered during the review process. Some papers were excluded because their scope extended beyond our project. For instance, we removed papers that focused solely on one specific effect of transportation investment from a scientific perspective or those centered on the application of BCA results in decision-making processes.

We placed 14 key papers in the "best practices" folder. During the full-text review, we identified 7 additional papers through backward and forward searches. Ultimately, 60 papers were

included in the literature review section.

1.3 Parameters

Transportation BCA lacks a universally accepted framework, resulting in varying parameters being used across studies and appraisal reports. Gossling et al. (2019) conducted a comprehensive analysis of different BCA frameworks, identifying 14 key parameters that serve as the foundation for the parameter review section of this paper. However, we have integrated additional significant parameters not covered in the paper into relevant categories or under 'other parameters' to ensure a more complete evaluation. **Error! Reference source not found.** p rovides a quick reference guide to a selection of key BCA studies that describe the definitions and measurement methods for each BCA parameter. The following sections describe these parameters in more detail.

Table 1 - Overview of Parameters in BCA Studies

Parameters	Papers
Environment	
Climate Change	Jakob et al. (2006), Kolosz and Grant-Muller (2015), Gossling and Choi (2015), Gossling et al. (2019)
Air Pollution	Jakob et al. (2006), Williges and Mahdavi (2008), Litman (2010), Rabl and de Nazelle (2012), Gerbec et al. (2015), Gossling and Choi (2015), Lawrence et al. (2018), Gossling et al. (2019), Ross et al. (2020)
Noise Pollution	Litman (2010), Gerbec et al. (2015), Gossling and Choi (2015), Gossling et al. (2019)
Soil and Water Quality	Gossling et al. (2019)
Land Use and Infrastructure	Williges and Mahdavi (2008), Sahin et al. (2009), Litman (2010), Lawrence et al. (2018), Gossling et al. (2019)
Traffic Infrastructure Maintenance	Williges and Mahdavi (2008), Litman (2010), Gossling and Choi (2015), Lawrence et al. (2018), Gossling et al. (2019)
Resource Requirements	Lawrence et al. (2018), Gossling et al. (2019)
Travel Time and Vehicle Operation	
Vehicle Operation	Jakob et al. (2006), Williges and Mahdavi (2008), Sahin et al. (2009), Litman (2010), Gerbec et al. (2015), Gossling and Choi (2015), Lawrence et al. (2018), Greer and Ksaibati (2019), Gossling et al. (2019), Ross et al. (2020)
Travel Time	Williges and Mahdavi (2008), Litman (2010), Gossling and Choi (2015), Batarce et al. (2016),

	Lawrence et al. (2018), Greer and Ksaibati (2019), Gossling et al. (2019)
Congestion	Litman (2010), Gerbec et al. (2015), Gossling and Choi (2015), Greer and Ksaibati (2019), Gossling et al. (2019), Ross et al. (2020)
Health, accidents and perceived comfort	
Health Effects	Wang et al. (2005), Boarnet et al. (2008), Cavill et al. (2008), Litman (2010), Rabl and de Nazelle (2012), Mulley et al. (2013), Gossling and Choi (2015), Gossling et al. (2019), Ross et al. (2020), Van Den Bijgaart et al. (2024)
Safety Effects	Jakob et al. (2006), Williges and Mahdavi (2008), Litman (2010), Gossling and Choi (2015), Kolosz and Grant-Muller (2015), Lawrence et al. (2018), Greer and Ksaibati (2019), Gossling et al. (2019), Ross et al. (2020)
Perceived Safety & Discomfort	Litman (2010), Gossling and Choi (2015), Gossling et al. (2019)
Quality of life, tourism and infrastructure	
Quality of Life, Branding and Tourism	Litman (2010), Gossling and Choi (2015), Gossling et al. (2019), Ross et al. (2020)

1.3.1 Environment

A. Climate Change

Climate change results from the accumulation of various greenhouse gases (GHGs), particularly carbon dioxide (CO2) (Jakob et al., 2006; Gössling & Choi, 2015; Gössling et al., 2019). Significant economic losses are anticipated due to climate change. The economic impact of carbon emissions is typically expressed as the cost per ton of CO2 equivalent emissions (Jakob et al., 2006; Gössling & Choi, 2015; Kolosz & Grant-Muller, 2015; Gössling et al., 2019). Carbon values are categorized into traded and non-traded sectors, with transportation emissions falling under the non-traded category (Kolosz & Grant-Muller, 2015). Generally, non-traded carbon values are higher than traded ones, but it is expected that these values will converge by 2030.

Each BCA report or framework relies on data from organizations that study the economic value of CO2 emissions. In the United States, this data is provided by the U.S. Environmental Protection Agency (EPA), while in most European countries, the EU Emissions Trading Scheme (EU ETS) is used. Furthermore, the accumulation of GHGs affects the climate over long periods and across broad regions, making precise measurement difficult (Jakob et al., 2006). Due to these characteristics, the USDOT applies a small discount rate of 2% when calculating the benefits of CO2 emissions reductions (USDOT, 2023b). The lower discount rate applied specifically to CO2 reflects the long-lasting and intergenerational impacts of GHGs, as it implies

that future benefits are valued more highly relative to immediate benefits.

B. Air Pollution

In BCAs, the air pollution parameter encompasses the health and economic impacts, as well as damage to vegetation and buildings, resulting from various pollutants emitted by different vehicles (Jakob et al., 2006; Williges & Mahdavi, 2008; T. Litman, 2010; Rabl & De Nazelle, 2012; Lawrence et al., 2018; Gössling et al., 2019). The specific pollutants include nitrogen oxides (NOx), sulfur oxides (SOx), particulate matter (PM2.5 and PM10), ozone (O3), carbon monoxide (CO), lead, and volatile organic compounds (VOCs). However, the pollutants considered can vary between studies. For example, Lawrence et al. (2018) do not include CO due to insufficient scientific evidence of its adverse health effects, while studies (Gerbec et al., 2015; Gössling et al., 2019; Gössling & Choi, 2015) in European countries often recognize and include CO due to its documented health impacts. Additionally, the reduction of CO2 is sometimes considered under the air pollution parameter (Gerbec et al., 2015), if the BCA does not account for the climate impacts of CO2.

All these impacts are estimated based on the type of vehicle or engine type and the type of facility (or area type). For example, Gerbec et al. (2015) conducted a BCA focused on three types of buses—diesel, hybrid, and CNG—and estimated the monetary values of each air pollutant by fuel type. This calculation requires three pieces of data: the amount of air pollutants emitted by each bus (g/km), the expected annual distance driven (km), and the monetary values for each pollutant ($/ton). Additionally, the Federal Highway Administration (FHWA) provides estimates of air pollution costs corresponding to CO, SOx, NOx, and PM emissions, which can be calculated as costs per vehicle miles traveled (VMT) (FHWA, 2020). These costs vary depending on three vehicle types, four highway types, and speed. Litman (2010) and Rabl and Nazelle (2012) estimated air pollution costs by the type of road environment in which vehicles travel. For instance, urban environments tend to incur higher costs because they are more prone to congested road conditions than rural areas.

Previous studies identified three key data requirements for estimating air pollution costs: (i) emission rates for each pollutant by vehicle type and speed, (ii) changes in travel speed, travel volumes, or VMT due to transportation policies or projects, and (iii) monetized values for each air pollutant. These data are derived from various modeling tools. For instance, the Cal-B/C tool calculates emission rates by speed using the California Air Resources Board (CARB) emissions model (Williges & Mahdavi, 2008). Additionally, travel demand modeling is essential to estimate travel speeds, volumes, and VMT after project implementation. Most studies source cost data for each pollutant from organizations such as the World Health Organization (WHO), the Environmental Protection Agency (EPA), the National Research Council (NRC), and the European Commission (EC), and these values are periodically updated as research into monetary valuations continues to evolve.

C. Noise Pollution

The direct impacts of noise pollution costs include annoyance and health-related costs due to exposure to transportation noise, while indirect impacts involve declines in property values near

transportation infrastructure and reduced productivity (FHWA, 1997; T. Litman, 2010; Gössling & Choi, 2015; Gössling et al., 2019). Estimating average noise pollution costs is more challenging than for other impacts. This is because noise impacts only occur when the noise exceeds the health-affecting threshold of 55 dB, happen at specific times of day, and are more severe near transportation infrastructure or in areas with high road density.

The factors that influence noise pollution impacts can be categorized as follows:

- **Vehicle-related factors**: These include vehicle type, engine type, weight, traffic speed, and acceleration/deceleration (FHWA, 1997; Victoria Transport Policy Institute, 2022). Heavy vehicles and older engines typically generate more noise. Additionally, noise increases when vehicles operate at higher speeds, accelerate, climb slopes, or brake suddenly.
- **Road environment factors**: Noise impacts are influenced by traffic volumes and pavement type (FHWA, 1997; Victoria Transport Policy Institute, 2022). Additional vehicles have a greater noise impact in areas with lower traffic volumes compared to high-traffic areas. Noise is also reduced on smoother roads.
- **Surrounding environment factors**: The impact of noise depends on the type and density of land uses adjacent to the transportation facility. Noise pollution costs are higher in the densely populated area due to the larger number of people affected (FHWA, 1997). Noise diminishes with distance from the facility and is further reduced by natural barriers, such as hills, or artificial barriers like walls (Victoria Transport Policy Institute, 2022).

Litman (2010) estimated noise costs per VMT based on location (urban peak, urban off-peak, and rural driving) and vehicle type. Gerbec et al. (2015) analyzed the noise pollution experienced by people at bus stops, measuring values for three different bus types. To monetize these values, they used a regression equation based on the willingness-to-pay (WTP) principle. FHWA (1997) provides noise impact costs by vehicle and area type, while CE Delft (2020) offers cost values by vehicle type and time period (daytime and nighttime). However, the USDOT (2023) continues to use noise pollution costs estimates from FHWA (1997), which may result in underestimation. When adjusted to 2024 dollars, FHWA's values for noise pollution costs are lower than those found in the more recent research (CE Delft, 2020). Moreover, the original FHWA method, which calculates noise costs as depreciation in residential property values due to noise exposure, may underestimate the true costs by not accounting for health impacts and stress related to noise exposure.

D. Soil and Water Quality

Soil and water quality pollution resulting from new transportation facilities and increased transport activities is often overlooked in BCAs. According to various studies, this impact includes several types of pollution. Firstly, stormwater runoff is exacerbated by the expansion of roads, which increases the surface area covered by materials like concrete or asphalt that have low rainwater absorption rates, thereby increasing stormwater runoff (Gössling et al., 2019). Conversely, transportation infrastructure projects can mitigate existing issues by improving stormwater management facilities (USDOT, 2023b). Secondly, vehicle operations contribute to ground pollution through oil spills and the deposition of heavy metals from vehicle brakes on

roads or railways (CE Delft, 2020). Additionally, groundwater and soil pollution are exacerbated by burning of fuel and, more extensively, this category includes impacts from oil spills at sea (CE Delft, 2020). Currently, there are few established methodologies for quantifying and monetizing the impacts mentioned above.

E. Land Use and Infrastructure

Land Use and Infrastructure costs encompass infrastructure construction costs and land use externality costs, which represent the loss of potential land uses (such as agricultural uses, natural ecosystems, etc.) (Gössling et al., 2019). Construction costs, also referred to as capital expenditures or initial costs, are defined consistently across various studies. These costs encompass direct construction expenses including land, labor, materials, and equipment used during the construction phase, as well as costs associated with right-of-way acquisition, planning, assessment, and engineering (Lawrence et al., 2018; USDOT, 2023b). For long-term projects, it is important to note that each cost should be recorded at the time it is incurred (USDOT, 2023b).

Land use costs, however, are defined differently across studies. In Gössling et al. (2019), this cost is confined to the loss of ecosystem service values, whereas in the VTPI BCA framework, land use impact assesses the effects of transportation activities and infrastructure on the existing land use from social, economic, and environmental perspectives (Victoria Transport Policy Institute, 2022). In the USDOT framework, land use is considered alongside agglomeration economies, detailing the negative impacts of transportation infrastructure on these economies by contributing to dispersed land use patterns (USDOT, 2023b). However, this does not include a methodology to quantify these impacts.

The SMART SCALE Technical Guide developed in Virginia evaluates land use by determining if the land around a transportation project facilitates access to non-work destinations within a reasonable walking distance, and measures how the project improves this access (Commonwealth Transportation Board, 2024). This assessment ensures that the transportation project aligns with surrounding land use. Additionally, Litman (2010) views non-motorized transportation infrastructure as a benefit that positively influences land use by promoting compact land use development.

Given the broad variation in how land use and infrastructure costs are defined, depending on the scale, purpose, and characteristics of the transportation project, it is crucial to be aware of potential overlaps with economic and environmental costs when utilizing this parameter. It is necessary to clearly specify the definition to avoid confusion and ensure accurate assessment.

F. Traffic Infrastructure Maintenance

Traffic infrastructure maintenance includes the costs of maintaining and managing transport infrastructure, as well as traffic police expenses (T. Litman, 2010; Gössling & Choi, 2015; Gössling et al., 2019). Since road wear varies depending on vehicle weight, speed, and size, maintenance costs are calculated differently for each type of vehicle (Gössling et al., 2019; T. Litman, 2010). In contrast, walking and cycling have minimal impact on roads, resulting in lower maintenance costs compared to automobiles (T. Litman, 2010; Gössling & Choi, 2015).

Particularly, maintenance costs may encompass a diverse array of items, depending on the transport facilities involved in the projects. Consequently, BCA necessitates a clear presentation of these items and a well-defined basis for when the costs are incurred (USDOT, 2023b).

G. Resource Requirements

Resource requirements cover the lifecycle costs associated with both the upstream and downstream processes for building and maintaining transportation infrastructure and vehicles (Gössling et al., 2019). These costs span from the production process of vehicles and transportation infrastructure to energy consumption and disposal processes. This category, which is relatively challenging to delineate in terms of influence relationships and impact measurement, is seldom addressed in other studies.

The Victoria Transport Policy Institute (Victoria Transport Policy Institute, 2022) elaborates on the economic and environmental costs incurred during the production, distribution, and consumption phases of energy, as part of the external costs of resource consumption. Additionally, the waste disposal category addresses the impact costs that arise when vehicle-related waste is improperly disposed of. VTPI (2020) estimates the waste disposal costs for tires, waste oil, and scrap cars by vehicle type.

In the work of Lawrence et al. (2018), end-of-life costs most closely align with this parameter. End-of-life costs cover the expenses associated with the management of transportation facilities after the period analyzed and are categorized into three types: residual value, salvage value, and close-out costs (Lawrence et al., 2018). Residual value is the expected worth of the facility if it continues to be used beyond the analysis period. Salvage value is the estimated worth of the asset if there is a market for its sale. Close-out costs pertain to expenses incurred after the service and operational periods coincide, such as deconstruction costs.

1.3.2 Travel time and vehicle operation

A. Vehicle Operation

Vehicle operating costs encompass the expenses associated with owning and operating a specific mode of transportation (Jakob et al., 2006; T. Litman, 2010; Gerbec et al., 2015; Gössling & Choi, 2015; Lawrence et al., 2018; Gössling et al., 2019; Ross et al., 2020). These costs could be divided into fuel and non-fuel categories (Lawrence et al., 2018). Most studies include expenses related to fuel, engine oil consumption, tire and brake wear, and repair costs. However, there are discrepancies concerning ownership costs and certain non-fuel expenses. For instance, Gössling et al. (2019) and Gerbec et al. (2015) account for ownership costs, whereas other studies do not. Additionally, vehicle registration fees, taxes, insurance, tolls, and parking fees, which fall under non-fuel costs, may be included or excluded depending on the study. Given these variations, it is crucial for users to clearly articulate the connection between the project and the costs being evaluated (USDOT, 2023b).

Several studies have discussed operating costs for public transit and active modes, not just automobiles. For public transit, operating costs vary by train type and movement type (USDOT, 2023b), and include bus drivers' salaries (Gerbec et al., 2015). For active modes like cycling and

walking, fuel costs are replaced by the cost of meals consumed by the travelers, and non-fuel operating costs include expenses for purchasing and maintaining bicycles or shoes over their average usage periods (T. Litman, 2010). Generally, active mode operating costs are significantly lower than those for automobiles (Gössling & Choi, 2015).

Fuel costs are calculated by multiplying the fuel price by the vehicle's fuel consumption rate and VMT (Williges & Mahdavi, 2008; Gerbec et al., 2015; Ross et al., 2020). However, for transportation projects that reduce travel time rather than distance, operating costs savings resulting from changes in time should be explicitly accounted for (USDOT, 2023b). This aligns with how Litman (2010) measured vehicle operating costs under different conditions—urban peak, urban off-peak, and rural—taking congestion into consideration. Moreover, for non-fuel costs, the average operating/maintenance cost per mile of a transport vehicle is typically used, but this value can vary depending on the age and type of the vehicle (Lawrence et al., 2018). Reflecting these differences, the USDOT's BCA considers operating costs for two vehicle types: light-duty vehicles and commercial trucks (USDOT, 2023b). Gössling and Choi (2015) also differentiated costs between private and business vehicles.

B. Travel Time

The cost of travel time is the monetary value of the time that drivers and passengers spend traveling, and it is considered a private cost (Gössling et al., 2019). Often, travel time reductions resulting from transportation projects are included in BCA as travel time benefits (Lawrence et al., 2018). The value of travel time (VOT)—the amount of money people are willing to pay to reduce travel time to arrive destinations—is a commonly used factor for estimating travel time. This value varies depending on factors such as the mode of transportation, sociodemographic, time of day, trip purpose, road conditions, and facility type (Williges & Mahdavi, 2008; T. Litman, 2010; Gössling & Choi, 2015; Lawrence et al., 2018). In addition to values for in-vehicle time, there are also valuations for transfer time, waiting time, access time, and standing time (Eliasson, 2013; USDOT, 2023b).

Since the VOT is measured by the population's willingness to pay, it varies across different regions and societies (Gössling & Choi, 2015; Lawrence et al., 2018). For this reason, it is recommended to use data from surveys conducted in local areas to determine the local value of travel time. Additionally, the VOT varies depending on the level of crowding in transit vehicles (Batarce et al., 2016; USDOT, 2023b). Generally, the VOT is higher in crowded vehicles compared to those with available seats (Batarce et al., 2016). Failing to consider this aspect could lead to underestimations or overestimations of the value of transit projects.

The value of travel time is also linked to travel time reliability. Travel time reliability refers to the predictability and certainty of users' experiences when using transportation systems (Gössling et al., 2019; Lawrence et al., 2018; USDOT, 2023b). It represents the value of being able to arrive at a destination on time and within a predictable timeframe, rather than the amount of money one would pay for a reduction in average travel time (USDOT, 2023b). The USDOT does not provide a specific methodology for quantifying travel time reliability because it is challenging to measure. However, Lawrence et al. (2018) proposes a method to monetize travel time reliability

by measuring changes in the standard deviation of travel time using real-time travel data collection.

C. Congestion

Congestion refers to the costs—a type of external cost—imposed on other travelers due to high traffic volume (T. Litman, 2010). This parameter encompasses costs associated with congestion, including additional travel time, fuel consumption, pollution, collisions, stress, and more (FHWA, 1997; T. Litman, 2010; Gössling & Choi, 2015; Gössling et al., 2019). However, since many of these factors are covered by other parameters, Gössling & Choi (2015) and Gössling et al. (2019) include only the time costs resulting from additional driving in congested conditions, as compared to free-flow traffic, to avoid double counting. Similarly, the congestion costs estimated by FHWA (1997) represent the extra travel time caused by increased traffic. This report breaks down congestion costs by highway class (urban/rural) and vehicle type (e.g., cars, trucks), recognizing that additional traffic on congested versus uncongested roads has different impacts on congestion.

Other studies have approached the impact of congestion by estimating the savings in various costs due to transportation projects (T. Litman, 2010; Gerbec et al., 2015; Greer & Ksaibati, 2019; Ross et al., 2020). For example, Ross et al. (2020) considered the monetary values of time and fuel savings as their congestion parameter. Greer and Ksaibati (2019) utilized travel time cost values based on the level of service (LOS) to calculate the travel time savings resulting from improvements in LOS due to transportation projects. Gerbec et al. (2015) defined travel time savings for non-public transit users as benefits of reduced congestion stemming from improvements in public transit. Virginia's Smart Scale guides congestion mitigation measures by giving equal weights (50%) to the benefits of increased human movement during peak periods and reduced driving time per person during peak periods (Commonwealth Transportation Board, 2024).

Previous studies confirm that congestion impacts encompass both the costs caused by additional traffic (in kilometers) and the savings resulting from reduced traffic (in kilometers). Additionally, since congestion impacts include various costs caused by increased or decreased driving, careful attention is required to avoid duplication with other parameters. Furthermore, estimating congestion costs demands detailed impact measurements, as the effects vary depending on vehicle type and road type.

1.3.3 Health, accidents and perceived comfort

A. Health Effects

Health effects refer to the direct and indirect advantages gained from using active transportation modes, such as walking and cycling (Wang et al., 2005; Cavill et al., 2008; T. Litman, 2010; Rabl & De Nazelle, 2012; Mulley et al., 2013; Gössling & Choi, 2015; Gössling et al., 2019; Ross et al., 2020). These benefits include savings in healthcare costs due to increased physical activity, reduced sick leave days, extended life expectancy, and decreased incidence of certain diseases, including cardiovascular diseases and type 2 diabetes, which are often linked

to sedentary lifestyles. Numerous studies have evaluated and monetized the health benefits of increased physical activity resulting from cycling and walking (Boarnet et al., 2008; T. Litman, 2010). However, there is a lack of consensus on the methodology for measuring health benefits, the data used, which diseases to include, and establishing a clear causal relationship (Cavill et al., 2008).

The USDOT (2023) provides a monetized value per induced trip for mortality reduction benefits that result from transitioning from motorized to active modes. This valuation is intended only for specific age groups and certain trips (switching from motorized modes to walking and cycling). It is recommended that qualitative research be conducted to assess health benefits for groups that do not meet these criteria (USDOT, 2023b).

There are arguments that health impacts should be considered not only in transportation projects and programs that directly encourage walking and biking but also in car-oriented policies or programs that contribute to increased physical inactivity, potentially leading to negative health impacts. When comparing the major costs of car use, the social costs of physical inactivity significantly outweigh those of air pollution, accidents, and congestion (Van Den Bijgaart et al., 2024). Therefore, by including the costs of inactivity in programs and policies that discourage active transportation and public transit use, a more comprehensive evaluation will be possible.

B. Safety Effects

Crash costs encompass expenses related to minor and major injuries, fatalities, and property or material damages resulting from traffic incidents (Jakob et al., 2006; Williges & Mahdavi, 2008; T. Litman, 2010; Gössling & Choi, 2015; Kolosz & Grant-Muller, 2015; Lawrence et al., 2018; Gössling et al., 2019; Greer & Ksaibati, 2019; Ross et al., 2020). Additionally, some studies also account for legal fees, emergency service costs, and productivity losses within crash costs (Jakob et al., 2006; Gössling & Choi, 2015; Lawrence et al., 2018). Reducing crashes and enhancing road safety are primary objectives of transportation projects, often quantified as 'safety benefits' in BCA (USDOT, 2023b).

Safety benefits—or disbenefits—are calculated by multiplying the change in the number of crashes, whether an increase or decrease, resulting from a transportation project by the cost per crash. The USDOT (2023) provides national default crash costs, categorizing injuries into six types according to the KABCO[1] injury severity scale. These values can be adapted based on the data available to a state. Some studies calculate the number of crashes relative to the total VMT in a year, which is expressed as crash rate by collision type (Williges & Mahdavi, 2008; Gössling & Choi, 2015). They then assess safety impacts through the corresponding changes in VMT

[1] The KABCO scale, developed by the National Safety Council, is a classification system used to categorize the severity of injuries in traffic accidents (FHWA, 2016). It employs letter designations for different levels of injury severity: K for fatal injuries, A for incapacitating injuries, B for non-incapacitating injuries, C for possible injuries, and O for no injuries. While the Abbreviated Injury Scale (AIS) provides a more medically precise assessment, the KABCO scale is widely utilized for on-scene assessments and in police reports. Some states may interpret these categories slightly differently or even introduce additional categories.

resulting from the project. Additionally, the USDOT also lists safety costs (costs per VMT) by vehicle and area type, which can be utilized when a project aims not specifically at safety improvements but at reducing traffic volumes. Moreover, studies focusing on active transportation calculate safety costs exclusively for incidents involving bicycles or pedestrians (T. Litman, 2010; Gössling & Choi, 2015).

C. Perceived Safety & Discomfort

Perceived safety and discomfort refer to the costs associated with the risks and annoyances experienced by users of non-motorized modes of transportation (Gössling & Choi, 2015; Gössling et al., 2019). Unlike automobile users, pedestrians and cyclists are directly exposed to pollutants, noise, and odors, and they face a higher risk of serious injury in traffic incidents. Despite its significance, this cost has not been monetized so far.

This cost also aligns with the "barrier effect" described by Litman (2010). The barrier effect suggests that automobiles worsen the travel environment for non-motorized travelers by increasing crash risk and pollution. It is measured by assessing factors that can heighten crash risk and pollution on the road, such as vehicle speed, traffic volume, and the proportion of trucks, as well as by estimating the demand for walking and cycling (T. Litman, 2010). Although this value represents a cost borne by non-motorized modes and is worth considering, it is not practically used due to the lack of a standardized methodology or adequate data for accurate measurement.

1.3.4 Quality of Life, Branding and Tourism

The quality of life improved by transportation projects can be defined and measured across various aspects, including social, economic, mental, and overall well-being. Different studies have defined and measured it in diverse ways. Gössling et al. (2019) describe quality of life as the difference between life in an environment improved by a transportation project and life prior to that improvement. For example, mental well-being could be enhanced by increased physical activity due to improved bike paths or pedestrian networks. Ross et al. (2020) addresses social aspects such as neighborhood connections, impacts on family life, and demographic changes. Similarly, Litman (2010) defines it as social benefits, including social connections and opportunities for recreation and entertainment.

However, because this impact is challenging to measure, no study has established a clear methodology for its assessment. When it comes to branding and tourism, several studies have measured their impacts. Generally, transportation projects that develop and enhance bike and pedestrian networks contribute to increased branding and tourism. Gössling & Choi (2015) included tourism values measured in bike-friendly countries in their BCA. It is still difficult to find specific impacts on quality of life, branding, and tourism in practical reports. Some reports classify these impacts as secondary and do not include them in the BCA (Sartori et al., 2015; Australian Transport Assessment and Planning, 2023).

1.3.5 Other Parameters

A. Economic Impacts

The economic impacts of transportation infrastructure projects are categorized into direct impacts, which include travelers' costs and the external costs of transport, and indirect impacts, which influence the entire market economy (Wangsness et al., 2017). These impacts arise from enhanced accessibility and mobility for various activities such as jobs, education, amenities, and services (Lawrence et al., 2018; USDOT, 2023b). Economic impacts encompass various types, but BCAs from different countries commonly include agglomeration effects, labor market effects, and changes in production within non-competitive markets (Wangsness et al., 2017).

Agglomeration impacts refer to productivity gains resulting from the efficient concentration of businesses and people in a single location, facilitated by improvements in the transportation system (Lakshmanan, 2011; Wangsness et al., 2017; Searle & Legacy, 2019; De Rus et al., 2022). Specifically, they encompass economic benefits arising from matching, sharing, learning, knowledge spillovers, and innovation due to agglomeration (Wangsness et al., 2017).

Labor market outcomes involve multiple effects: improved transportation networks reduce commuting costs, increase the labor pool, and potentially extend workers' hours (Lakshmanan, 2011; Wangsness et al., 2017). Furthermore, these enhancements allow employers to access a broader pool of qualified candidates, and workers to find better jobs, leveraging wider labor markets (Wangsness et al., 2017).

Production changes refer to the outcomes resulting from increased competitiveness in an imperfect market due to enhanced transportation accessibility (Lakshmanan, 2011; Wangsness et al., 2017; De Rus et al., 2022). Specifically, heightened competition among firms can lead to increased production, lower prices, and greater product diversity, thereby benefiting firms' markets and providing consumers with better products (Wangsness et al., 2017).

However, reports that clearly outline methods for measuring these economic impacts due to transportation projects are rare and lack uniformity (Wangsness et al., 2017). This challenge arises because the types of economic impacts vary widely, and their inclusion depends significantly on the size and purpose of the project, making it difficult to present generalized parameters for economic impacts (USDOT, 2023b). Additionally, there is some debate over the appropriateness of including economic impacts as a part of BCAs. Some advocate for their inclusion to create a more comprehensive framework, while others argue that it could decrease the accuracy of BCA results and risk duplicating direct economic impacts without clearly establishing causal relationships (Wangsness et al., 2017; Searle & Legacy, 2019; USDOT, 2023b).

B. Freight-related Parameters

Freight transportation in the U.S. encompasses various modes such as air, port, train, and truck. This discussion, however, focuses specifically on how commercial truck traffic and freight trains, which operate across U.S. land, are treated in BCA. Notably, the volume of freight carried by

trucks and rail significantly surpasses that of other freight modes[2]. In the U.S., freight vehicles are categorized into eight classes based on gross vehicle weight rating (GVWR), which the FHWA divides 8 classes into three categories: Light Duty, Medium Duty, and Heavy Duty. The impact of trucks on road wear, noise, operating costs, air pollution, crashes, and traffic flow varies based on the vehicle's weight or size, and is substantially greater than that of light vehicles, necessitating distinct treatment.

While existing BCAs address freight vehicles, the level of detail provided is often insufficient. The USDOT classifies freight trucks as a single category within commercial trucks in terms of vehicle operating costs (USDOT, 2023b). Trains are similarly grouped under a single category labeled "freight train". Lawrence et al. (2018) distinguished trucks from other vehicle types only in the indicator of vehicle operating costs. The FHWA also categorized trucks into three types based on their impact on air pollution, including two truck categories by weight and one specifically for diesel trucks (FHWA, 1997). Such classifications simplify the representation of trucks and may not adequately consider their impact across all parameters. As online shopping continues to grow, so too does freight traffic. Therefore, giving specific attention to freight vehicles can enhance the results of BCA.

Within Oregon, it may be appropriate to draw upon findings from the biennial Highway Cost Allocation Study. This study allocates highway user taxes across different vehicle types to ensure equity and proportionality between light and heavy vehicles (ECONorthwest, 2023)(ECONorthwest, 2023). It categorizes vehicles into two main groups: light vehicles (under 10,000 pounds) and heavy vehicles (over 10,000 pounds), further dividing these into six categories. The study establishes varying tax rates for freight trucks, considering factors such as weight and the number of axles. These differentiations are a result of roadway shares of each vehicle category, enabling a more accurate calculation of each vehicle's impact on the roadway.

C. Parameters related to Emerging Modes

In recent years, advancements in transportation technologies and the rise of shared mobility and mobility-as-a-service (MaaS) platforms have not only transformed travel behavior but also altered vehicle ownership patterns. These changes necessitate a reevaluation of the BCA. With significant technological progress in autonomous vehicles (AVs), the commercialization of AVs is nearing reality. Legal, institutional, and technological foundations are being established to enable the application of these technologies in real-world road environments. As AVs replace conventional vehicles, they are expected to significantly impact the parameters in BCA. Several studies have explored which parameters are likely to see the most change with the introduction of AVs and what additional factors should be incorporated into the analysis.

Parameters expected to see positive changes include safety, congestion, parking demand reduction, vehicle operation costs, and freight movements (Fagnant & Kockelman, 2015; Österle et al., 2022). Given that 93% of traffic incidents in the United States are caused by human error,

[2] U.S. Department of Transportation. (2023). “Ton-miles of freight by mode and distance”, Retrieved from: https://data.bts.gov/stories/s/Moving-Goods-in-the-United-States/bcyt-rqmu/

the deployment of AVs promises substantial safety improvements: a 10% share of AVs could reduce the number of crashes by 50%, and a 90% share by 90% (Fagnant & Kockelman, 2015). In terms of congestion, a 90% AVs-share could reduce highway congestion delays by 60% (Fagnant & Kockelman, 2015). The introduction of AVs is also expected to lower the costs of parking and reduce individual operating expenses such as fuel, insurance, and parking fees through efficient operations and car-sharing (Fagnant & Kockelman, 2015; Österle et al., 2022). Freight trucks may benefit from fuel savings and faster delivery times by operating in coordinated formations that reduce air resistance (Fagnant & Kockelman, 2015).

However, the deployment of AVs will also necessitate various infrastructure changes, incurring additional costs. Initially, since AVs are still not mass-produced, their high prices mean ownership costs will be significant (Fagnant & Kockelman, 2015; Österle et al., 2022). Furthermore, as AVs operate using data on road structures and traffic flows, the construction and maintenance costs for infrastructure, such as road sensors and communication technology, must also be considered (Österle et al., 2022).

These changes will require adjustments to the reference values used in existing BCA parameters. For instance, the operating costs per hour for human-driven cars and AVs will differ, necessitating separate measurements for AVs. Additionally, as the integration of AVs onto real roads will be phased, the impact of AVs will not increase linearly at each stage. Particularly in the early stages, where AVs mix with human-driven vehicles, larger accidents or unforeseen events may occur, suggesting that detailed discussions will be necessary in future BCAs to address these issues.

However, beyond AVs, shared mobility—which is rapidly expanding in both services and usage—remains insufficiently addressed in existing BCAs. For instance, Litman (T. A. Litman, 2024) explores the costs and benefits of carsharing. One of the most significant advantages of carsharing is its ability to enhance mobility for individuals for whom private vehicle ownership is economically burdensome. By improving mobility for low-income individuals, carsharing can enhance job accessibility, generate economic benefits, and promote equity. Additionally, from a societal perspective, decreased private vehicle ownership can lead to reduced social costs, such as alleviating congestion and decreasing the need for parking spaces. However, discussions surrounding ride-hailing services (e.g., Uber and Lyft) and shared micromobility devices remain notably absent in many BCAs.

1.4 Sensitivity Analysis

Sensitivity Analysis evaluates the vulnerability of BCA outputs to the input variables and parameters used in the BCA, and is also referred to as risk analysis or probabilistic analysis (Wang et al., 2005; Boarnet et al., 2008; Williges & Mahdavi, 2008; Salling & Leleur, 2011; Lawrence et al., 2018; Zahed et al., 2018; Österle et al., 2022). This analysis is particularly emphasized in cases where there is high uncertainty in input data or when data is insufficient (Lawrence et al., 2018; Chi & Bunker, 2021). For instance, during sensitivity analysis for an input value labeled A, all other variables are held constant while only variable A is adjusted to observe the impact on the results. The findings from this analysis enable decision-makers to examine

and compare how results vary under different assumptions and help in assessing the reliability and robustness of these outcomes. Despite its importance, not all BCAs include sensitivity analysis, and there is a lack of comprehensiveness in conducting sensitivity analysis (Salling & Leleur, 2011; Chi & Bunker, 2021).

Sensitivity analysis is conducted based on various parameters or assumptions. For example, when input data is estimated, the extreme values of the confidence interval for the input are applied to observe changes in the result (Boarnet et al., 2008; Lawrence et al., 2018). Alternatively, input value may be categorized to examine how results differ across groups (Boarnet et al., 2008), or the total cost or benefit values are altered by a specified amount to assess changes in the outcome (Österle et al., 2022). Salling and Leleur (2011) identified construction costs and travel time savings as variables that significantly affect the uncertainty of BCA results, and they also highlighted maintenance costs and estimated changes in crash rates as additional factors.

Changes in assumptions involve arbitrarily assumed values for the analysis. Commonly, the discount rate is altered to evaluate its impact on the results (Lawrence et al., 2018; Chi & Bunker, 2021). Furthermore, assumptions used in travel modeling or safety modeling, such as toll price assumptions or the proportion of commercial vehicles, are also modified (Chi & Bunker, 2021). Such changes in assumptions require the analyst's judgment and involve criteria deemed crucial in decision-making processes for the transportation projects under evaluation.

1.5 Equity and Distributional Considerations

BCA offers the advantage of quantifying the pros and cons of various projects and providing directly comparable outcomes, such as NPV or BCR, which facilitate intuitive decision-making (Lucas et al., 2016). However, BCA has been consistently criticized for failing to account for equity and distributional concerns (Van Wee, 2012; Martens & Di Ciommo, 2017).

Firstly, BCA's focus on monetizable indicators often excludes critical values like environmental effects and social impacts that are difficult to quantify in monetary terms (Van Wee, 2012; Lucas et al., 2016). Secondly, the aggregate results provided by BCR and NPV make it challenging to assess how benefits and costs are distributed, as they compare total benefits against total costs without highlighting disparities (Nurmi & Ahtiainen, 2018). Despite the growing emphasis on equity in transportation planning, its integration into BCA remains limited in practice.

The following are the main methods used to develop a BCA that incorporates equity and distributional considerations. The first method is the use of accessibility measurements. Unlike mobility, which traditionally focuses on travel time savings and improvements in speed, accessibility includes an equity component (Martens & Di Ciommo, 2017; Pereira et al., 2017; Litman, 2024). Mobility-based measures prioritize higher speeds and longer trips, using indicators like travel time savings, congestion delays, and LOS. In contrast, accessibility-based measures are defined as the ability to reach desired services and activities (T. A. Litman, 2024). These measures have the potential to reflect various modes of transport and account for the needs of different social, economic, and physical groups, offering a more inclusive evaluation of

transportation systems.

Lucas et al. (2016) propose a method to evaluate accessibility impacts that align with the equity principles of egalitarianism and sufficientarianism. This method combines two accessibility measures, the Lorenz curve and the Gini index. Notably, the study focuses on accessibility to essential service destinations, which plays a crucial role in preventing social exclusion, making it a strong representation of equity in accessibility analysis. However, in practice, it remains rare to find a BCA that incorporates accessibility indicators, and when used, accessibility measures often only focus on access to employment[3]. Virginia DOT's transportation project evaluation guide, SMART SCALE, attempts to provide an accessibility indicator that incorporates an equity perspective. The accessibility measures in this report are divided into three categories: access to jobs for the total population, access to jobs for disadvantaged populations, and access to multimodal choices (Commonwealth Transportation Board, 2024). Each of these categories is weighted differently to reflect their relative importance.

The second method is the use of distributional weights. Distributional weights are an analytical method that assigns weights to different groups, such as by income level, demographic group, or geographic region, to account for differences in the distribution of costs and benefits. In BCA based on utilitarianism, a project is considered justified if the total benefits outweigh the total costs, or have a positive NPV. However, using distributional weights allows for differentiation between individuals or groups that benefit or incur costs. Although many scholars have recommended the use of distributional weights in BCA, it is rare to find a framework that applies this method (Adler, 2016). In particular, discussions on distributional weights are less common in the United States compared to other countries (Australian Transport Assessment and Planning, 2023; de Jong, 2013; Department for Transport, 2023; Ministry of Land, Infrastructure and Transport, 2022). The primary reason is that USDOT does not recommend applying this method in transportation BCA due to the need for more detailed data than what is typically required for the BCA of transportation infrastructure projects.

Robinson et al. (2016) propose two approaches for conducting distributional analysis in BCA: a separate analysis and an integrated method. The first approach involves conducting the traditional BCA while separately measuring and reporting how benefits, costs, and net benefits are distributed. The second approach requires applying distributional weights to the benefits and costs so that distributional analysis can be integrated into the BCA framework (Australian Transport Assessment and Planning, 2023; de Jong, 2013; Department for Transport, 2023; Ministry of Land, Infrastructure and Transport, 2022). An essential aspect of this approach is the estimation of appropriate weights, which this study addresses by using the marginal utility of income and societal preferences for distribution. Discussing the weighting methods suitable for BCA, Adler (2016) and Nurmi and Ahtiainen (2018) also present and compare various weighting approaches.

[3] Colorado DOT uses the term of accessibility to measure the number of jobs reachable by driving or public transit. This measurement falls under the category of economic impacts but is not reflected in the analysis due to the challenges associated with quantification.

Finally, Multi-Criteria Analysis (MCA) or Multi-Criteria Decision Analysis (MDCA) is frequently suggested as an alternative or complement to BCA (Thomopoulos et al., 2009; Van Wee, 2012; Lucas et al., 2016). Since BCA focuses exclusively on monetized values, it often overlooks indicators that are difficult to quantify in financial terms, such as environmental and social values, which limits its ability to address equity issues. In contrast, MCA or MDCA can incorporate a broader range of measurements, including ordinal scores or quantitative levels, and allows for the inclusion of evaluation criteria that specifically address equity considerations.

The methods currently used to consider equity have limitations, particularly in addressing the equity issue from multiple perspectives. Equity should be assessed based on various factors such as demographic features like income, race/ethnicity, and physical disability, geographical characteristics, and transportation modes. From the above-mentioned measurements, it is clear that there is a lack of a detailed analysis framework for equity at multiple levels. For instance, distributional weights primarily address income disparities, and the term "disadvantaged population"—a key focus in equity analysis—blends criteria from income, race, and disability, which dilutes the granularity of the analysis. Moreover, methods for analyzing geographical distribution are seldom discussed.

Table 2 - Summary of Literature on Sensitivity and Equity/Distributional Analysis

Type of Analysis	Papers
Sensitivity Analysis	Wang et al. (2005), Boarnet et al. (2008), Williges and Mahdavi (2008), Salling and Leleur (2011), Lawrence et al (2018), Zahed et al. (2018), Chi and Bunker (2021), Österle et al. (2022)
Equity and Distributional Analysis	Thomopoulos et al. (2009), Van Wee (2012), Adler (2016), Lucas et al. (2016), Martens and di Ciommo (2016), Pereira et al. (2016), Robinson et al. (2016), Nurmi and Ahtiainen (2018), Litman (2024)

1.6 Alternative Methods

BCA is the most commonly used method in transportation planning. However, there are alternative methods such as multi-criteria analysis (MCA) or multi-criteria decision analysis (MCDA), economic impact analysis (EIA), and cost-effectiveness analysis (CEA), fiscal/financial impact analysis (FIA), and computable general equilibrium models (CGE). The following section explains these methods, detailing their roles as well as their advantages and disadvantages compared to BCA.

1.6.1 Multi-Criteria Decision Analysis (MCDA)

MCA or MCDA is a method conventionally used alongside BCA to evaluate transportation policies or planning. MCA and MCDA are often considered either substitutes for or complements to BCA. The advantages and disadvantages of these methods are notable. BCA is regarded as an objective and neutral decision-making tool because it converts all variables into monetary terms and presents results in terms of NPV or BCR. This approach facilitates communication among decision makers and other authorities and simplifies the comparison of different alternatives. However, BCA predominantly focuses on monetized aspects and often fails to capture non-economic factors, such as environmental and social impacts, thus limiting its effectiveness in assessing sustainable transport policies (Marleau Donais et al., 2019).

MCA or MCDA, on the other hand, involves stakeholders directly in the decision-making process through qualitative methods like interviews, surveys, and group workshops. It selects parameters based on the project's objectives to evaluate the project, which helps decision-makers understand how well each alternative meets the policy goals (Marleau Donais et al., 2019). This method accommodates non-monetary and intangible aspects, and can also incorporate equity-related criteria as described previously (Thomopoulos et al., 2009; Van Wee, 2012; Lucas et al., 2016) Nonetheless, direct stakeholder participation can be both a benefit and a drawback. Since parameter selection is influenced by stakeholders' objectives and preferences, the evaluation can be criticized as arbitrary and subjective. Additionally, the possibility of double-counting impacts is a significant concern; poorly defined parameters can lead to multiple measurements of the same impact (Lucas et al., 2016; Marleau Donais et al., 2019).

1.6.2 Economic Impact Analysis (EIA)

EIA, or input-output analysis, is a popular economic analysis method that measures the economic changes that projects or policies induce in a specific region, such as the change in income, employments, business sales, or tax revenue (Weisbrod & Duncan, 2016; Weisbrod et al., 2016). This analysis allows analysts to demonstrate the legitimacy of a project by assessing the economic impacts within a specific region, industry, or market. Both BCA and EIA quantify impacts in monetary terms. However, the primary difference lies in the geographic scope of the analysis: BCA considers impacts on both users and non-users of transportation infrastructure, while EIA focuses solely on changes in economic activity within a specified region (Weisbrod &

Grovak, 1998; Weisbrod & Duncan, 2016). EIA is typically conducted through input-output modeling and regional economic impact modeling.

As the scope of impacts included in BCA has expanded, the distinction between BCA and EIA has become increasingly blurred. Originally, BCA and EIA were designed for different purposes, but over time, their areas of focus have begun to overlap (Weisbrod et al., 2016; Weisbrod & Duncan, 2016). For instance, since BCA initially concentrated on the impact of travel time savings, it faced challenges in adequately assessing rural projects designed to foster economic growth through improved transportation connectivity. As a result, BCA started incorporating broader economic impacts, such as statewide business cost savings (Weisbrod & Duncan, 2016).

Despite these overlaps, the economic impacts measured by BCA and EIA are fundamentally different. Specifically, the economic impact in BCA includes only the direct effects on GDP, whereas the economic impact measured in EIA encompasses direct, indirect, and induced impacts, collectively referred to as multiplier effects (Weisbrod et al., 2016). Because both methods use similar terminology, analysts and decision-makers can sometimes confuse them, often referring to these impacts as 'wider economic benefits/impacts' (Lakshmanan, 2011; Weisbrod et al., 2016). Therefore, it is crucial to clarify the definition of "economic impact" in both methods. When this distinction is unclear, there is a risk of double counting impacts.

1.6.3 Cost Effectiveness Analysis (CEA)

CEA is commonly used to evaluate the efficiency of specific programs or policies (Browne & Ryan, 2011; Michelly Gonçalves Brandão et al., 2023). The aim of CEA is to determine whether the intended goals of a project are achieved at the lowest possible cost (Browne & Ryan, 2011). The outcome of CEA is expressed through a cost-effectiveness index, calculated by dividing the PVC by the result achieved by the programs or policies. For example, if the project's objective is to reduce the number of crashes, the denominator in this calculation would be the number of crashes reduced (Lawrence et al., 2018). In CEA, costs are measured in monetary values, while benefits are quantified in natural units, making it suitable for targets where benefits are challenging to convert into monetary terms (Lawrence et al., 2018). However, as the analysis process reveals, benefits must be defined in a very specific and narrow manner (Browne & Ryan, 2011). Thus, projects requiring the consideration of a broad range of benefits might find CEA limiting.

2 Transportation BCA Best Practices Review

2.1 United State Context

BCA is a key decision-making tool for transportation practitioners in the U.S., particularly for evaluating the viability and efficiency of infrastructure projects (Sallman et al., 2012). Practically, BCA is used to assess whether the benefits of a transportation project, such as reducing travel time, improving safety, or lowering emissions, outweigh the costs, which can include construction, operation, and maintenance expenses. Agencies like the USDOT and state transportation departments rely on the BCA framework for several reasons. First, it provides a systematic process for evaluating the economic feasibility of infrastructure projects by comparing the anticipated benefits and costs over a defined period (AECOM, 2021b; USDOT, 2023b). Second, the framework assists in decision-making by offering an objective assessment of whether, when, and which projects or strategies should be implemented to optimize resource allocation (Findley et al., 2007). Lastly, BCA helps ensure accountability and transparency in transportation project investments by presenting clear, reproducible analyses for funding decisions (Commonwealth Transportation Board, 2024; Fitch et al., 2022). While BCA is a critical and systematic tool for evaluating projects, it is not always the sole determinant in decision-making; rather, it is often used alongside other criteria such as environmental justice, community impact, and political priorities to ensure a comprehensive assessment of transportation investments (Lawrence et al., 2018).

The operation of BCA varies across different regions, reflecting local priorities, funding mechanisms, and transportation needs. Each state or region might adopt specific guidelines or methodologies tailored to local circumstances, though federal guidance from agencies like the USDOT, the Federal Rail Association (FRA), and the FHWA ensures some level of standardization (Federal Railroad Administration, 2016; Lawrence et al., 2015; USDOT, 2023b). Regional planning agencies, Metropolitan Planning Organizations (MPOs), and state departments conduct BCAs in accordance with both federal and state criteria.

The types of transportation projects subjected to BCA are diverse, ranging from road expansions, highway improvements, and bridge replacements to public transit investments, bicycle and pedestrian facilities, and airport or port enhancements. Policies related to tolling, fuel efficiency standards, and emissions reduction strategies can also be subjected to BCA. Any project or policy with significant long-term impacts, especially those requiring federal funding, typically undergoes this analysis to determine if it aligns with national or regional transportation goals (USDOT, 2023b).

BCA in the U.S. transportation sector is often conducted using sophisticated models and tools depending on project and policy types. Since these tools typically require high levels of accuracy and rigor, some agencies and private companies have developed one-off BCA frameworks suitable for specific projects, while others have developed more complex tools that are updated regularly (Behr, 2020; Lawrence et al., 2015). For example, federal agencies such as the FHWA distribute standardized software such as BCA.net and Tool for Operations Benefit/Cost (TOPS-

BC), and some states like California, Colorado, and Virginia develop their own BCA framework or adapt federal ones for their own use (Colorado Department of Transportation, 2021; Commonwealth Transportation Board, 2024; Fitch et al., 2022). Additionally, some states and regions may also commission private sector enterprises to conduct benefit-cost analysis for their specific projects.

2.1.1 Framework Rules

In practice, BCA frameworks generally follow a structured and methodical approach to standardizing how transportation projects are evaluated. This ensures consistency and comparability across different scenarios.

First, the discount rate converts future costs and benefits into present values. Federal guidance has changed over time. The 2024 USDOT BCA Guidance recommended a 3.1% real discount rate for discretionary grants[4], while the FY 2026 guidance specifies 7%, following OMB Circular A-94 (USDOT, 2024; USDOT, 2025; OMB, 1992). OMB Circular A-4 applies to federal regulatory analysis rather than USDOT grants. Its 2023 revision was revoked in 2025, restoring the 2003 guidance, which recommends evaluating regulatory benefits at both 3% and 7% (OMB, 2003). State agencies may adopt different rates, such as the 4% rate used in California's 2022 Cal-B/C guidance (California Department of Transportation, 2022), and 7% rate used in others states like Missouri, New York, and Oklahoma.

Second, common metrics used to summarize the results of BCA include NPV, BCR, and internal rate of return (IRR) as described in more detail in the previous literature review chapter. Among those measurements, NPV and BCR are commonly used in the U.S., either alone or together, while IRR is rare in the U.S. context. Lastly, the analysis period is a crucial aspect of transportation BCA. This period refers to the time over which the costs and benefits of a project are assessed, often ranging from 20 to 30 years or more, depending on the project's expected lifespan. For instance, FRA recommends 40 years as the period due to not only uncertainty of market and travel behaviors changes but also heavily discounted dollar calculations (Federal Railroad Administration, 2016). Most states' benefit-cost analysis period falls within a similar range in accordance with the federal guidance.

2.1.2 Contents of the BCA Frameworks

In this review of BCA best practices within the U.S., the research team conducted a comprehensive search of BCA-related materials from federal agencies, state departments of transportation and other sub-state level agencies. While many states and metropolitan planning organizations conduct individual BCA analyses or case studies for transportation projects, not all of them utilize a customized BCA framework. We found examples of BCA frameworks or

[4] The current recommended value of 3% (USDOT, 2023a) is significantly lower than 7%, which was the USDOT's recommended discount rate since the 2003 edition of Circular A-94.

individual BCA analyses for projects or policies in 27 states (See Figure 1). Some states such as California, Oregon, Florida, and Washington have their own state-specific BCA frameworks or methodologies, while others like Tennessee, New Jersey, Michigan, and Connecticut perform individual case studies or analyses of their projects using a standardized BCA framework, often related to federal funding applications. Other states marked as 'not available' refer to states where no BCA framework or case study could be found and unavailable websites.

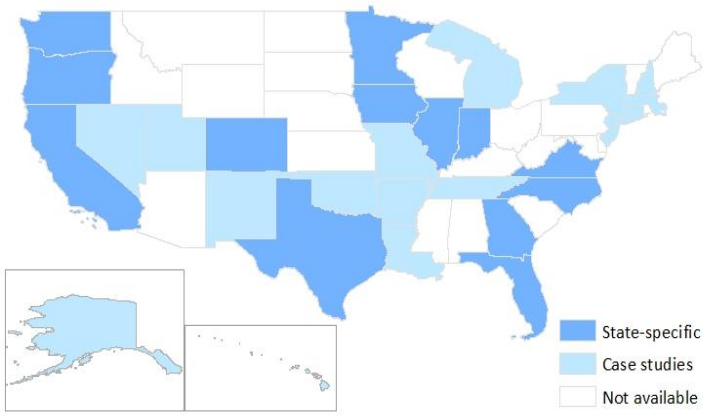


Figure 1 - BCA frameworks or case studies by state

A. Modes of Transportation

The BCA frameworks employed by various entities—federal agencies, state DOTs, and MPOs—are mostly used to assess transportation projects. These projects typically include infrastructure construction, expansions (extensions), improvements, and other policies. In general, the projects usually address automobile-focused infrastructure (highway, interstate, roads, etc.), but may also encompass a broad range of transportation modes, including public transit, rail, and non-motorized transportation.

At the federal level, agencies like USDOT and its sub-agencies use BCA frameworks that explicitly include multimodal transportation projects. Programs such as Rebuilding American Infrastructure with Sustainability and Equity Grant Program (RAISE) and Nationally Significant Multimodal Freight and Highway Projects Grants Program (INFRA) allocate funding to projects across various modes, not just highway or automobile-focused infrastructure (USDOT, 2023b). For example, BCAs for rail projects through FRA focus on benefits such as reduced freight congestion, improved passenger rail services, and decreased emissions, compared to automobile travel or trucking (Federal Railroad Administration, 2016). Moreover, aviation projects are also subject to BCA, particularly by the Federal Aviation Administration (FAA), which uses the framework to evaluate improvements to air traffic control systems and airport expansions (Federal Aviation Administration, 2020).

State DOTs also regularly apply BCA frameworks that account for a wide range of transportation

modes. Many state DOTs oversee both highway and public transit systems. In states like New York, the New York State Department of Transportation (NYSDOT) utilizes a BCA framework that places a strong emphasis on multimodal transportation. Given the complexity of New York's transportation network, which includes extensive urban transit systems like subways, commuter rail, and ferries, NYSDOT's BCA framework is designed to assess projects across these modes (NYSDOT, 2023). In Texas, the Texas Department of Transportation (TxDOT) has a BCA framework that is particularly focused on balancing the needs of freight transportation, highways, and transit systems. Given Texas's role as a major transportation hub for both commercial and passenger traffic, their BCA framework addresses projects that support economic growth by improving freight rail and highway systems, as well as urban transit projects like bus rapid transit (BRT) and light rail (AECOM, 2021b).

A few MPOs integrate BCA frameworks that prioritize multimodal projects. North Central Texas Council of Governments (NCTCOG), which oversees the Dallas-Fort Worth area, applies BCA in its evaluations of highway, transit, and freight projects. In practice, for example, it examined the Tower 55 intersection of two main railroads crossing at grade in terms of travel savings, costs, and environmental impacts (HDR, 2009). Similarly, the Puget Sound Regional Council (PSRC) in Seattle adopts a BCA framework designed to evaluate the economic, environmental, and social impacts of expanding its Sound Transit light rail network and other transit projects. PSRC's customized BCA tool focuses on estimating benefits and costs of public transit projects (Puget Sound Regional Council, 2009).

B. Commonly Used Parameters

In both practice and academic literature, benefit and cost parameters in transportation BCA share several core elements. For instance, both approaches typically consider direct benefits like travel time savings, reduced vehicle operating costs, safety improvements (e.g., fewer traffic incidents), and environmental benefits (such as reduced emissions). Costs, similarly, include common elements such as capital expenditures, operating and maintenance costs, and sometimes user costs like delays during construction. These parameters form the backbone of BCA in transportation practice across federal agencies, state DOTs, and MPOs, as well as in academic research. Government agencies often rely on quantifiable and readily measurable parameters from analytical software and tools in practice, such as time savings or traffic incident reductions, which can be easily integrated into policy decisions and project prioritization (Lawrence et al., 2015; Sallman et al., 2012). We explore the frequently used cost and benefit parameters in the following discussion.

Costs

In practice, cost parameters are standardized to ensure consistency and comparability across projects. These parameters typically focus on quantifiable, monetized costs associated with constructing, operating, and maintaining transportation infrastructure, and are directly tied to real-world budgeting, funding decisions, and resource allocations (Federal Railroad Administration, 2016). Transportation agencies at the federal, state, and local levels typically operate within strict financial constraints and must ensure that projects are financially viable and justifiable to taxpayers, policymakers, and stakeholders.

Capital Costs

Capital costs represent the initial expenses involved in planning, designing, and constructing a transportation project. This includes costs for land acquisition, materials, labor, and the equipment necessary to build roads, bridges, railways, or other infrastructure. Agencies use detailed cost estimates for each phase of the project, often with built-in contingencies to account for uncertainties in the project's scope or unexpected costs (often around 10-30%). For example, STV (2022) and AECOM (2019) included contingency capital costs of 15 and 25 percent in their analyses, respectively.

Operating and Maintenance (O&M) Costs

O&M costs, incurred over the lifespan of a project, cover regular repairs, upkeep, and administrative operations. Operating costs include expenses related to managing and running the infrastructure, such as staffing, utilities, and administrative functions. Maintenance costs cover the upkeep of the infrastructure, including regular repairs, resurfacing, inspections, and upgrades to ensure safety and functionality. Unlike capital costs, O&M costs are spread over many years and fluctuate based on infrastructure usage, environmental conditions, and technological changes compared to the base case. They can significantly impact the long-term financial sustainability of a project, making them key considerations in lifecycle cost analysis (Missouri Department of Transportation, 2020; USDOT, 2023b).

Rehabilitation and Replacement Costs

Rehabilitation and replacement costs involve expenditures required to restore, upgrade, or replace infrastructure as it ages or becomes obsolete. Rehabilitation includes activities such as resurfacing roads, reinforcing bridges, or upgrading transit vehicles to extend their useful life and maintain performance standards. Replacement costs refer to the complete replacement of infrastructure components at the end of their useful life, such as replacing an old bridge or repaving a deteriorated highway. These costs tend to be periodic and are incurred at intervals throughout the lifecycle of the project. They are calculated based on the expected life span of infrastructure components and typically involve major works such as bridge deck replacements or roadway overhauls (Federal Railroad Administration, 2016; Minnesota Department of Transportation, 2005).

Remaining Costs

Remaining costs, also known as residual value, refer to the value of the infrastructure at the end of the analysis period. If a transportation project has a lifespan longer than the analysis period (often 20-30 years), its residual value represents the net worth of the infrastructure that can still provide benefits beyond the evaluation period. Typically, residual value is treated as a negative cost (or a benefit) in BCA, as it reflects future value and reduces the net cost of the project. By considering remaining costs, agencies can assess the future value of their investments and make informed decisions about asset management and decommissioning. For estimation, the depreciation approach is commonly used to estimate

remaining costs, which are especially relevant for long-lived assets like bridges, rail lines, or tunnels (Nevada Department of Transportation, 2023; USDOT, 2023b).

Benefits

Just as the academic literature crucially addresses benefit parameters, BCA in practice also includes a wide range of benefit parameters used to quantify the positive impacts of transportation projects. These parameters typically capture the economic, safety, and environmental benefits that result from improved transportation assets. In many cases, the general components have similar definitions, calculation methods, and usage to those described in the academic literature. The most commonly utilized benefit parameters in practice include travel time savings, vehicle operating cost savings, safety improvements, and environmental benefits.

Travel Time Savings

Travel Time Savings is a parameter representing the reduction in time that users spend traveling as the result of improvements in the transportation infrastructure. These savings arise from projects that increase road capacity, improve traffic flow, or enhance public transportation systems, thereby reducing delays, congestion, or travel distances.

Depending on the type of project or policy, the Travel Time Savings parameter is typically characterized by several components, including the value of time, vehicle occupancy, and travel time reliability, and the savings can be converted into monetary terms by assigning a value to the time saved. The value of time (VOT) reflects how much individuals or businesses are willing to pay to save time, and it varies based on factors like trip purpose (e.g., work-related, leisure, or personal) and income levels. Vehicle occupancy is also considered, referring to the number of people in a vehicle, including both drivers and passengers. For example, the time saved for a vehicle carrying multiple passengers has a greater aggregate value than for a vehicle with a single occupant, as the benefits multiply as the number of people experiencing the time savings increase. Reliability is also a key component, highlighting the value of consistency and predictability in travel times. Reliability improvements are particularly valued in BCA because they reduce uncertainty, allowing travelers and businesses to plan trips more accurately and reduce buffer times, which is especially important for freight operations and time-sensitive activities.

Estimating the VOT parameter involves several steps, starting with measuring the current travel times under existing conditions and predicting the reduced travel times under future conditions after the transportation project is completed. Once travel times are estimated, these savings are monetized by assigning a value to time. USDOT and many state DOTs provide standardized values in their BCA guidelines. The values of VOT, vehicle occupancy, and reliability across agencies and DOTs guidelines vary depending on trip purposes, locations, transportation modes, and other elements like peak time (AECOM, 2021b; California Department of Transportation, 2022; Cambridge Systematics, 2014; Federal Railroad Administration, 2016; Sound Transit, 2015; USDOT, 2023b).

Vehicle Operating Cost Savings

Vehicle Operating Cost Savings is a parameter that indicates the reduction in the costs incurred by vehicle owners and operators due to improved transportation infrastructure. These costs include fuel consumption, maintenance, tire wear, and vehicle depreciation, as well as transit-related maintenance and labor costs. In terms of measuring savings, vehicle operating costs are influenced by several factors, including road conditions, traffic speeds, vehicle type, and driving behavior. For example, poor road conditions with potholes or rough surfaces increase fuel consumption, wear and tear on tires, and overall vehicle maintenance.

The estimation typically uses variables such as fuel efficiency, maintenance requirements, vehicle type (e.g., passenger cars, trucks), and driving conditions (urban or rural). For auto-vehicle-related projects, practitioners often rely on standardized cost-per-mile estimates and models that account for changes in road conditions, traffic flow, and vehicle performance to calculate expected savings. By making transit faster, more reliable, and less expensive to operate, agencies can also estimate the additional benefit of attracting new transit riders, particularly those who chose to substitute private vehicles with public transit. The direct savings in public transit operating expenses can also be incorporated in this category. For example, the San Francisco Municipal Transportation Agency evaluated operating cost savings for its transit priority project using hourly costs of $197.16 for diesel buses and $164.34 for trolley buses, combining the resulting transit operating cost savings with automobile VOC savings (SFMTA, 2015).

Federal and state transportation agencies like USDOT and state DOTs provide standardized methods and cost-per-mile estimates for different vehicle types. For instance, USDOT provides estimates for operating costs per mile for light duty vehicles and commercial trucks ($0.52 and $1.32 per mile, respectively). The parameter is often represented as a value of vehicle miles traveled (VMT) reduction. The estimation typically starts by calculating baseline operating costs under existing conditions, then adjusting those costs based on the expected improvements in road conditions and traffic flow resulting from the project (California Department of Transportation, 2022; HNTB, 2022; Sound Transit, 2015; USDOT, 2023b).

Safety Improvements

Safety Improvements refer to the reductions in crashes, injuries, and fatalities resulting from transportation projects designed to enhance road safety. This parameter stems from an improved outcome achieved through various means, including better road designs, traffic calming measures, improved signage, enhanced traffic control systems, and the introduction of safer modes of transportation.

Estimating the benefits of safety improvements involves calculating the expected reduction in crashes, injuries, and fatalities due to the proposed transportation project. Injury severity scales, such as the KABCO scale and the Maximum Abbreviated Injury Scale (MAIS), are used

primarily to categorize injuries and assign monetary values based on medical costs, lost productivity, and quality of life impacts. The KABCO scale classifies injuries from fatal (K) to no injury (O), while the MAIS provides a more detailed classification, ranging from minor injuries (MAIS 1) to fatal injuries (MAIS 6).[5] In addition to these scales, a wide range of modeling approaches, such as the Interactive Highway Safety Design Model (IHSDM) or the Grade Crossing Accident Prediction System (GXAPS), and Crash Modification Factors (CMFs), are used to predict the expected reduction in crashes due to safety interventions. Based on these scales such as KABCO or MAIS, overall savings by severity and crash types are monetized by multiplying them with the Value of Statistical Life (VSL) (Federal Railroad Administration, 2016; Lawrence et al., 2018; URS, 2006; USDOT, 2023b).

Emission Reduction Benefits

Emission reduction benefits are a critical aspect of environmental benefits, reflecting the positive impacts of reducing harmful emissions, such as greenhouse gases (GHG), nitrogen oxides (NOx), sulfur dioxide (SO2), and particulate matter (PM). This emission reduction often accounts for either improvements in vehicle technology (e.g., electric buses, hybrid cars) or reductions in traffic congestion that decrease fuel consumption. Shifting travelers from private vehicles to public transportation or non-motorized modes like cycling or walking are also accounted for in emission reductions.

The calculation of emission reduction benefits involves quantifying the reduction in harmful pollutants as the result of transportation projects and assigning a monetary value to these reductions. On one hand, for estimating GHG reductions, the Social Cost of Carbon (SCC) is often used to value the benefits of reducing carbon dioxide (CO2) emissions. The EPA estimates the social cost of GHG (SC-GHG), monetized as future global climate change damages, using integrated socioeconomic, climate, damage, and discounting models at different discount rates. Varying by specific type of GHG (CO_2, CH_4, and N_2O) and emission year, practitioners may apply the corresponding values applied to emission changes to calculate monetary benefits. On the other hand, the benefits of reducing criteria pollutants like NOx, PM, and SO2 are monetized using established per-ton values. These values are based on the health and environmental damage caused by each pollutant. USDOT and other agencies have adopted standardized values for these emission reductions by referencing the monetized values of avoided economic damages by the U.S. Environmental Protection Agency (EPA) (California Department of Transportation, 2022; Colorado Department of Transportation, 2021; Federal Railroad Administration, 2016; STV, 2022; USDOT, 2023b).

[5] The MAIS was developed by the Advancement of Automotive Medicine (AAAM). However, USDOT acknowledges difficulties in getting crash data reported using the MAIS. Therefore, it offers recommended MAIS-based values from the Value of a Statistical Life guidance translating them to KABCO values using the National Highway Traffic Safety Administration (NHTSA)-provided conversion matrix.

C. Less Commonly Used or Emerging Parameters

In addition to the broadly applicable parameters that federal agencies provide, there are less frequently considered benefit and cost parameters that often address indirect or hard-to-quantify impacts. While these costs and benefits tend to be standard across all BCAs, they can still be crucial for certain projects containing specific social, economic, or environmental benefits and costs.

1. **Noise Reduction**: Noise reduction benefits occur when transportation projects lower the exposure of communities to traffic, rail, or airport noise. This is particularly relevant for projects that involve noise barriers, quieter vehicle technologies (like electric buses), or changes in traffic flow that reduce noise levels. The methods for estimating noise reduction benefits are similar to approaches presented in the academic literature, commonly involving measuring changes in decibel levels and translating those reductions into economic benefits such as improved health outcomes and increased property values in affected areas. A simpler approach applies marginal external noise costs per vehicle-mile, differentiated by road or vehicle conditions. However, due to the challenges of quantifying noise pollution, federal agencies have generally recommended qualitative measurements, and we observe few case studies that provide monetized values of noise reduction per VMT by modes (AECOM, 2021a; Federal Railroad Administration, 2016; FHWA, 1997; Rutgers, 2010; USDOT, 2023b).
2. **Public Health Benefits**: Public health benefits are less commonly included in traditional BCAs but are gaining attention as transportation agencies recognize the impact of transportation systems on health outcomes. These benefits mostly include reductions in mortality risks due to increased physical activity (from biking or walking infrastructure), and fewer injuries related to transportation crashes. They remain challenging to quantify comprehensively, and many case studies use induced values from mode changes (STV, 2022; USDOT, 2023b). Sound Transit (Sound Transit, 2015) estimates health benefits from increased walking among new transit riders, assuming 8–15 additional minutes of daily physical activity to be valued at approximately $0.014 per minute in avoided healthcare costs. Similarly, Cal-B/C AT estimates reduced absenteeism benefits from active transportation using a 6% reduction in sick days associated with at least 30 minutes of daily physical activity (California Department of Transportation, 2022). It also estimates mortality reduction benefits using WHO HEAT-based risk reductions of 4.5% for cycling and 9% for walking per 365 annual miles, monetized using a value of statistical life of $11.8 million.
3. **Resilience and Climate Adaptation**: Resilience and climate adaptation benefits are becoming more relevant as transportation agencies focus on creating infrastructure that can withstand extreme weather events and long-term climate change impacts. These benefits can include reduced costs from avoided damage, lower maintenance costs due to more durable infrastructure, and improved reliability of transportation networks during emergencies. Its estimation involves forecasting the potential costs of inaction or infrastructure failure in the face of climate risks (USDOT, 2023b). As a representative case, Hawaii's approach to resilience and climate adaptation in the Hilo

Harbor Pier 4 improvements emphasizes the role of transportation infrastructure in emergency preparedness and recovery. This includes ensuring quick access to relief supplies and minimizing disruptions to the island's critical economic activities, particularly tourism and shipping. By incorporating the likelihood of hazardous events and emergency recovery costs, it calculates benefits associated with a functioning infrastructure as a resilience factor (Hawai'i Department of Transportation, 2014).

4. **Facility and Vehicle Amenity Benefits**: The Facility and Vehicle Amenity Benefits parameter is derived from improvements made to transportation infrastructure and vehicles that enhance user comfort, accessibility, and safety. By enhancing these aspects, these transportation projects aim to improve overall user satisfaction, encourage higher ridership, and reduce dependence on private vehicles. To estimate this parameter as a benefit, analysts utilize user preferences and willingness-to-pay studies, assessing how much users value the improvements by analyzing real-world choices or hypothetical scenarios that reveal their preferences. Depending on the types of amenity improvements by projects such as widening sidewalks, adding bike lanes, or reducing vehicle crowding on buses and trains, it may be assigned a monetary value by estimating how much these changes improve travel convenience and safety (HNTB, 2022; Oklahoma Transportation, 2023; USDOT, 2023b).
5. **Economic Development (Job Creation)**: The Economic Development (Job Creation) parameter highlights the positive economic impacts of transportation projects through job creation during construction and operation phases, particularly for large-scale infrastructure. These projects not only create direct jobs but also stimulate indirect employment in related industries and induce local economic activity. By improving access to jobs and markets, transportation projects can attract new businesses, enhance productivity, and promote regional economic growth, with economic multipliers used to estimate these broader impacts. For instance, Colorado Department of Transportation (2021) uses fiscal multipliers to estimate the number of jobs created per dollar spent by considering affected industries by transportation planning, ensuring that the economic benefits from job creation in fields such as construction and transportation services are accurately quantified.
6. **Economic Development (Agglomeration Economy)**: Unlike the parameter of job impacts, the Economic Development (Agglomeration Economy) parameter captures the benefits of improved transportation that enhance the clustering of businesses and industries, leading to greater productivity and efficiency across the region. By reducing travel time and improving accessibility, transportation projects foster collaboration, resource sharing, and labor market access, especially in urban areas. These benefits result in lower production costs, increased wages, and long-term economic growth, which contribute to regional competitiveness. Although federal agencies acknowledge the importance of agglomeration economy benefits, we did not find any cases that utilize this parameter. Federal guidance documents suggest utilizing qualitative descriptions (Federal Railroad Administration, 2016; USDOT, 2023b).
7. **Travel Time Reliability**: Travel Time Reliability is often considered as a standalone parameter that measures the consistency and predictability of travel times. Unlike the

parameter that monetizes travel time savings, which focuses on the reduction in overall travel duration, travel time reliability is concerned with minimizing unpredictable fluctuations in travel time. The assumption is that users place significant value on consistent and predictable travel times, and this leads to mode shifts, which reduce congestion, increase transit ridership, and generate benefits by improving overall system efficiency and reducing the need for buffer time in daily travel. A few practical examples employ this, estimating these benefits by calculating the value of reduced uncertainty and using metrics such as the buffer time index (BTI) or the planning time index (PTI) (Commonwealth Transportation Board, 2024; Federal Railroad Administration, 2016; Lawrence et al., 2018; STV, 2022).

Other less commonly used parameters in practice include land use and natural resources impacts. While these emerging parameters are often mentioned in academic literature, individual BCA analyses and case studies in practice often only mention or discuss these parameters. The following describes a few examples of these less common parameters:

- **Natural Resource Impacts** assess the effects of a project on ecosystems, wildlife habitats, and natural resources like water and air quality. These impacts can include degradation or preservation of natural areas and are often monetized through ecosystem service valuation methods. Projects that protect or restore natural resources may receive additional benefits by supporting biodiversity and environmental sustainability (USDOT, 2023b). For example, Federal Emergency Management Agency (FEMA) estimates ecosystem service benefits using land-cover-specific values expressed in dollars per acre per year, accounting for services such as flood risk reduction, air quality improvement, and climate regulation (FEMA, 2022). For wildlife impacts, Nevada Department of Transportation evaluate wildlife crossings and fencing based on avoided wildlife-vehicle collision costs and species-specific conservation values, including an estimated passive-use value of $5,075 per deer collision in 2020 dollars (Nevada Department of Transportation, 2022).
- **Stormwater Runoff** benefits refer to the reduction in surface water runoff caused by transportation infrastructure improvements, particularly in urban areas. Projects that incorporate green infrastructure or better drainage systems can mitigate the negative impacts of flooding and water pollution, leading to long-term environmental and financial savings. These benefits are increasingly recognized in BCAs as municipalities face stricter environmental regulations (USDOT, 2023b).
- **Accessibility Improvements** measure the degree to which a transportation project improves access to jobs, services, and amenities, particularly for underserved communities. Enhanced accessibility can lead to denser, more efficient land use patterns, such as transit-oriented development, which reduces sprawl and promotes more sustainable urban growth. This parameter is often evaluated through improvements in travel time and connectivity for different demographic groups (Commonwealth Transportation Board, 2024).
- **Emergency Service Improvements** focus on the benefits transportation projects offer in terms of quicker response times for emergency services like fire, medical, and law

enforcement. Improved road networks or better public transportation systems can reduce delays, enhance service efficiency, and ultimately save lives. These benefits are important in projects that address congestion or improve access to critical infrastructure (Hawai'i Department of Transportation, 2014; STV, 2022).

- **Property Value Increases** refer to the rise in real estate values resulting from transportation infrastructure improvements, particularly in areas where accessibility and connectivity are enhanced. Increased property values reflect the desirability of living near better transit options or improved roadways, often translating into higher tax revenues for local governments. BCAs may include these benefits as a long-term financial gain for the community (Sound Transit, 2015; USDOT, 2023b).
- **Parking-Related Benefits** evaluate how transportation projects reduce parking demand or enhance the efficiency of parking systems. By encouraging public transportation or active transportation modes (e.g., cycling, walking), projects can lower the need for extensive parking infrastructure, saving both land and operational costs. Parking-related benefits also include reduced congestion and environmental benefits from fewer vehicles circling or cruising for parking spots (Sound Transit, 2015).
- **Quality of Life Benefits** reflect improvements in individuals' daily experiences, such as reduced commute times, increased safety, and better access to essential services. These projects often enhance environmental and health outcomes by promoting cleaner air, lower noise pollution, and encouraging active transportation, leading to improved public health and a more livable urban environment. Additionally, transportation projects that increase mobility for disadvantaged groups contribute to social equity and community cohesion, fostering long-term societal benefits (CH2MHill, 2014; Rutgers, 2010).

D. Sensitivity Analysis

Sensitivity analysis is used to assess how variations in key assumptions, such as travel demand, fuel costs, construction expenses, or discount rates, impact project outcomes. Since these variables are inherently uncertain, sensitivity analysis allows decision-makers to test how changes within a plausible range affect the overall measures. By varying these inputs, agencies can identify potential risks, such as cost overruns or lower-than-expected benefits, and adjust their project designs and evaluations accordingly.

A common focus of sensitivity analysis is the discount rate, as it directly influences the present value of future costs and benefits. Even slight changes in the discount rate, such as testing scenarios with 3% versus 7%, can significantly alter project viability, particularly with benefits or costs that occur toward the end of the analysis period. Additionally, agencies often adjust projections for travel demand or construction costs by 10-20% to assess how these changes affect a project's economic justification.

For example, in the Sound Transit ST3 project BCA, sensitivity analysis examines how varying key factors like discount rates and future demand projections affect the overall benefit-cost ratio. Specifically, the ST3 analysis tests scenarios by adjusting discount rates between 3% and 7%, and by altering demand growth projections by +/- 10%. These changes help to assess how

fluctuations in financial and demand assumptions might influence project feasibility, ensuring that decision-makers are aware of potential risks and opportunities (Sound Transit, 2015). Similarly, NCDOT's Redbook Wizard integrates sensitivity analysis by adjusting variables such as projected traffic volumes and construction costs by up to 20% to test the effects on the project's benefit-cost ratio, providing a clearer understanding of how these critical assumptions influence project outcomes (Findley et al., 2007).

Additionally, other tools like Mosaic, used by the Oregon Department of Transportation (ODOT), apply sensitivity analysis to a wide range of variables, including discount rates, capital costs, and external factors like fuel prices and travel demand. The Mosaic framework allows users to adjust assumptions within its sensitivity testing worksheet, offering insights into how different assumptions about cost, travel behavior, and environmental impacts affect the economic viability of projects (CH2MHill, 2014).

In the US-75 and W 81st Street Interchange project in Oklahoma, sensitivity analysis was conducted by varying key factors such as vehicle delays, pedestrian growth rates, crash modification factors, capital costs, and the project's operational period. For example, a 20% increase in capital costs reduced the BCR from 1.48 to 1.23, while extending the analysis period from 20 to 30 years increased the NPV by 73%. These sensitivity tests allowed Oklahoma DOT to understand how sensitive the project's economic outcomes are to changing assumptions and ensured the project's viability under different scenarios (Oklahoma Transportation, 2023). By incorporating these adjustments, agencies can ensure that their project evaluations are robust under different future conditions, helping to mitigate risks and make better-informed investment decisions.

E. Equity

In the context of BCA frameworks, equity considerations, referred to as distributional impacts or ladder of opportunity, focus on assessing how the benefits and costs of transportation projects are distributed across different geographies and population groups. In other words, equity considerations in BCAs capture the fact that transportation investments do not always equitably benefit or incur costs on regions and people, especially disadvantaged communities, low-income populations, and racial and ethnic minorities. Distributional impacts often include evaluating whether a project improves access to jobs, education, healthcare, and essential services for these historically disadvantaged groups, or whether it imposes additional burdens like noise, pollution, or increased travel costs.

We found very few examples that utilize equity considerations in practice because incorporating distributional impacts into traditional BCA evaluations is complex and requires specific data on how different demographic groups experience benefits and costs. Equity analysis demands additional methodologies, such as geospatial analysis and demographic weighting, which are not always standard in conventional BCAs. Furthermore, the challenge of quantifying social and distributional equity in monetary terms presents additional difficulties for a seamless integration into the BCA framework. Therefore, many agencies recommend either using qualitative descriptions of equity impacts or trying to quantify them by referencing available

external resources such as GROW AMERICA ACT (Federal Railroad Administration, 2016; USDOT, 2023b).

To operationalize equity in BCAs, agencies use tools like equity weighting, which adjusts the valuation of benefits and costs to reflect the distributional effects on various demographic groups. For example, in Virginia DOT's BCA framework, benefits accruing to low-income or vulnerable populations might be weighted more heavily than those benefiting wealthier groups, reflecting the higher social value of improving access for disadvantaged communities (Commonwealth Transportation Board, 2024). Additionally, some agencies use geospatial analyses or equity mapping to visualize how different groups are affected by transportation projects, ensuring that distributional impacts are explicitly accounted for in the BCA calculations. For instance, the Mosaic framework used by the Oregon DOT incorporates equity considerations by requiring the use of geospatial mapping and demographic analysis to assess how benefits like emissions reductions and travel time savings are distributed across different population groups. It evaluates the spatial distribution of benefits and costs, focusing on disadvantaged communities, and ensures that transportation projects address environmental justice concerns (CH2MHill, 2014). By incorporating equity considerations into BCA frameworks, transportation agencies can make more informed and just decisions that promote inclusivity and reduce systemic inequalities in transportation access. However, no standardized methodology or guidance for incorporating equity impacts into the BCA framework exists within the U.S. context.

F. Other Transportation Modes

There is growing attention to non-traditional transportation domains in the BCA framework, such as active transportation, micro mobility, ridesharing, freight, and the like in practice. These modes present unique challenges and opportunities, requiring tailored approaches to evaluate their impact effectively. Although these specific transportation modes are rarely addressed in BCAs, the following discussions highlight the adaptability of the BCA framework to diverse and evolving modes, ensuring that transportation investments can align with broader economic, environmental, and social goals.

Electric Vehicles

The BCA approach to EV deployment requires a multidimensional evaluation of benefits and costs from societal, participant, and utility ratepayer perspectives. It includes key considerations such as the incremental costs of EVs, fuel savings from reduced gasoline usage, maintenance savings, and emissions reductions (MJB&A, 2020; NYSERDA, 2019). For instance, the studies highlight that EV adoption provides significant societal benefits through reductions in GHG emissions and local air pollutants like NOx. These benefits are monetized using metrics such as the Social Cost of Carbon (SCC). In one case study from New Mexico (MJB&A, 2020), the SCC ranged from $41 per metric ton to $79 between 2015 and 2050 with a 3% discount rate. Additionally, the framework examines the impact of EV-related infrastructure development, including costs and benefits of charging stations and smart charging mechanisms to optimize grid usage, reduce peak load impacts, and lower electricity generation costs.

Numerous scenarios can be included in the BCA, including ones that analyze how strategies like time-of-use rates, financial incentives for off-peak charging, and expanded fast-charging infrastructure can mitigate barriers like range anxiety and grid strain. For example, behavior modification scenarios demonstrate that smart charging can reduce utility costs and improve net societal benefits by encouraging EV owners to charge during non-peak hours. One BCA case study in New York (NYSERDA, 2019) revealed that incentivizing off-peak charging through time-of-use (TOU) rates could reduce grid costs by nearly 25% compared to the base case, equating to utility cost savings of $1,200 per vehicle while maintaining customer convenience and environmental benefits. Regional analyses further highlight variations in net benefits based on electricity prices, driving patterns, and infrastructure availability.

Active Transportation

In terms of active transportation projects, we found several examples of BCAs that highlight specific characteristics tailored to non-motorized travel modes like cycling and walking (California Department of Transportation, 2022; Kansas Department of Transportation, 2022). They integrate benefits specific to active transportation such as journey quality improvements, reduced absenteeism, reduced mortality due to increased physical activity, and environmental benefits like reduced emissions. The models emphasize state-specific crash rates and monetized values for safety improvements, applying metrics for crash modification and enhanced mobility for cyclists and pedestrians. The inclusion of parameters such as changes in pedestrian and cycling speeds, mode share, and proximity-based ridership underscores the focus on the user experience and safety impacts of these projects.

Moreover, these frameworks acknowledge additional societal and economic benefits of active transportation, often extending their analyses to areas such as tourism impacts through Economic Impact Analysis (EIA), property value increases, and healthcare cost savings. Specifically, the Kansas Active Transportation Toolkit BCA framework estimates that there are 66,000 annual visitors to the Prairie Spirit Trail, with 80% being day trips and 20% as overnight stays (averaging 2 nights). Based on this approach, Kansas estimates that active transportation related tourism direct expenditures contribute towards economic outputs, jobs, income, and levied taxes in the region. These models are designed with flexible user inputs, allowing localized customization for factors like population growth, facility quality, and operational impacts.

Freight

Freight-related BCAs focus on evaluating the economic implications of highway and intermodal freight improvements, emphasizing factors such as travel time savings, vehicle operating costs, accident reductions, and emissions impacts (California Department of Transportation, 2022; FHWA, 2008). For example, the Cal-B/C model for intermodal freight (Cal-B/C IF) incorporates parameters for analyzing truck and rail operations, accounting for factors like fuel costs, maintenance, and emission rates specific to heavy vehicles. It also evaluates benefits from infrastructure improvements that enhance network efficiency, reduce congestion, and improve travel reliability. These frameworks consider logistics improvements, including supply chain reorganizations and changes in inventory practices, as key components of project benefits.

Freight-specific tools also assess the trade-offs between transportation costs and logistics costs, such as inventory holding and handling expenses, to capture a broader economic perspective.

A distinctive aspect of a freight BCA is its consideration of additive benefits related to improved highway performance. For instance, FHWA incorporated elasticity measures to estimate demand changes based on improvements in performance metrics like travel time reliability and congestion reduction into its TOPS-BC model in 2008 (FHWA, 2008). They estimate that a 10% reduction in delay per mile increases freight demand by 1% in corridors with high volume-to-capacity ratios, based on regional elasticity values. These calculations utilize corridor-specific data like average annual daily truck traffic (AADTT) and delay metrics to determine additive benefits, such as logistics reorganization, which add 13-17% to conventionally measured benefits depending on the region. These analyses often yield region-specific results that reflect differences in freight movement patterns and commodity mixes. Additionally, freight BCAs often integrate advanced modeling techniques, including regression analyses and elasticity estimations, to better understand the dynamic interactions between freight demand, transportation costs, and infrastructure performance.

Emerging Modes

The integration of emerging transportation modes such as micro-mobility, e-scooters, and ridesharing services into urban transport systems underscores a growing need for their inclusion in BCA frameworks. These modes hold the potential to enhance urban mobility, reduce congestion, and contribute to sustainability goals. However, these emerging modes are very rarely accounted for in U.S. BCAs (or even internationally). As a result, despite a wide range of evolving transportation modes, these emerging modes are frequently overlooked in transportation project evaluations, limiting practitioners and decision-makers from fully capturing their societal value and implications.

2.1.3 Best Practices

In this section, we highlight a few state transportation agencies that have developed their own BCA framework, mostly based on adaptation of federal guidelines, and a few example individual analyses examples (case studies) from other agencies. The key difference between agencies that have developed their own BCA frameworks and those that conducted individual case studies lies in the consistency, scope, and replicability of their analyses. By adhering to a unified framework, the agencies that have developed or adapted their own BCA frameworks can streamline decision-making processes and apply a broader perspective to how various projects align with long-term transportation goals, such as environmental sustainability, equity, and economic development. On the other hand, state agencies that conduct individual analysis for projects focus on tailoring the analysis to the specific characteristics and context of a single project, and may allow for more flexibility to account for unique local conditions, stakeholder needs, and project-specific factors that may not fit within a standardized framework. For instance, unique environmental impacts, local economic considerations, or specific community concerns might be explored more deeply in an individual BCA case study, providing a more customized understanding of a project's benefits and costs; these individual BCA case studies

may, on the other hand, be less consistent or comparable with other projects or analyses.

In this following section, we highlight four examples because of their distinct approaches that meet both statewide and project-specific needs. The first two states, California and Washington, developed their own comprehensive, standardized BCA frameworks—Cal-B/C and Sound Transit's ST3 BCA, respectively—which allow for consistent, repeatable evaluations of various transportation projects. These frameworks emphasize long-term sustainability, environmental goals, and regional mobility. In contrast, Utah and Oklahoma's BCAs focus on specific projects—Utah's Westside Express Project and Oklahoma's US-75/W 81st Street Interchange—demonstrating the flexibility of case-by-case analysis that address unique local conditions, such as emissions reductions, safety improvements, and community connectivity.

A. Case 1 (state-level BCA framework): California DOT

Caltrans developed their Cal-B/C framework over the past few decades, covering multiple transportation modes such as highways, transit, active transportation, and intermodal freight (California Department of Transportation, 2022). Since the early 2000s, Caltrans began formalizing its BCA framework, building on federal guidance from agencies like FHWA to create a state-specific approach. Over time, the framework has evolved to integrate advancements in data collection, modeling tools, and policy priorities, such as environmental sustainability and equity, with major updates aligning with legislative changes like SB1 in 2017, which emphasized accountability and performance-based project evaluation. Originating as a model for highway and transit projects, Cal-B/C has expanded over time to accommodate various specialized project types, resulting in a suite of tools tailored to California's diverse transportation needs. This structured framework allows Caltrans to evaluate projects for the State Transportation Improvement Program (STIP), the State Highway Operations and Protection Program (SHOPP), and other grant applications. The models have been continuously updated, with the latest version including detailed parameters for risk analysis, sensitivity analysis, and new types of transportation improvements, reflecting California's unique geographic, economic, and policy contexts.

As seen in Table 1, highway operation parameters are methodologically defined to capture essential factors like traffic capacity and average vehicle occupancy (AVO) in Cal-B/C. AVO values are based on data from the California Household Travel Survey, with separate values for peak and non-peak traffic. For example, the AVO for general non-peak traffic is set at 1.30 occupants per vehicle, while it is reduced to 1.15 occupants per vehicle during peak times to reflect congestion and travel patterns. For High Occupancy Vehicle (HOV) lanes, AVOs are higher, set at 2.15 for HOV 2+ lanes and 3.15 for HOV 3+ lanes, reflecting the higher minimum occupancy requirements. Another critical parameter, the Bureau of Public Roads (BPR) curve, estimates roadway speeds based on the volume-to-capacity ratio (v/c). For instance, the model calculates speed on freeways, with a capacity parameter set at 2,000 vehicles per hour per lane (vphpl) for freeways and expressways. These parameters are integral for accurately modeling traffic flow, speed, and occupancy across different highway types.

The framework includes general parameters that commonly appear in the academic literature

and in practice at other state agencies, such as those for travel time and vehicle operating costs, to standardize project evaluations across transportation types. Travel time values, for example, are based on the USDOT's VOT guidelines and are adapted to California's specific wage data. For in-vehicle personal travel, Cal-B/C uses a VOT of $16.20 per hour for passenger vehicles, reflecting 50% of the average wage rate, as well as a higher VOT of $35.90 per hour for truck drivers (aligning with VOT parameters of average hourly wages from 2021 USDOT guidelines). Vehicle operating costs are divided into fuel and non-fuel components. Fuel costs are calculated based on fuel consumption rates, with prices set at $3.81 per gallon for gasoline and $3.87 per gallon for diesel. Non-fuel costs for passenger vehicles, which include maintenance, repair, and depreciation, are estimated at $0.356 per mile, while the non-fuel cost for trucks is slightly higher at $0.44 per mile. These parameters provide standardized measures for assessing operational costs and travel efficiencies across projects.

Cal-B/C also incorporates accident and emissions cost parameters to address the safety and environmental impacts of transportation projects. Accident costs are based on incident data from state and federal sources. For example, the average cost per fatal highway crash event is valued at $11.8 million, while the cost per incapacitating injury is $536,800. Emissions parameters include rates for pollutants like CO, NOx, PM10, and VOCs, with separate values for urban and rural areas in California. For example, the cost per ton of CO emissions in the Los Angeles/South Coast area is set at $170 in 2021 dollars per ton, given the high public health impact in densely populated regions. For greenhouse gases, the model uses a social cost of carbon of $48 per ton of CO2 equivalent, with a built-in annual growth rate of 2% to reflect increasing future damages from emissions.

Specific Cal-B/C models contain distinct parameters designed for targeted project types, such as freight efficiency improvements or reduced absenteeism benefits from active transportation projects. The Cal-B/C IF (Intermodal Freight) model includes parameters for calculating shipping cost savings, where freight time savings are valued based on average hourly wages for logistics workers and operational costs for freight trucks. For instance, a truck's VOT in freight contexts can be set at $22.40 per hour per vehicle-mile, adjusted for cargo value and time-sensitive deliveries. In active transportation projects under Cal-B/C AT, parameters like absenteeism benefits are included to measure the health and productivity gains from physical activity. The absenteeism parameter assumes a reduction in sick days based on increased activity levels, valued using California's average wage rate, which is approximately $32.44 per hour in 2021 dollars. These specific parameters are meticulously defined to ensure that Cal-B/C accurately captures the unique benefits and costs associated with each project type.

Table 3 - Parameters in California BCA framework

Parameter Category	Description	Value/Details
Discount Rate		4% (3% and 7% tested for sensitivity analysis)
Average Vehicle	Distinct averages applied for	Peak: 1.15; Non-peak: 1.3; HOV 3+:

Occupancy	peak/non-peak hours and HOV/HOT lanes	3.15; HOV 2+: 2.15; Trucks: 1.0
Bureau of Public Roads (BPR) Curve	Models speed-volume relationships	Alpha (Freeway/Expressway): 0.20; Beta: 10; Capacity per Lane: 2,000 vphpl
Capacity per Lane	Standard capacities for different road types	Freeways/Expressways: 2,000 vphpl; Conventional Highways: 800 vphpl; HOV/HOT Lanes: 1,600 vphpl
Maximum Volume-to-Capacity (V/C) Ratio	Limits V/C ratio to maintain realistic speed estimates on congested roads	Capped at 1.56
Percent Average Daily Traffic (ADT)	Differentiates traffic by day in peak and off-peak hours	Weekday travel: 70%; Weekend travel: 30%
Percent Trucks	Estimates truck traffic proportion	9% statewide default
Value of Time (VOT)	Personal travel at 50% of average wage, trucks at 100% of average wage	Automobiles: $16.20/hr; Trucks: $35.90/hr; Composite: $22.40/hr
Fuel Costs	Based on 2021 averages from the American Automobile Association (AAA)	Gasoline: $3.81/gal; Diesel: $3.87/gal
Non-Fuel Costs	Costs of maintenance, repair, tires, and vehicle depreciation for Automobile	Maintenance: 9.55 cents/mile; Depreciation: 26.0 cents/mile
	Costs of maintenance, repair, tires, and vehicle depreciation for Truck	Maintenance: 11.9 cents/mile; Tires: 3.4 cents/mile; Depreciation: 28.0 cents/mile
Safety (Crash) Cost	Comprehensive cost approach (USDOT's value of statistical life and injury severity)	Death: $13M; Incapacitating Injury: $536.8K; Non-Incapacitating Injury: $146.2K; Possible Injury: $74.7K; PDO value: $2.9K
Safety (Crash) Cost for Transit	Same approach to cost distributions; Property damage by transit mode	Passenger Train (PDO): $90K; Light Rail (PDO): $14.2K; Bus (PDO): $4.3K
Emissions Costs (Pollution)	Health-related costs vary by pollutants (LA urban)	CO: $90; NOx: $20.3K; PM10: $163.7K; SOx: $81.7K; VOC: $1.415K

		per ton
	Health-related costs vary by pollutants (LA rural)	CO: $80; NOx: $15.1K; PM10: $116.7K; SOx: $59K; VOC: $1.11K per ton
	Social cost of Green House Gas Emission (CO2) with yearly escalation	$48/ton, increasing 2% annually

B. Case 2 (regional-level BCA framework): Washington (Sound Transit)

Similar to the case of Caltrans, the Sound Transit (ST) agency in Washington developed its own BCA framework for the ST3 Regional High-Capacity Transit System Plan (Sound Transit, 2015). This framework is designed to evaluate major rail and transit investments and ensure alignment with regional transportation goals set by the Puget Sound Regional Council (PSRC). The methodology follows a consumer surplus approach, where benefits are derived from travel time savings, cost reductions, and improved mobility for both transit and non-transit users. The analysis includes factors like vehicle operating costs, reduced vehicle collisions, and environmental impacts, providing a comprehensive evaluation of the project's societal benefits.

Table 4 shows all the parameters used in the Sound Transit BCA framework. A key focus of the ST3 BCA is transit user benefits, primarily travel time savings. These savings are calculated based on travel demand models from ST and PSRC, which estimate the reduction in travel time between pre- and post-investment scenarios. The value of time for transit users is based on regional wage rates, with peak-period travel time valued at 60% of the average wage rate, and off-peak travel at 50%. The model also considers mode shifts from auto to transit and the benefits to remaining highway users, such as improved traffic flow and reduced congestion. Non-transit users also gain from reduced vehicle operating costs, accident costs, and travel time savings due to fewer cars on the road.

Environmental and societal benefits are also incorporated into the analysis. Reductions in VMT from auto to transit mode shifts lead to decreased emissions and energy consumption, contributing to cleaner air and lower greenhouse gas emissions. Environmental savings are quantified at average $0.06 per VMT, including pollutants like VOCs, NOx, PM 2.5, and CO2. Health benefits from increased walking to and from transit are also monetized, with assumptions that new transit users walk an additional 8–15 minutes per day, resulting in an estimated $150 annual health benefit per new rider.

The ST3 BCA methodology also accounts for project costs, including initial capital investments, operating and maintenance costs, and periodic rehabilitation. These costs are discounted at a real rate of 3%, which is consistent with federal guidance for evaluating long-term infrastructure projects. The evaluation period covers 40 years of operation, and sensitivity tests are conducted to assess the potential impacts of extending the evaluation period or adjusting the discount rate. Overall, the framework ensures that transit investments are evaluated rigorously, emphasizing regional mobility, environmental sustainability, and economic efficiency.

Table 4 - Parameters in Washington BCA framework

Category	Description	Value/Details
Discount Rate		3.00%
Evaluation Period	Stage 1 - Primarily Construction	2021-2028 (No benefits in this stage)
	Stage 2 - Partial Operations & Benefits	2029-2032 (Escalating partial system benefits)
	Stage 3 - Full Operations & Benefits	2033-2072 (Full rail benefits accrue)
Growth Rate	Real Benefits Growth Rate	Linear ramp-up 2029-32; model interpolated or extrapolated rates 2033-72
	Real Wage Growth Rate	1.0% per year
	Real O&M Cost Growth Rate	Per ST3 Financial Plan 2021-32; 1.3% per year 2033-72
Transit Travel Time Savings	Consumer surplus calculation from ST model outputs	-
Transit User Time Savings	Peak (Commute) Trips	Value of time = 60% of average wage rate
	Off-Peak (Non-Commute) Trips	Value of time = 50% of average wage rate
Vehicle Operating Cost Savings	Monetized value per mile for operating cost savings	19 cents (per mile)
	Monetized value per mile for reduced usage (ownership)	32 cents (per mile)
	Monetized value per mile for reduced vehicle (ownership)	11 cents per mile (applied to 10% of VMT reduction)
Accident Costs	Fatal Damage - 0.39 – 2.41 rates (per 100 million VMT)	$4,677,900 / accident
	Injury Damage - 32 – 118 rates (per 100 million VMT)	$28,900 - $237,100 / accident
	Property Damage - 70 – 215 rates (per 100 million VMT)	$9,200 / accident

Environmental Cost Savings	Per VMT	VOCs: $0.002; NOx: $0.012; PM2.5: $0.01; CO2: $0.02; Noise: $0.001 Average for autos: $0.06
Costs	Initial Project Investment	Estimates provided by ST
	Regular Operating & Maintenance	
	Periodic Replacement & Rehabilitation	
	Residual Value	
Sensitivity	Analyses of scenarios depending on increase/decrease parameters (benefits, initial capital costs, discount rate) and assumption change (analysis period, real wage growth)	

Table 5 shows that the Washington ST Authority and Caltrans BCA models have distinct parameter sets tailored to their specific regional and policy environments. In Washington's ST model, the framework emphasizes parameters for phased project evaluations, detailing stages from construction to full operational benefits over a multi-decade timeline. It incorporates growth rates in wages and operational costs and offers explicit values for transit user time savings, vehicle operating costs, accident costs, and environmental costs per VMT. Additionally, the Washington model implements sensitivity analysis by adjusting key parameters, including the discount rate and cost growth assumptions, providing a comprehensive outlook on long-term transit benefits and costs.

Conversely, the Caltrans model in California incorporates a more extensive breakdown of traffic and safety-related parameters, reflecting the state's emphasis on diverse transportation modes and emissions. For instance, it includes distinct vehicle occupancy rates for peak and off-peak hours, detailed vehicle operating costs for both automobiles and trucks, and emissions costs for various pollutants. Caltrans also places a high value on safety by including a detailed breakdown of crash costs and health-related costs from pollutants across different urban and rural settings. The California model's focus on fuel costs based on American Automobile Association (AAA) data and its annual escalation of greenhouse gas emissions costs highlights an approach centered on fluctuating economic and environmental factors tailored to environmental policies.

Table 5 - Parameters Comparison Between California and Washington

	California		**Washington**	
Objectives	Toolsets for evaluating investment across transportation projects focusing on diverse modes from highway and transit modes to freight and active transportation		Developing the BCA methodology for the proposed program of transit construction and investments resulting from the major investment plan (ST3)	
Dollar year	2021		2014	
Discount rate	4% (3% and 7% tested for sensitivity analysis)		3%	
Category	Factors	Value/Details	Factors	Value/Details
Trip assumptions	Vehicle occupancy	Peak traffic - 1.15; Non-peak traffic - 1.3 (average number of people per vehicle)	Daily auto and transit traffic	Varies according to the travel demand model's outputs
	Capacity	Freeway & Expressway - 2000; Conventional highway - 800; HOV/HOT lanes - 1600 vphpl	Annualized factors for daily vehicle trips	Peak hour travel - 255
	Maximum ratio of traffic volume per capacity	1.56		Off peak hour travel - 400
	Average daily traffic ratio	70% of weekday; 30% of weekend; 9% of truck travel in ADT		Peak and off peak hour parking - 305
Travel time savings	Value of time for travel savings, derived from hourly wage rate	Automobile and transit - $16.2 per hour	Value of time for travel savings by modes, derived from hourly wage rate	(Transit user) Peak hour - $15.47; Off peak hour - $12.89 per hour
		Trucks - $35.9 per hour		(Non-transit user) Peak hour - $15.47; Off peak hour - $12.89 per hour
				(Commercial vehicle) Peak hour

				- $28.99; Off peak hour - $28.86 per hour
Vehicle operation cost savings	Fuel and Non-fuel costs	Fuel costs: Gasoline - $3.81/gal; Diesel - $3.87/gal	Reductions in vehicle operation costs and auto ownership costs, applied to VMT reduction (based on a fuel price of $3.28/gal)	Operating costs: $0.19 per mile
		Non-fuel costs: Autos: $0.356/mile; Trucks: $0.433/mile		Vehicle ownership cost: $0.32 per mile + $0.11 per mile (10% of VMT reduction resulting from lower ownership rates)
Safety benefits	Crash rates by severity and modes (per million VMT)	(Passenger vehicle) Fatality - 0.005; Injury - 0.28; PDO crashes - 0.61; Non-freeway crash rate - 1.04	Collision rates by severity (per 100 million VMT)	(Interstate highway) Fatality - 0.39; Injury - 32.0; PDO crashes - 70.0
		(Transit - Passenger Train) Fatality - 0.0804; Injury - 0.2855; All - 0.3128		
		(Transit - Light Rail) Fatality - 0.2416; Injury - 2.9209; All - 4.1374		(Combined principal & minor arterials) Fatality - 1.21; Injury - 59.0; PDO crashes - 107.5
		(Transit - Bus) Fatality - 0.0372; Injury - 3.5526; All - 2.0523		
	Accident costs per event by severity and modes	(Passenger vehicle) Death - $13M; Incapacitating Injury - $536.8K; Non-Incapacitating Injury - $146.2K; Possible Injury - $74.7K; PDO value - $2.9K	Accident costs per event by severity	Death - $4.538M; Incapacitating Injury - $230K; Non-Incapacitating Injury - $58.7K; Possible Injury - $28K; PDO value - $8.9K
		(Transit - Passenger Train) Same injury distribution; PDO - $90K		
		(Transit - Light Rail) Same injury distribution; PDO - $14.2K		
		(Transit - Bus) Same injury distribution; PDO - $4.3K		

Emission reduction benefits	Emission rates, Emission costs by region	Varies according to emission rates from EMFAC2021 data Health cost of emissions (in CA urban areas): CO - $90; Nox - $20.3K; PM10 - $163.7K; SOx - $81.7K; VOC - $1.415K per ton	Average cost savings by reduction in air pollution	Cost of emissions: NOx - $0.012; PM2.5 - $0.01; VOC - $0.002 per VMT
Climate change	Emission rates, Emission costs	Varies according to emission rates from EMFAC2021 data Health cost of emissions (CO2): $48 per ton (2% annual increase)	Average cost savings by reduction in greenhouse gases	Cost of emissions: CO2- $0.02 per VMT
Noise reduction			Average cost savings by reduction in noise	Cost of emissions: Noise- $0.001 per VMT
Health benefits			Increase in walking time, Value of annual walking time	(Assuming 30 minutes daily): $0.014 per minute

Source: California Department of Transportation (2022); Sound Transit (2015)

C. Case 3 (individual analysis): Utah (Utah Transit Authority)

The HNTB (2022) case study showcases the Utah Transit Authority's (UTA) BCA analysis for the Westside Express Project, evaluating the economic efficiency of the proposed bus transit service on the west side of Salt Lake County. The project is designed to enhance mobility, reduce congestion, and improve access to regional job centers. The BCA model developed for this project follows USDOT guidance, incorporating key factors like ridership, vehicle operating costs, crash reduction, and environmental impacts.

Several benefits are analyzed, such as avoided crashes, operating cost savings, external cost savings, emissions reductions, and travel time savings. For instance, it estimates the reduction in VMT due to increased transit use, which in turn reduces the number of crashes. The avoided crash costs are calculated based on local crash statistics and crash severity rates, while operating cost savings are determined using average vehicle operating costs per mile. External cost savings, which include reduced congestion, noise, and pavement damage, are also factored in, based on unit cost values for each type of impact. The UTA's case also evaluates emissions cost savings by calculating the reduction in pollutants like carbon dioxide and nitrogen oxides as fewer vehicles are used. Emission rates are applied to the avoided VMT, and the resulting reductions are monetized using values provided by the USDOT. In addition to environmental benefits, the analysis incorporates travel time savings, estimating the value of time for both existing and new transit users.

The analysis results for the Westside Express Project concluded with a benefit-cost ratio of 1.29. It highlighted significant economic gains, including $55.2 million in operating cost savings, $27.3 million from avoided crashes, and $14.6 million in external cost savings, alongside additional benefits from emissions reductions and travel time improvements. With a net present value of $14.7 million, the findings underscore the project's economic viability and its potential to enhance regional mobility and environmental sustainability.

D. Case 4 (individual analysis): Oklahoma DOT

The BCA for the proposed multimodal improvements at the US-75 and W 81st Street Interchange in Tulsa, Oklahoma, is designed to assess the economic efficiency of reconstructing the interchange as a Diverging Diamond Interchange (DDI) (Oklahoma Transportation, 2023). This project, proposed by the Oklahoma Department of Transportation (ODOT) and the City of Tulsa (COT), aims to improve traffic flow, safety, and access for both vehicular and non-vehicular users, such as pedestrians and cyclists. The BCA framework, following USDOT guidance, incorporates a 23-year analysis period, with total construction and development costs estimated at $21.8 million in 2021 dollars. The project's benefits include enhanced mobility, improved safety, and reduced congestion, which are monetized for comparison against project costs.

Key benefits evaluated in the BCA include travel time savings, reduced vehicle operating costs, emissions reductions, and safety improvements. Travel time savings are a primary benefit, with the DDI design expected to decrease vehicle delays at the interchange, yielding $17.62 million in

discounted benefits. Vehicle operating costs, mainly fuel savings from reduced idling and delays, contribute an additional $0.70 million in benefits. Emissions reductions, from lower idling times, result in $0.07 million in savings, reflecting decreased VOCs, CO2, and NOx emissions. Safety improvements, particularly the reduction in crashes due to the DDI design, are estimated to provide $1.51 million in benefits. The introduction of pedestrian facilities, currently non-existent at the interchange, will enhance mobility and safety for non-vehicular users, adding $0.82 million in pedestrian-related benefits.

Another important factor in the BCA is the extended lifespan and reduced maintenance needs of the proposed interchange. By replacing the bridges at US-75 with new 70-foot-wide steel structures, the project mitigates the risk of bridge hits, reducing associated repair costs and providing a residual value of $0.93 million for the new infrastructure. These improvements also contribute to long-term savings in maintenance costs, estimated at $1.2 million over the analysis period, discounted at 7%. Additionally, the sensitivity analysis demonstrates that the project maintains a positive Net Present Value (NPV) and Benefit-Cost (B/C) ratio, even under varying assumptions about key factors like vehicle delays and capital costs.

In conclusion, the BCA for the US-75 and W 81st Street Interchange project demonstrates that the proposed improvements will deliver substantial economic benefits, with a B/C ratio of 1.48 and a net present value of $7.0 million. These benefits, derived from improved safety, reduced travel times, and enhanced pedestrian connectivity, significantly outweigh the costs, making the project economically viable and beneficial for the Tulsa region's transportation network.

2.2 Oregon Context

In this chapter, we turn our attention to the Oregon context, exploring how local tools and methodologies, particularly the Mosaic and VisionEval models, can complement the BCA framework being developed as a part of this project. ODOT's Mosaic tool serves as a foundational element for this project, due to the incorporation of BCA concepts in its planning level analysis framework. VisionEval, a transportation modeling tool, can provide essential inputs needed for BCA. Our review of ODOT's existing tools aims to understand and articulate the current capabilities and future enhancement possibilities of the BCA framework. This section will provide a detailed description and discuss the applications of these tools.

To ensure a thorough understanding of each framework, we draw upon specific key materials. For the Mosaic framework, the primary sources include the Mosaic User Guide (CH2MHill, 2014), information available on the ODOT site concerning Oregon Mosaic, and the Mosaic Excel file tool. For VisionEval, we reference the VisionEval User Guide, which is available in a web-based format[6].

[6] VisionEval User Guide, Retrieved from https://visioneval.github.io//docs/index.html

2.2.1 Mosaic Framework

Developed by the Oregon Department of Transportation, Oregon Mosaic is a comprehensive tool designed to streamline transportation decision-making at the system level by evaluating a range of projects and actions collectively. Mosaic is crafted around the goals and policies set forth in the Oregon Transportation Plan (OTP). This framework adopts the principles of Oregon's least cost planning (LCP). Since the original LCP terminology initially caused some confusion, it has since been renamed and refined while still adhering to its foundational principles.

Mosaic stands out by incorporating Multi-Objective Decision Analysis (MODA) alongside BCA. This dual approach allows for the evaluation of both monetized and non-monetized values, providing a more holistic tool for users who may be hesitant to base decisions solely on monetized value metrics. This feature ensures that decisions can reflect a broader spectrum of impacts, akin to looking through both a microscope for detail and a telescope for broader impacts.

The parameters within Mosaic are divided into nine categories: Economic Vitality, Accessibility, Funding/Finance, Environmental Stewardship, Quality of Life, Mobility, Equity, Safety and Security, and Land Use. Table 4 presents a comparison between the indicators used in Mosaic and those suggested by Gossling et al. (Gössling et al., 2019), which were mainly reviewed in the literature review section. Altogether, there are 40 indicators spread across these categories. These indicators are reported in four ways: monetized values, quantitative scoring, qualitative scoring, and report-only formats. However, only a subset of these indicators—13 out of 40—can be expressed in monetary terms and are thus utilized in the BCA component of the analysis. Notably, three categories—Accessibility, Equity, and Land Use— do not include monetized indicators.

Table 6 - Comparison of parameters between MOSAIC and Gossling et al. (2019)

Mosaic Category	Indicators	Gossling Category	Indicators
Mobility	Travel Time (MO1)	Travel time and vehicle operation	Travel Time
	User Costs (MO5)	Travel time and vehicle operation	Vehicle operation
Economic Vitality	Agglomeration benefits (EV4)	n/a	n/a
Environmental Stewardship	Criteria Air Contaminants (ES1)	Environment	Air pollution
	Life-Cycle CO2e (ES3)	Environment	Climate Change
Funding the	Capital Costs (FT1)	Environment	Land Use and

Transportation System/Finance			Infrastructure
	Other Lifecycle Cost (FT2)	Environment	Traffic infrastructure maintenance
	Total Operating Revenue (FT3)	n/a	n/a
Safety & Security	Fatal, Injury A and Injury B Crashes (SA1)	Health, accidents and perceived comfort	Accidents
	Property Damage Only (PDO) accidents (SA2)	Health, accidents and perceived comfort	Accidents
Quality of Life and Livability	Health Benefits of Active Transportation (QC1)	Health, accidents and perceived comfort	Health benefits
	Quality of the Travel Environment (QC2)	Health, accidents and perceived comfort	Perceived safety & discomfort
	Noise Impacts (QC3)	Environment	Noise pollution

The input variables for mobility indicators are mostly derived from the travel demand model. It is essential to thoroughly understand the assumptions and outputs of the model. (Users may utilize local travel demand models for input.) The results from the travel demand model, such as Origin-Destination (O-D) travel data or aggregated travel data, can be used as input. Using this data, Mosaic extracts crucial information such as the number of person-trips per day, average travel time, VMT, and user cost savings. In the Mobility category, monetizable indicators like travel time (MO1) and user costs (MO5) can be calculated using the results from the travel demand model and parameters such as the VOT and vehicle operating costs.

In the Environmental Stewardship category, the BCA includes two indicators, ES1 and ES3, which utilize results from the EPA's MOVES model and the travel demand model. ES1 assesses the impact of VOCs and the six pollutant compounds (NOx, SO2, PM, ozone, CO, and lead) recognized as air contaminants by the EPA. Calculating this indicator requires three components: the emission rate per VMT from the MOVES model, the change in VMT from the travel demand model, and the cost per ton of each pollutant as per the Mosaic model to determine the monetized costs of each pollutant. ES3 (Life-Cycle CO2e) also requires three

components for evaluation: changes in GHG emission rates by vehicle type and VMT through ODOT's Regional Strategic Planning Model (RSPM), and the cost per metric ton as per Mosaic.

The three indicators in the Finance and Funding category—capital costs, incremental O&M costs and other lifecycle costs, and total operating revenues—directly use the estimated life-cycle costs and revenues initially entered by users, without the need for additional tools.

In the Safety & Security category, to estimate the monetized indicators SA1 (Fatal, Injury A, and Injury B crashes) and SA2 (Property Damage only accidents), Mosaic recommends using the planning-level safety sketch tool to estimate the crash rate. Using the safety tool, users determine the crash rate per VMT for each crash category, then multiply this value by the VMT and the cost per incident to calculate the monetized value of the change in total injuries.

The Quality of Life category includes three indicators: QL1 (Health Benefits of Active Transportation), QL2 (Quality of the Travel Environment), and QL3 (Noise Impacts), all of which can be monetized using models from various sources. QL1 assesses the health impacts resulting from increased physical activities, specifically cycling and walking, driven by transportation investments. For this analysis, travel modeling inputs are required to calculate the increase in cycling and walking. Users must also input the number of statistical lives saved due to these activities. However, Mosaic incorporates models to measure changes in these activities, sourced from the UK Department for Transport and CH2M Hill, along with statistical data on lives saved from Oregon Vital Statistics. This allows users to evaluate health benefits without needing to conduct additional analysis.

QL2 quantifies the value derived from enhancements to pedestrian and cycling environments. Users can input improvements such as better lighting and curb adjustments for pedestrian areas, and lane widening or the addition of segregated cycle lanes for cycling infrastructure. These enhancements are then translated into monetized values, using valuation figures provided by the UK Department for Transport. QL3 addresses the impacts of noise by requiring users to input the number of households located within a certain proximity to a transportation infrastructure project. The resulting noise impacts are monetized using data from the UK Department for Transport, providing a monetized value for the noise levels experienced by these households.

The Mosaic tool presents the results of MODA and BCA separately. The BCA results display annual and total monetized values categorized by all benefits and costs, and also include values of NPV, BCR, and IRR derived from these amounts. Indicators that cannot be monetized are assigned a value of zero in the BCA calculations. Conversely, in the MODA results, monetized values are translated into quantitative or qualitative scores and are integrated into the evaluation.

Mosaic features a dedicated category for equity, which encompasses four detailed indicators. However, these indicators yield results only in qualitative scores or as reports, hence they cannot be included in the BCA. The indicators assess distribution across geographic and demographic categories—including urban/rural distinctions, racial and ethnic groups, and

income levels—focusing on transportation time/cost savings, air pollutants, health impacts, and safety impacts. These indicators require qualitative or quantitative analysis to measure how impacts are spatially distributed. For instance, by overlaying a map that highlights the increase in PM due to transportation investments with a demographic map of the same geographic areas, it is possible to pinpoint changes in regions where targeted groups are densely concentrated.

Sensitivity analysis is used to determine whether the results are especially sensitive to certain parameters. The tool allows users to assess how changes in various parameters, such as discount rate, VOT, and social cost of air pollutants, impact the BCR and NPV for each bundle. Users can adjust the "percent change in parameter values" for each parameter individually. This approach ensures that the results specifically reflect the impact of each parameter in isolation.

2.2.2 VisionEval

VisionEval models represent a sophisticated evolution from the initial GreenSTEP suite of analytical tools, initially developed by the ODOT. These models provide robust estimates on the impacts of transportation investments and community development plans on variables such as VMT, energy usage, carbon dioxide equivalent (CO2e) emissions, and the mode split among vehicles, transit, bicycles, and pedestrians. They enable more precise measurement of indicators within BCA frameworks, enhancing the ability to effectively quantify a broader range of impact indicators.

VisionEval is comprised of three distinct models, each designed to cater to specific planning needs and scales:

VERSPM (VisionEval Regional Strategic Planning Model) - Originating from the GreenSTEP model, VERSPM was tailored by ODOT to aid in the preparation of metropolitan area scenario plans. This model primarily functions at the zonal level, making it suitable for regional planning areas and Metropolitan Planning Organizations (MPOs). It expands upon the policies encompassed by state statutory requirements, providing a broadened analytical perspective.

VE-State - This statewide implementation of VERSPM operates similarly at the zonal level but accommodates larger zones suitable for statewide applications. Known as Bzones, these zones are designed to reflect activity density, diversity, and destination accessibility. Common boundaries for Bzones in VERSPM include Traffic Analysis Zones (TAZs), Census Tracts, or Census Block Groups.

VERPAT (VisionEval Rapid Policy Analysis Tool) - Developed under the federal Strategic Highway Research Program (SHRP2), VERPAT utilizes elements from the GreenSTEP model but introduces substantial revisions, including the use of land use place type categories. This model is less spatially detailed than VERSPM and requires inputs at the place type level, making it ideal for evaluating the potential effects of growth policies on regional travel.

The operational scope of these models covers a wide array of drivers and factors. Inputs include

household synthesis (e.g., population by age and employment), land use (e.g., dwelling units and land use patterns), household travel behavior (e.g., transit, biking, walking trips, and parking), vehicle types, fuel types, and emissions, along with economic variables like pricing, household costs, and budgets. Outputs from VisionEval models can illustrate a comprehensive picture of travel impacts, environmental and energy impacts, financial and economic impacts, location impacts, and community impacts. These include metrics like daily VMT, daily vehicle and transit trips, fuel consumption, greenhouse gas emissions, regional accessibility, and the social implications of transportation such as accidents and job accessibility by income group.

Practical Applications of VisionEval

ODOT and the Corvallis Area Metropolitan Planning Organization (CAMPO) employed the RPAT and RSPM tools to evaluate multiple scenarios in two main parts: testing individual policies in isolation and assessing combined policy scenarios (ODOT, 2016). The analysis covered 13 policies categorized into four groups: Land Use, Parking, Supportive Multi-modal, and Transportation Options. For instance, the Land Use category includes policies such as increasing developments in the Central Business District (CBD) and concentrating new developments near alternative transportation modes. The Parking category includes expanding parking districts, increasing parking fees, and introducing cash-out parking programs. The Multi-modal category features increasing transit frequency and expanding bicycle facilities, while the Transportation Options category includes expanding car sharing and promoting teleworking.

The objective was to assess the impact of each policy on regional outcomes related to GHG Emission Reductions, Public Health, Sustainability, and Equity. CAMPO's Technical Advisory Committee (TAC) developed these goals based on the indicators derived from the models' outputs. For example, the public health goal was evaluated through outcomes such as daily air quality pollutants, accident rates, annual social costs, and the diversion of traffic to lighter vehicles or bicycles. The analysis determined that significant changes in the vehicle fleet and the pricing of vehicle travel externalities are crucial for effectively reducing GHG emissions. Furthermore, pricing strategies enhance the effectiveness of multi-modal investments by reducing automobile ownership. Additionally, transit policies are consistently effective in both models for reducing GHG emissions.

The Durham-Chapel Hill-Carrboro Metropolitan Planning Organization (DCHC) utilized the RPAT tool to evaluate the effects of policies such as transit-oriented development (TOD) and smart growth on regional travel behavior (DCHC, 2016). This study aimed to enhance collaborative long-range planning activities and assess policies that had previously been challenging to evaluate, including changes in auto-operating costs, TOD land use policies, and smart growth development.

The analysis was designed to evaluate transportation improvement programs and policy impacts on travel demand, GHG emissions, safety, and economic efficiency. The results demonstrated that RPAT effectively addressed several challenges previously encountered in the Metropolitan Transportation Plan (MTP) process. Specifically, the study compared travel metrics such as VMT per capita, vehicle hours of travel (VHT) per capita, the number of vehicle and

transit trips per capita, and the amount of walking per capita across various scenarios. Additionally, it evaluated cost, safety, and environmental measures, including changes in the number of accidents and GHG emissions. These metrics enable analysts to compare multiple scenarios, assisting in the selection of projects that achieve multiple goals.

Miller et al. (Miller et al., 2022) evaluated the utility of VisionEval in analyzing 43 scenarios for the Virginia Department of Transportation, focusing on their impacts on VMT and CO2e emissions. These scenarios included increasing fuel tax, enhancing carsharing services, and adjusting fuel and electricity prices. The study showcased VisionEval's capability to project environmental impacts from various policy changes, with one scenario achieving up to a 19.6% reduction in emissions through telecommuting, truck electrification, and vehicle electrification strategies. This demonstrates the model's effectiveness in supporting strategic planning and policy analysis, crucial for developing long-term, sustainable transportation strategies.

2.3 International Context

We moved beyond the U.S. to examine how other countries developed and operationalized BCA frameworks for transportation. Internationally, BCA frameworks are widely used to evaluate infrastructure projects, but they often differ from U.S. approaches in terms of scope and emphasis. While the core principle remains the same—comparing costs and benefits to assess the economic viability of projects—many countries incorporate broader social, environmental, and cultural factors into their BCA frameworks. In contrast to the U.S., where BCA often focuses heavily on economic efficiency metrics like travel time savings and vehicle operating costs, international frameworks frequently integrate objectives related to sustainability, equity, and long-term environmental impacts.

In these countries, BCA is often seen as part of a larger appraisal process rather than a standalone tool. This means that while economic benefits remain important, non-monetary factors like public health, carbon emissions reductions, and social inclusivity are also central to the evaluation. These considerations reflect the growing global emphasis on sustainability and addressing climate change, as well as ensuring that transportation investments align with broader societal goals beyond immediate economic returns (Department for Transport, 2023; Sartori et al., 2015). Additionally, international BCA frameworks often emphasize equity and distributional impacts, analyzing how transportation projects affect different social and demographic groups. This may include considerations of how projects benefit rural areas, low-income populations, or marginalized communities, ensuring that infrastructure investments contribute to reducing inequalities. Unlike in the U.S., where equity is becoming more recognized but is not always fully integrated into the BCA process, international practices more consistently account for how transportation benefits and costs are distributed across society (Australian Transport Assessment and Planning, 2023; NZ Transportation Agency, 2020).

2.3.1 Framework Rules

International countries often set up the principles of measurement tools, analysis periods, and discount rates with a broader focus on long-term sustainability, social equity, and environmental externalities compared to the U.S. While both international countries and the U.S. commonly use standard BCA metrics like NPV, BC R, and IRR, we found significant differences in the analysis period and discount rates utilized to estimate present value.

International BCAs tend to use longer horizons, often between 30 to 60 years, particularly for large-scale infrastructure like rail and public transport, compared to the typical 20-30 year analysis period in the U.S. This extended timeframe allows international frameworks to capture the full lifecycle benefits of long-term projects. For instance, the UK's TAG Unit uses a 60-year analysis period for major transport infrastructure projects to ensure a comprehensive assessment of their benefits over time (Department for Transport, 2023; Quinet, 2000).

The discount rates applied internationally are analogous to those applied in the U.S., where a range from 3% to 7% is commonly used. European countries and others like New Zealand and

Australia typically apply discount rates ranging from 3-5%, reflecting a stronger emphasis on intergenerational equity and the long-term societal benefits of projects, especially in relation to environmental sustainability and climate resilience (Applications Management Consulting, 2017; de Jong, 2013; Sartori et al., 2015).

2.3.2 Basic Principles and Target Subjects

BCAs in European countries are grounded in multi-criteria analysis (MCA), which allows for the inclusion of non-monetary benefits, such as environmental quality, health impacts, and social equity. For instance, the ASEK (Arbetsgruppen för SamhällsEkonomiska Kalkyler in Swedish, meaning the working group for BCA) guidelines in Sweden and the Overview of the Effects of Infrastructure (OEI) guidelines in the Netherlands include the valuation of externalities like emissions and noise pollution, while the European Commission's guide to cost-benefit analysis incorporates shadow pricing for environmental costs, estimated values for environmental amenities that do not have market prices (de Jong, 2013; Eliasson, 2013; Sartori et al., 2015).[7] This holistic approach ensures that transportation projects are evaluated not just on their immediate financial feasibility but also on their broader societal impacts.

Similarly, other countries outside of Europe also often emphasize sustainability, equity, and long-term societal benefits. In Australia, for instance, the BCA framework is designed to assess the distributional (equity) impacts of transport initiatives, ensuring that projects do not disproportionately affect vulnerable populations (Australian Transport Assessment and Planning, 2023). In South Korea, the guidelines for transport investment appraisal stress both economic efficiency and broader social welfare outcomes, applying methodologies that incorporate demand forecasting, environmental considerations, and regional equity (Ministry of Land, Infrastructure and Transport, 2022). This reflects a broader trend in international BCAs where the focus extends beyond cost savings to include improvements in the quality of life, regional equity, and environmental sustainability.

International BCAs often have more diverse coverage, covering multimodal transport systems, sustainable urban mobility, and regional accessibility. Unlike the U.S., where road and highway projects tend to dominate, European cases place strong emphases on public transport, cycling infrastructure, and active travel as key focus areas (Odgaard et al., 2006). This approach highlights global priorities on reducing greenhouse gas emissions and promoting healthier, more sustainable cities. Additionally, BCAs in countries like the Netherlands and Sweden frequently assess projects aimed at improving connectivity in rural areas to ensure balanced regional

[7] Shadow pricing is used to adjust market prices for distortions and to reflect the true economic value of resources. From the agencies like the European Commission, it is applied to account for externalities such as environmental costs (e.g., emissions) and to estimate values like the shadow wage for underemployed labor, ensuring that project impacts are assessed in terms of their broader societal benefits.

development (de Jong, 2013; Eliasson, 2013).

We also found numerous non-European BCA frameworks that extend their analyses beyond highways and road networks, focusing on multi-modal transport systems. For example, the evaluation frameworks in New Zealand and Australia include comprehensive assessments of public transport, walking, and cycling infrastructure alongside traditional road projects (Australian Transport Assessment and Planning, 2022; NZ Transportation Agency, 2024). In Japan, BCAs cover a wide range of transportation modes, including railways, airports, and seaports, each with tailored methodologies for estimating benefits, particularly in terms of environmental and social equity impacts (Morisugi, 2000). This holistic approach allows for a more inclusive assessment of how transportation projects contribute to national development goals.

A. Commonly Used Parameters

Costs

The key differences in cost parameters between international countries and the U.S. lie in the broader inclusion of externalities and lifecycle costs in international practices. While BCA frameworks all account for capital costs (construction, land acquisition), operating and maintenance (O&M) costs, and other costs, we observe that international frameworks often place greater emphasis on environmental externalities, such as emissions and noise pollution, as well as residual value at the end of a project's lifecycle.

Construction costs, or capital expenditures, typically encompass direct costs related to land acquisition, labor, materials, and equipment. As observed in the UK's Transport Analysis Guidance (TAG), base costs need to be adjusted for risks and potential optimism bias, ensuring that project estimates reflect realistic scenarios (Department for Transport, 2024a). Similarly, guidelines from other European nations, such as those from Germany, provide detailed methods for estimating project costs, including indirect costs such as environmental mitigation and compensation for affected communities (Gühnemann, 2013). The guidelines from Australia, New Zealand, and Korea emphasize capital investment, requiring detailed estimates over the project lifecycle and adjustments for construction inflation or other contingencies, as well as additional base costs with detailed breakdowns including compensation for affected properties and land acquisition ranging from 10% to 20% of the base costs, depending on the project’s complexity (Australian Transport Assessment and Planning, 2022; Ministry of Land, Infrastructure and Transport, 2022; NZ Transportation Agency, 2024).

Although the inclusion of major components of operation and maintenance costs and residual costs is common internationally and in the U.S., international BCA frameworks typically incorporate environmental costs or externalities, such as pollution, noise, and carbon emissions, as essential cost parameters. For instance, the European Commission’s BCA guide mandates the monetization of environmental impacts, particularly emissions and noise pollution, to reflect the societal costs imposed by transportation projects (Sartori et al., 2015). Countries like Sweden and Australia follow similar methods, using tools such as shadow pricing to assign monetary values to environmental damages and reductions in emissions (Australian Transport

Assessment and Planning, 2022; Eliasson, 2013).

Benefits

One key area of difference between international BCA frameworks and the U.S. BCAs stem from the broader scope of benefits considered in international practices. International BCA frameworks, such as those developed in Europe, Australia, and New Zealand, often emphasize environmental and social benefits, including reductions in greenhouse gas emissions, air quality improvements, noise reduction, and equitable access to transportation. For instance, these countries commonly assign monetary values to environmental and health benefits, focusing on long-term sustainability and societal well-being. In contrast, U.S. BCA frameworks traditionally prioritize economic efficiency metrics, such as travel time savings and vehicle operating cost reductions, though environmental and equity considerations are becoming more prevalent.

In fact, benefit parameters share commonalities with U.S. practices but exhibit distinct methodologies and assumptions that reflect local and regional priorities. Both frameworks typically include travel time savings, vehicle operating cost reductions, safety improvements, and environmental benefits as core parameters in the evaluation of transportation projects. For instance, Sweden and France emphasize travel time savings as a critical factor, similar to the U.S. approach. However, the methodologies for calculating these savings in international contexts can vary, with countries like Sweden applying more specific valuation methods tailored to regional economic conditions and user preferences (Odgaard et al., 2006; Quinet, 2000). In Japan, there is a significant focus on regional development and the integration of multimodal transportation systems, which influences how travel time savings are evaluated. Travel time is often monetized using wage-based approaches but can be adjusted for specific contexts, such as discomfort due to congestion in railway networks, as seen in Japan's transportation project evaluations (Australian Transport Assessment and Planning, 2022; Morisugi, 2000).

Where international BCAs diverge from U.S. frameworks is in their broader approach to additional societal impacts, regional development, and broader environmental considerations. For example, the Swedish framework places a higher emphasis on health outcomes related to pollution reduction and encourages active travel modes, such as walking and cycling, which contribute positively to public health (Eliasson, 2013). Additionally, frameworks like New Zealand's incorporate public health and physical activity benefits into the evaluation of active transportation projects, a parameter that is less commonly emphasized in the U.S. (NZ Transportation Agency, 2020). European BCA frameworks, particularly those under the European Commission, adopt more comprehensive methods for evaluating long-term environmental sustainability, including assumptions about carbon pricing and the marginal cost of public funds[8]—elements that are not always as prominent in U.S. evaluations (Applications Management Consulting, 2017; Department for Transport, 2024b; Ministry of Transportation

[8] Carbon pricing, as utilized in international BCAs, assigns a monetary value to greenhouse gas emissions to account for environmental externalities and incentivize emission reductions. The marginal cost of public funds reflects the economic cost of raising additional revenue through taxation, emphasizing efficient resource allocation and ensuring that public investment projects generate net societal benefits.

and Infrastructure, 2014).

Another significant distinction in international BCA practices is the focus on multimodal integration and regional economic development impacts, particularly in countries like Japan and Germany. These countries often assess how transportation projects support broader regional economic goals, including freight logistics improvements and the promotion of long-term regional sustainability. This contrasts with the more mode-specific focus in U.S. BCAs, where the primary concern often centers around the direct impacts of individual projects. International BCAs tend to adopt a more holistic approach, integrating assumptions about how projects affect overall regional development, connectivity, and equity (Quinet, 2000; Strategic Research and Analysis Division, 2023). Referred to as Wider Economic Benefits (WEB), they include agglomeration economies, improved labor market accessibility, productivity gains, and indirect economic growth. These frameworks reflect the specific priorities of each region, where broader economic and environmental outcomes are evaluated alongside immediate transport efficiency improvements. In countries like Sweden and New Zealand, transportation projects are evaluated not only for their immediate economic returns but also for their capacity to stimulate long-term regional development and reduce economic disparities between urban and rural areas (Eliasson, 2013; NZ Transportation Agency, 2020). The European Commission's guidelines encourage the use of multi-sectoral models to evaluate how transportation projects impact various industries and regions, considering spillover effects such as increased trade and investment flows (Sartori et al., 2015). Thus, while international and U.S. BCAs share common benefit parameters, international practices often utilize more expansive methodologies and assumptions, aiming for longer-term and more regionally aligned outcomes (Ministry of Transportation and Infrastructure, 2014; Odgaard et al., 2006).

B. Equity

In practice, international BCAs typically address equity considerations more comprehensively than those in the U.S., focusing on both geographic and social equity. The exact application varies, but there is an apparent increasing focus on ensuring that the distribution of benefits and costs accounts for the needs of vulnerable populations. In the United Kingdom, the TAG framework emphasizes a distributional impact appraisal, which assesses how different social groups are affected by transportation interventions. These groups often include low-income households, ethnic minorities, children, and people with disabilities. The appraisal process involves identifying both positive and negative impacts on these groups, particularly in terms of accessibility, noise, and air quality (Department for Transport, 2022, 2024c). In the Netherlands, distributional impacts are integrated into the evaluation of transportation projects, particularly in terms of accessibility and environmental justice. The guidelines require an analysis of how transportation improvements affect both users and non-users, with a focus on ensuring that all population groups benefit fairly from public investments (de Jong, 2013).

In non-European countries, there is also emphasis placed on ensuring that transportation investments do not disproportionately impact certain communities, particularly disadvantaged groups, aiming to evaluate how the benefits and costs of transportation projects are distributed

across different population segments. In these cases, equity analysis is integrated into the BCA process by identifying vulnerable populations and assessing the project's impacts on these groups, often through tools like distributional impact assessments or social impact appraisals (Australian Transport Assessment and Planning, 2023; Ministry of Land, Infrastructure and Transport, 2022). For example, in Australia, the ATAP guidelines provide detailed methodologies for assessing distributional and equity impacts by evaluating how transportation initiatives affect various socio-economic groups (Australian Transport Assessment and Planning, 2023). In this case, distributional weights derived from a diminishing utility function with respect to income are used. The Australian guidelines recommend reporting distributional impacts to decision-makers separately from the BCA results in order to ensure efficiency and equity impacts are addressed on a case-by-case basis. Similarly, New Zealand's Land Transport Benefits Framework includes measures for evaluating how projects improve accessibility for all people to social and economic opportunities such as work, education, and health care, ensuring that the benefits of transportation infrastructure are equitably shared (NZ Transportation Agency, 2024). In Japan, while equity is considered in transportation project evaluations, it is often more qualitative, with tools like the Benefit Incidence Table (BIT) used to identify the origin and transfer of benefits to different population groups (Morisugi, 2000).

Case 1: UK Distributional Impact (DI) Appraisal

In the UK, the Department for Transport (2024b) addresses distributional impacts within their BCA framework through a detailed Distributional Impact (DI) Appraisal process. This process begins by identifying social groups likely to experience positive or negative impacts from a transportation intervention, focusing on vulnerable populations such as low-income individuals, ethnic minorities, the elderly, and those with disabilities. This approach is applied across eight key indicators—user benefits, noise, air quality, accidents, security, severance, accessibility, and affordability—each analyzed individually to assess how different social groups may be disproportionately affected. A screening step initially determines which indicators require detailed appraisal, aiming to ensure a proportionate approach to the analysis.

For indicators that pass the screening, the appraisal process involves a localized assessment of socio-demographic characteristics using Geographic Information Systems (GIS). This mapping procedure captures variations in impacts across different areas and provides a clear picture of where particular social groups might bear greater benefits or costs. By analyzing detailed datasets, the DI appraisal identifies and maps the spatial distribution of groups affected by each impact indicator. Comparisons are made against local authority averages to highlight significant disparities. When necessary, further assessment may be undertaken to examine anticipated future demographic changes, allowing the analysis to reflect likely shifts in the socio-economic profile of the impact area.

The DI appraisal results are then summarized in a matrix that categorizes each social group’s impact as either beneficial, adverse, or neutral (see Figure 2). The matrix uses specific assessment criteria: a “Large Beneficial” (√√√) score is assigned if the benefit significantly exceeds the proportion of the impacted group in the population, while “Moderate” (√√) or

"Slight Beneficial" (√) scores indicate lesser degrees of benefit alignment. Conversely, adverse impacts are scored as "Slight Adverse" (×××), "Moderate Adverse" (××), or "Large Adverse" (×××), depending on whether the impacted group experiences a greater-than-average adverse effect relative to their population share. The matrix also has an evaluative checkpoint to assess whether the benefits or disbenefits of a transport intervention are equitably shared across different social groups. By identifying any disproportionality in the distribution of impacts, flagging whether specific groups are disproportionately affected compared to the broader population, it allows decision-makers to pinpoint and address inequities by modifying or compensating for interventions that might otherwise exacerbate social disparities. Lastly, the matrix provides a descriptive summary of the main distributional effects experienced by different social groups due to the transport intervention. These qualitative statements complement the quantitative assessment by offering context-specific insights that explain how and why certain groups may be disproportionately impacted. This scoring system supports decision-makers by identifying key disparities and summarizing the relative benefits or disadvantages experienced by various social groups within the Appraisal Summary Table (AST).

	Distributional impact of income deprivation					Are the impacts distributed evenly?	Key impacts – Qualatitive statements (example below)
	0-20%	20-40%	40-60%	60-80%	80-100%		
User benefits	✓	✓✓	✓✓	✓✓	✓✓✓	No	Although benefits are felt by all income quintiles, the benefits favour those in the least deprived income quintiles. Those in the least deprived income quintile (income quintile 5) experience a considerably higher than expected proportion of benefits, whereas those in the most deprived areas (quintile 1) experience a smaller than expected proportion of benefits.
Noise	×××	✓	✓✓✓	✓✓	✓✓✓	No	Noise impacts favour those in the least deprived income quintiles. Those in the most deprived income quintile experience noise disbenefits, whereas all other income quintiles experience benefits of the intervention.
Air quality	✓✓✓	✓✓	✓	××	✓	No	Air quality impacts favour residents in the most deprived income quintiles. Those in the most deprived income quintile (quintile 1) that may be considered to be the most vulnerable experience a considerably higher proportion of air quality benefits than may be expected from an even distribution. Residents living in income quintile 4 experience air quality disbenefits.
Affordability	××	×	××	✓	✓✓	No	Personal affordability benefits favour those in the least deprived income quintiles. Those in income quintiles 4 and 5 experience benefits in terms of affordability, whereas those in the least deprived income quintiles (who may are the most vulnerable) experience disbenefits as a result of the intervention.
Accessibility	×	×	×	×	×	Yes	Accessibility impacts are appraised as slight adverse for all of the income deprivation quintiles and therefore although the impact is adverse the impact is distributed evenly.

Figure 2 - UK's Distributional Impact Appraisal Summary Table (AST) (source: Department for Transport (2024))

Case 2: EU Distributional Impacts

The European Commission emphasizes that distributional impacts should be documented in all BCA reports, requiring that all relevant groups' benefits and disadvantages to be included in the appraisal (Sartori et al., 2015). It suggests using welfare weights to adjust the value of benefits and costs according to the socio-economic profile of affected groups, which ensures that

impacts on different income groups are properly considered. This approach highlights the importance of equitable distribution, allowing the BCA to reflect societal preferences for benefiting disadvantaged communities or individuals who are less capable of bearing costs. This is especially relevant for projects that might disproportionately impact low-income populations, thus promoting a more inclusive investment strategy. More specifically, the welfare weight approach applies specific weights to benefits or costs affecting different groups, adjusting their value based on social welfare considerations. The idea is that an economic gain or loss does not have the same impact across all income levels or demographics, so benefits to disadvantaged groups—such as low-income populations—are often assigned a higher weight to reflect their greater social value. This means that benefits accruing to these groups, such as improved access to public transportation, are considered more impactful for overall social welfare.

Applying welfare weights involves identifying groups affected by a transportation project and setting weights that align with equity goals. For instance, consider a project that reduces travel time across various regions with different socioeconomic profiles. Standard BCA might undervalue benefits in lower-income neighborhoods, where time savings could have a more substantial impact on daily life. By applying welfare weights, time savings for these lower-income groups receive a higher value, potentially increasing the project's overall benefit rating. Similarly, in assessing improvements to a public bus system, welfare weights can give more importance to benefits experienced by non-car-owning households who rely heavily on public transit. In this way, welfare-weighted BCA better captures the value of transportation improvements to groups for whom these benefits are most essential.

Calculating welfare weights typically involves estimatinga the relative marginal utility of income for different groups, reflecting how additional income or benefits affect their well-being compared to others. This process often starts by determining the elasticity of marginal utility of income, a parameter that reflects how much utility or value an additional dollar brings to lower-income individuals compared to higher-income ones.[9] In reference to the tables provided (see the top table in Figure 3), this method is demonstrated by assigning varying welfare weights based on income level, with higher weights for lower-income groups and lower weights for higher-income ones.

$$W = \left(\frac{\overline{C}}{C_i}\right)^e$$

Where: $\overline{C}$ is the overall average consumption level, C_i is the per capita consumption in the group, and e is the elasticity of marginal utility of income. For example, the $\frac{\bar{c}}{C_i}$ parameter for the high income group in Figure 3 below would be 2,250 divided by 3,000, which equates to 0.75.

[9] A meta-analysis conducted by Acland and Greenburg (2023)concludes that the elasticity of marginal utility of income can be reasonably based at 1.6, with "lower- and upper-bound sensitivity testing at 1.2 and 2.0".

In applying this framework, welfare weights amplify the benefits to disadvantaged groups, boosting the perceived project value when benefits are distributed progressively. Conversely, it also demonstrates a scenario where benefits are weighted regressively, resulting in a lower total social value. Through such tables, the welfare weight approach allows analysts to quantify and highlight the social value of projects that favor equity, ensuring that benefits to vulnerable or low-income groups receive greater emphasis in the BCA (see Figure 3).

Classes	Consumption	$(\bar{C} / C_i)$	e=0	e=0.3	e=0.7	e=1.2
High income	3,000	0.75	1	0.9173	0.8176	0.7081
Medium income	2,500	0.90	1	0.9689	0.9289	0.8812
Low income	1,250	1.80	1	1.1928	1.5090	2.0245
Average	2,250	1	1	1	1	1

Classes	Net benefits	Elasticity 1.2	Distributional impact
High income	60	0.7081	42.49
Medium income	100	0.8812	88.12
Low income	140	2.0245	283.43
Total	**300**		**414.04**

Figure 3 - Examples of welfare weights and those for progressive distributional impact (source: Sartori et al. (2015))

2.4 Comparisons between U.S. and International Practices

Table 4 summarizes the frequency that each BCA parameter is used across three groups: U.S. federal agencies, state DOTs and MPOs, and international cases. At the federal level, we observe consistent application of fundamental parameters such as capital costs, O&M costs, travel time savings, and vehicle operation cost savings, with nearly all parameters reaching 100% usage. Safety benefits and environmental considerations like emissions reduction are also universally adopted, although health benefits (33%) and more nuanced metrics like reliability and non-automobile amenity benefits are less emphasized.

State DOTs and MPOs exhibit slightly more varied application of parameters. Core metrics such as capital costs, O&M costs, and travel time savings remain dominant, though they are applied somewhat less consistently than at the federal level (e.g., 77-94% usage). Health and environmental benefits, including climate change considerations, are less frequently included, reflecting a potential prioritization of traditional economic and operational metrics over broader societal impacts. Unlike federal BCAs, state and MPO analyses show greater variability in newer or less standardized metrics such as reliability (13%) and non-automobile amenity benefits (10%), suggesting a less uniform approach to integrating these emerging considerations.

International BCAs in practice point toward a more holistic approach that frequently

incorporates environmental and economic development impacts. Parameters like emission reduction benefits (100%) and climate change considerations (92%) are nearly universally used, indicating a higher prioritization of sustainability. However, basic cost metrics like replacement costs (25%) and residual value (25%) are less commonly applied compared to U.S. practices. Additional parameters such as tourism benefits and external impacts like overcrowding, which are rarely considered in U.S. practices, highlight the broader scope of international BCA methodologies. This contrast underscores differing priorities, with international cases placing more emphasis on multi-dimensional benefits while U.S. federal and state agencies focus heavily on traditional cost and operational metrics.

The distinctive differences in parameters also manifest in the qualitative parameters (see Table 5). At the federal level, qualitative parameters such as economic development (e.g., agglomeration economy), emergency service improvements, and equity considerations (e.g., distributional impacts) are prominently discussed. These reflect a focus on broad societal and systemic benefits, with attention to distributional equity and resilience. State/MPO practices show a more diverse and localized approach, incorporating factors like livability, accessibility, and regional competitiveness (e.g., population and employment thresholds). These reflect a stronger focus on community-level impacts and connectivity.

Comparatively, international practices emphasize spatial impacts (e.g., planning achievements through connectivity improvements and mode shift) and environmental considerations, showcasing a holistic perspective on long-term sustainable development. Additionally, international practices incorporate user satisfaction, fiscal impacts, and distributional impacts, which are largely absent in U.S. practices, demonstrating a broader integration of human-centered and economic evaluation parameters, and a balance between technical and experiential metrics.

Table 4 - Quantitative BCA Parameters - U.S. Federal, State/MPOs, and International

Parameters		Federal (n=3)	State/MPOs (n=31)	International (n=12)
Costs	Capital (construction) cost	100%	77%	100%
	O&M cost	100%	77%	100%
	Replacement cost	67%	19%	25%
	Residual value	100%	39%	25%
Travel time and vehicle operation	Travel time savings	100%	94%	100%
	Vehicle operation cost savings	100%	68%	83%
Health and safety	Safety benefits	100%	94%	100%
	Health benefits	33%	13%	8%
Environment	Emission reduction benefits	100%	77%	100%
	Climate change	100%	45%	92%
	Noise reduction	33%	19%	83%
Other parameters (quantified)	Economic development impacts	0%	10%	58%
	Reliability	33%	13%	50%
	Non-automobile amenity benefits	33%	10%	8%
	Resilience	0%	6%	8%
Other qualitative parameters		-	▪ Avoided cost savings (infrastructure operation, transport, freight, research projects, and other VMT reduction-related policies) ▪ Emergency response savings ▪ Equity ▪ Highway operation costs ▪ State of good repair ▪ User satisfaction ▪ Utility costs and revenue (EV)	▪ Administration costs ▪ Cross-modal and network effects ▪ Distributional effects ▪ External impacts (overcrowding) ▪ Impacts on transportation provider ▪ Revenue ▪ Tourism benefits ▪ User experience benefits

		▪ Work zone impacts	

Table 5 - Qualitative BCA Parameters - U.S. Federal, State/MPOs, and International

Category	Parameters	Federal	State/MPOs	International
Other benefits (qualitative)	Economic development	Economic development (agglomeration economy)	Economic development (jobs, employment, value of transport, increased capacity for other projects)	-
	Emergency service improvements	Emergency service improvements	Emergency response savings	-
	Environmental benefits	Other environmental impacts (stormwater runoff and wildlife)	Other environmental impacts (natural resources)	Environmental impacts (protection or conservation of nature)
	Equity consideration	Ladders of opportunity (distributional impacts)	Equity	Distributional impacts
	Quality of life	Livability	Quality of life	-
	Land use benefits	-	Regional competitiveness (connectivity); Accessibility (population and employment within threshold)	Spatial impacts (planning achievements by connectivity improvements and mode shift)
	Satisfaction		User satisfaction	User satisfaction
	Others	▪ Resilience ▪ State of good repair ▪ Property value	▪ Reduced delay impact by technology ▪ Reliability	-

		increase ▪ Work zone impact	▪ Congestion reduction impacts ▪ Financial impacts (share of life cycle cost, fiscal impacts)	

3 BCA Workshops

To supplement our BCA literature and best practices reviews, the research team attended two separate workshops organized by the Society for Benefit-Cost Analysis (SBCA) and Transportation Research Board (TRB) to incorporate the latest methodologies and practices into this study.

- **SBCA Workshop – Assessing Distribution and Equity** (November 19 and 21, 2024)
  This workshop focused on integrating equity considerations into BCA, discussing the rarity of distributional analyses and the normative challenges of measuring equity impacts.
  Presentations by Lisa A. Robinson (Harvard University), Dan Acland (University of California, Berkeley), Matt Adler (Duke University), Maddalena Ferranna (University of Southern California), James K. Hammitt (Harvard University), and Jim Neumann (Industrial Economics, Inc.).
- **TRB Workshop – Evolving the Practice of Benefit-Cost Analysis** (November 21, 2024)
  This session highlighted the need to expand BCA frameworks to include broader impacts such as environmental sustainability and social equity, reflecting current federal policy priorities.
  Presentations by Glen Weisbrod (EBP), Robin Ayers (Texas Department of Transportation), Mario Tartaglia (Ferrovie dello Stato Italiane), Dan Hodges (Cambridge Econometrics)

We found that the workshops highlighted themes consistent with our findings from the BCA literature and practice reviews. Both workshops emphasized the insufficient consideration of equity and distribution in BCAs, as well as the lack of consistent methodologies or guidelines for addressing equity issues. The presenters highlighted several important considerations and challenges related to equity and distributional analysis in BCA. One of the key discussions centered on the uneven treatment of diverse demographic groups in BCA. While income is the most frequently analyzed category, other important demographic factors, such as race, ethnicity, and physical disability, are often overlooked (Robinson, 2024). This limited focus reduces the ability of BCA frameworks to address equity concerns across diverse populations comprehensively.

Another significant topic was the emphasis on the distribution of benefits over costs in distributional analyses. James K. Hammitt (2024) and Glen Weisbrod (2024) noted that it is often easier to estimate the distribution of benefits than costs, leading most analyses to prioritize benefits while leaving cost distributions underexplored. This imbalance can obscure important equity considerations, as the costs of transportation projects may disproportionately affect specific groups, such as low-income households or marginalized communities.

Daniel Acland (2024), Matthew D. Adler (2024), and Maddalena Ferranna (2024) explored the methodological process of conducting distributional analyses. One notable point was the stark differences between the results of traditional BCA and those derived from weighted BCA or social welfare functions (SWFs). Weighted BCAs, which apply distributional weights to account

for disparities, often reveal significant inequities in the distribution of benefits and costs. They also addressed the limitations of WTP as a metric, noting that WTP inherently assigns higher value to wealthier individuals' time and lives, which can perpetuate existing inequalities.

James E. Neumann (2024) highlighted the importance of spatial distribution impacts analysis, as outlined in the USEPA's report. This analysis focuses on four distinct groups: low-income individuals, minority populations, those with limited education, and old populations. By overlaying the distribution map of impacts with the distribution map of focus groups, they identify which individuals in specific areas are most vulnerable. Spatial distribution impacts consider how transportation projects affect different geographic areas, which can be crucial for addressing equity in regions with significant disparities in access to jobs, services, and opportunities.

Finally, Mario Tartaglia (2024) argued that integrating BCA with other transportation impact assessment frameworks, such as MCA and social impact analysis, could offer effective solutions. These complementary frameworks have the potential to incorporate broader equity considerations and address the limitations of existing BCA.

4 Lessons from the Literature and Best Practices Reviews

Throughout our reviews of BCA frameworks in the literature and in practice, we find numerous common characteristics as well as distinct emphases. Our academic literature review finds more focus on definitions, measurement methods, and discourse surrounding BCA frameworks and its parameters, while our review of best practices centers on real-world applications, highlighting how agencies like USDOT, state DOTs, and international governments tailor the general BCA framework to fit diverse transportation modes and regional priorities. Overall, we find a shared focus on consistency, measurable outcomes, and tools. The following details notable commonalities within the literature and practice reviews:

- In both areas, the definitions of parameters and measurement methods for indicators vary depending on the scale of the project, program, or policy being evaluated, the transportation mode in focus, and the intended purpose.
- Both highlight the importance of adapting the general BCA framework to local needs. BCA frameworks are tailored to meet the specific state or regional context, reflecting the unique transportation demands, environmental policies, and socio-economic goals of each area. For example, states like California, Virginia, and Washington have developed their BCA frameworks to align with local priorities.
- In both sections of the review, parameters commonly used across multiple studies, such as Infrastructure/Vehicle Construction (Capital Cost, Capital investment), Operating and Maintenance Costs, Travel Time (avoided travel time costs, travel time savings), Safety Effects, and Air Pollution, exhibit a broad consensus in their definitions.
    - Although the specific terminology varies, we find that costs associated with the life cycle of transportation infrastructure and vehicles—including construction, rehabilitation, recycling, and disposal—as well as operation and maintenance costs are generally accounted for both in the academic literature and in practice.

    - The travel time indicator represents the value of changes in travel time, converted into monetary terms using VOT. It reflects changes experienced by users in a road environment, such as increased or decreased traffic, resulting from transportation investments.
    - Safety effects refer to the monetary value of crashes that are either caused or mitigated by transportation projects. This value is determined based on the severity or type of crash and the number of crashes that have increased or decreased.
    - There is a consensus on recognizing environmental benefits, particularly emission reductions. Although the specific pollutants considered vary across frameworks, the impacts are assessed based on the quantity of air pollutants reduced or increased by transportation projects and the monetary value attributed to each pollutant.
- While most BCAs traditionally focus on motorized vehicles, assessments of multi-modal and active transportation options (e.g., for cycling or walking infrastructure) are increasingly considered, driven by their health, social, and environmental advantages.
- The inclusion of equity impacts is a growing trend in both literature and practical applications, with many BCA frameworks exploring how benefits and costs are distributed across different population segments or geographic areas.

However, we also find significant differences between the academic literature and practical applications:

- While published papers often do not clearly differentiate between the costs and benefits of transportation programs and policies, most practical reports delineate the impacts of these programs and policies in distinct sections. For instance, while transportation investments can have both positive and negative impacts on travel time or health, practical reports typically include terms that specify the outcomes, such as 'travel time savings' and 'health benefits,' within the parameters.
- BCA in practice is predominantly applied to infrastructure projects, particularly those seeking state or federal funding. Policy-level applications, such as evaluating pricing strategies or emission regulations, are less common due to the inherent challenges of measuring indirect or systemic impacts. The academic literature calls for broader application of BCA, but in practice BCA is less frequently applied given the resource-intensive nature of evaluating complex, non-infrastructure initiatives.
- Practical applications of BCA emphasize parameters that are directly measurable and policy-relevant, focusing primarily on quantifiable outcomes like travel time and cost savings, accident reductions, and air quality improvements. Conversely, the literature review extends to parameters that necessitate qualitative analysis, including perceived safety and discomfort, the incorporation of crowding in the value of time, and the mental health impacts of congestion.
- Distributional analysis and sensitivity analysis (also known as risk analysis) are components often absent in applied BCA frameworks. While these methods and processes are extensively discussed and applied in the academic literature, they are less

commonly addressed in practical reports. Although practitioners recognize the importance of such analyses, insufficient guidance on their practical application exists within federal guidelines and state-level BCA frameworks to produce consistent and comparable results.

- In practice, emerging transportation modes, such as autonomous vehicles (AVs), sharing services, and micro-mobility, are still in the early stages of integration into BCA frameworks. Unlike the literature, which discusses their anticipated benefits—such as improved safety, reduced congestion, and operational cost savings—real-world practice has been slow to incorporate the costs and benefits of these emerging technologies into the BCA frameworks. Uncertain deployment timelines, a lack of standardized data, and universal impacts are a few notable challenges that arise in practically applying BCA for emerging modes. Although the academic literature emphasizes the transformative potential of emerging modes, practical BCA applications and case studies remain focused on conventional transportation systems and proven technologies.

5 Bibliography

Acland, D. (2024, November 21). *Distributional Weighting in Benefit-Cost Analysis*.

Acland, D., & Greenberg, D. H. (2023). The Elasticity of Marginal Utility of Income for Distributional Weighting and Social Discounting: A Meta-Analysis. *Journal of Benefit-Cost Analysis*, *14*(2), 386–405. https://doi.org/10.1017/bca.2023.29

Adler, M. D. (2016). Benefit–Cost Analysis and Distributional Weights: An Overview. *Review of Environmental Economics and Policy*, *10*(2), 264–285. https://doi.org/10.1093/reep/rew005

Adler, M. D. (2024, November 21). *Social Welfare Functions (SWFs) and Health Policy*.

AECOM. (2019). *Benefit Cost Analysis Memorandum: Globalplex Multi-Modal Connections Project*.

AECOM. (2021a). *Benefit Cost Analysis Memorandum: Fixing LOw Water Bridges for Emergency, Transportation, Technology, Equity, and Resilience (FLOW BETTER)*.

AECOM. (2021b). *TxDOT Statewide TSMO Benefit-Cost Analysis*.

Applications Management Consulting. (2017). *Alberta Benefit Cost Model User Guide*.

Australian Transport Assessment and Planning. (2022). *Australian Transport Assessment and Planning Guidelines: T2 Cost Benefit Analysis*.

Australian Transport Assessment and Planning. (2023). *Australian Transport Assessment and Planning Guidelines: T5 Distributional and equity effects of transport initiatives*.

Batarce, M., Muñoz, J. C., & Ortúzar, J. D. D. (2016). Valuing crowding in public transport: Implications for cost-benefit analysis. *Transportation Research Part A: Policy and Practice*, *91*, 358–378. https://doi.org/10.1016/j.tra.2016.06.025

Behr, C. (2020). *White Paper on BCA Approaches for New Arterial Roadway Improvements*.

Beukers, E., Bertolini, L., & Te Brömmelstroet, M. (2012). Why Cost Benefit Analysis is perceived as a problematic tool for assessment of transport plans: A process perspective. *Transportation Research Part A: Policy and Practice*, *46*(1), 68–78. https://doi.org/10.1016/j.tra.2011.09.004

Boarnet, M. G., Greenwald, M., & McMillan, T. E. (2008). Walking, Urban Design, and Health: Toward a Cost-Benefit Analysis Framework. *Journal of Planning Education and Research*, *27*(3), 341–358. https://doi.org/10.1177/0739456X07311073

Browne, D., & Ryan, L. (2011). Comparative analysis of evaluation techniques for transport policies. *Environmental Impact Assessment Review*, *31*(3), 226–233. https://doi.org/10.1016/j.eiar.2010.11.001

California Department of Transportation. (2022). *Cal-B/C Parameter Guide Version 8.1*.

Cambridge Systematics. (2014). *Tool for Operations Benefit/Cost (TOPSBC) for Florida DOT Applications*.

Cavill, N., Kahlmeier, S., Rutter, H., Racioppi, F., & Oja, P. (2008). Economic analyses of transport infrastructure and policies including health effects related to cycling and walking: A systematic review. *Transport Policy*, *15*(5), 291–304. https://doi.org/10.1016/j.tranpol.2008.11.001

CE Delft. (2020). *Handbook on the external costs of transport: Version 2019 – 1.1.* Publications Office. https://data.europa.eu/doi/10.2832/51388

CH2MHill. (2014). *Mosaic User Guide—Prepared for Oregon Department of Transportation*. https://www.oregon.gov/odot/Planning/Documents/Mosaic-Users-Guide.pdf

Chi, S., & Bunker, J. (2021). An Australian perspective on real-life cost-benefit analysis and assessment frameworks for transport infrastructure investments. *Research in Transportation Economics*, *88*, 100946. https://doi.org/10.1016/j.retrec.2020.100946

Colorado Department of Transportation. (2021). *Cost-Benefit Analysis For Rules Governing Statewide Transportation Planning*.

Commonwealth Transportation Board. (2024). *SMART SCALE Technical Guide*.

Damart, S., & Roy, B. (2009). The uses of cost–benefit analysis in public transportation decision-making in France. *Transport Policy*, *16*(4), 200–212. https://doi.org/10.1016/j.tranpol.2009.06.002

DCHC. (2016). *Implementing the Rapid Policy Assessment Tool*.

de Jong. (2013). *International Comparison of Transport Appraisal Practice: Annex 3 Nertherlands Country Report*.

De Rus, G., Socorro, M. P., Valido, J., & Campos, J. (2022). Cost-benefit analysis of transport projects: Theoretical framework and practical rules. *Transport Policy*, *123*, 25–39. https://doi.org/10.1016/j.tranpol.2022.04.008

Department for Transport. (2022). *TAG Unit A4.1—Social Impact Appraisal*.

Department for Transport. (2023). *TAG Unit A1.1—Cost Benefit Analysis*.

Department for Transport. (2024a). *TAG Unit A1.2—Scheme costs*.

Department for Transport. (2024b). *TAG unit A3 environmental impact appraisal*.

Department for Transport. (2024c). *TAG Unit A4.2—Distributional impact appraisal*.

ECONorthwest. (2023). *Highway Cost Allocation Study*.

Eliasson, J. (2013). *International Comparison of Transport Appraisal Practice—Annex 4 Sweden Country Report*.

Fagnant, D. J., & Kockelman, K. (2015). Preparing a nation for autonomous vehicles: Opportunities, barriers and policy recommendations. *Transportation Research Part A: Policy and Practice*, *77*, 167–181. https://doi.org/10.1016/j.tra.2015.04.003

Federal Aviation Administration. (2020). *FAA AIRPORT BENEFIT-COST ANALYSIS GUIDANCE*.

Federal Railroad Administration. (2016). *Benefit-Cost Analysis Guidance for Rail Projects*.

FEMA. (2022). *FEMA Ecosystem Service Value Updates*.

Ferranna, M. (2024, November 21). *Assessing Pandemic Management Using BCA v. SWFs*.

FHWA. (1997). *1997 Federal Highway Cost Allocation Study*. https://www.fhwa.dot.gov/policy/otps/costallocation.cfm

FHWA. (2008). *Freight Benefit/Cost Study: Phase III - Analysis of Regional Benefits of Highway-Freight Improvements*.

FHWA. (2020). *The 23rd Conditions and Performance Report*.

Findley, D. J., Stone, J. R., Fain, S. J., & Foyle, R. S. (2007). *NCDOT BENEFIT/COST ANALYSIS FOR PLANNING HIGHWAY PROJECTS*.

Fitch, D. T., Kamalapuram, S., Favetti, M., & Handy, S. L. (2022). *Caltrans Active Transportation Benefit-Cost Tool: Technical Documentation*.

Gerbec, M., Samuel, R. O., & Kontić, D. (2015). Cost benefit analysis of three different urban bus drive systems using real driving data. *Transportation Research Part D: Transport and Environment*, *41*, 433–444. https://doi.org/10.1016/j.trd.2015.10.015

Gössling, S., Choi, A., Dekker, K., & Metzler, D. (2019). The Social Cost of Automobility, Cycling and Walking in the European Union. *Ecological Economics*, *158*, 65–74. https://doi.org/10.1016/j.ecolecon.2018.12.016

Gössling, S., & Choi, A. S. (2015). Transport transitions in Copenhagen: Comparing the cost of cars and bicycles. *Ecological Economics*, *113*, 106–113. https://doi.org/10.1016/j.ecolecon.2015.03.006

Greer, N., & Ksaibati, K. (2019). Development of Benefit Cost Analysis Tools for Evaluating Transportation Research Projects. *Transportation Research Record: Journal of the Transportation Research Board*, *2673*(1), 123–135. https://doi.org/10.1177/0361198118821675

Gühnemann, A. (2013). *International Comparison of Transport Appraisal Practice—Annex 2 Germany Country Report*.

Hammitt, J. K. (2024, November 19). *Theory and Conceptual Framework*.

Hawai'i Department of Transportation. (2014). *Benefit-Cost Analysis, Pier 4 Wharf Improvements, Hilo, Hawaii*.

HDR. (2009). *Cost-Benefit Analysis in Support of TIGER Application: Tower 55 At-Grade Project, Fort Worth, Texas, for BNSF Railway and Union Pacific Railroad*.

HNTB. (2022). *Benefit-Cost Analysis of Westside Express Project*.

Jakob, A., Craig, J. L., & Fisher, G. (2006). Transport cost analysis: A case study of the total costs of private and public transport in Auckland. *Environmental Science & Policy*, *9*(1), 55–66. https://doi.org/10.1016/j.envsci.2005.09.001

Jones, H., Moura, F., & Domingos, T. (2014). Transport Infrastructure Project Evaluation Using Cost-benefit Analysis. *Procedia - Social and Behavioral Sciences*, *111*, 400–409. https://doi.org/10.1016/j.sbspro.2014.01.073

Kansas Department of Transportation. (2022). *Kansas Active Transportation Plan: Benefit-Cost Analysis Tool User Guide*.

Kolosz, B., & Grant-Muller, S. (2015). Extending cost–benefit analysis for the sustainability impact of inter-urban Intelligent Transport Systems. *Environmental Impact Assessment Review*, *50*, 167–177. https://doi.org/10.1016/j.eiar.2014.10.006

Koopmans, C., & Mouter, N. (2020). Cost-benefit analysis. In *Advances in Transport Policy and Planning* (Vol. 6, pp. 1–42). Elsevier. https://doi.org/10.1016/bs.atpp.2020.07.005

Lakshmanan, T. R. (2011). The broader economic consequences of transport infrastructure investments. *Journal of Transport Geography*, *19*(1), 1–12. https://doi.org/10.1016/j.jtrangeo.2010.01.001

Lawrence, M., Hachey, A., Bahar, G., & Gross, F. (2018). *Highway Safety Benefit-Cost Analysis Guide*.

Lawrence, M., Nguyen, P., Skolnick, J., Symoun, J., Hunt, J., & Alfelor, R. (2015). *Transportation Systems Management and Operations Benefit-Cost Analysis Compendium*. https://ops.fhwa.dot.gov/publications/fhwahop14032/fhwahop14032.pdf

Litman, T. (2010). *Quantifying the Benefits of Nonmotorized Transportation For Achieving Mobility Management Objectives*.

Litman, T. A. (2024). *Evaluating Transportation Equity*.

Lucas, K., Van Wee, B., & Maat, K. (2016). A method to evaluate equitable accessibility: Combining ethical theories and accessibility-based approaches. *Transportation*, *43*(3), 473–490. https://doi.org/10.1007/s11116-015-9585-2

Marleau Donais, F., Abi-Zeid, I., Waygood, E. OwenD., & Lavoie, R. (2019). A review of cost–benefit analysis and multicriteria decision analysis from the perspective of sustainable transport in project evaluation. *EURO Journal on Decision Processes*, *7*(3–4), 327–358. https://doi.org/10.1007/s40070-019-00098-1

Martens, K., & Di Ciommo, F. (2017). Travel time savings, accessibility gains and equity effects in cost–benefit analysis. *Transport Reviews*, *37*(2), 152–169. https://doi.org/10.1080/01441647.2016.1276642

Michelly Gonçalves Brandão, S., Brunner-La Rocca, H.-P., Pedroso De Lima, A. C., & Alcides Bocchi, E. (2023). A review of cost-effectiveness analysis: From theory to clinical practice. *Medicine*, *102*(42), e35614. https://doi.org/10.1097/MD.0000000000035614

Miller, J. S., Flynn, D. F. B., Englin, E., Raw, J., Adel, S. H., & Dougald, L. E. (2022). *Feasibility of Adapting VisionEval for Scenario Planning*.

Ministry of Land, Infrastructure and Transport. (2022). *Appraisal Guidelines for Transport Facilities Investment*.

Ministry of Transportation and Infrastructure. (2014). *Benefit Cost Analysis Guidebook: Guidelines for the Benefit Cost Analysis Of Highway Improvement Projects In British Columbia*.

Minnesota Department of Transportation. (2005). *Mn/DOT Benefit Cost Analysis Guidance*.

Missouri Department of Transportation. (2020). *Benefit-Cost Analysis Supplementary Documentation for I-270 North GAP Project*.

MJB&A. (2020). *Electric Vehicle Cost-Benefit Analysis*.

Morisugi, H. (2000). Evaluation methodologies of transportation projects in Japan. *Transport Policy*, *7*(1), 35–40. https://doi.org/10.1016/S0967-070X(00)00013-5

Mulley, C., Tyson, R., McCue, P., Rissel, C., & Munro, C. (2013). Valuing active travel: Including the health benefits of sustainable transport in transportation appraisal frameworks. *Research in Transportation Business & Management*, *7*, 27–34. https://doi.org/10.1016/j.rtbm.2013.01.001

Neumann, J. E. (2024, November 19). *Case Study: Assessing Climate Impacts on Vulnerable Populations*.

Nevada Department of Transportation. (2022). *Cost–benefit analyses of mitigation measures along highways for large animal species: An update and an expansion of the 2009 model*.

Nevada Department of Transportation. (2023). *2023 Performance Management Report*.

Nurmi, V., & Ahtiainen, H. (2018). Distributional Weights in Environmental Valuation and Cost-benefit Analysis: Theory and Practice. *Ecological Economics*, *150*, 217–228. https://doi.org/10.1016/j.ecolecon.2018.04.021

NYSDOT. (2023). *PFRAP Benefit Cost Analysis Tool Instruction*.

NYSERDA. (2019). *Benefit-Cost Analysis of Electric Vehicle Deployment in New York State*.

NZ Transportation Agency. (2020). *Monetised benefits and costs manual*. Waka Kotahi, NZ Transport Agency.

NZ Transportation Agency. (2024). *Land Transport Benefits Framework measures manual*.

Odgaard, T., Kelly, C. E., & Laird, J. (2006). *Current practice in project appraisal in Europe.*

ODOT. (2016). *Implementing the Rapid Policy Assessment Tool*.

Oklahoma Transportation. (2023). *Benefit Cost Analysis Narrative: Multimodal Improvements to Safety Connect Tulsa at the US-75 and W. 81st Street Interchange*.

Österle, I., Ulrich, C., Herwartz-Polster, S., Sigle, S., Weimer, J., Conzelmann, M., Fleck, T., & Zofka, M. (2022). Benefits and costs of shared, modular automated vehicles for freight and passenger transport: The case of *U-Shift*. *Transportation Planning and Technology*, *45*(3), 203–225. https://doi.org/10.1080/03081060.2022.2094930

Parsons Brinckerhoff. (2014). *2014 California High-Speed Rail Benefit-Cost Analysis*.

Pereira, R. H. M., Schwanen, T., & Banister, D. (2017). Distributive justice and equity in transportation. *Transport Reviews*, *37*(2), 170–191. https://doi.org/10.1080/01441647.2016.1257660

Puget Sound Regional Council. (2009). *Benefit-Cost Analysis: General Methods and Approach*.

Quinet, E. (2000). Evaluation methodologies of transportation projects in France. *Transport Policy*, *7*(1), 27–34. https://doi.org/10.1016/S0967-070X(00)00014-7

Rabl, A., & De Nazelle, A. (2012). Benefits of shift from car to active transport. *Transport Policy*, *19*(1), 121–131. https://doi.org/10.1016/j.tranpol.2011.09.008

RITS. (2010). *Cost/Benefit Analysis of NJDOT Route 18/Hoes Lane Improvement Project*. RITS (Rutgers Intelligent Transportation Systems Laboratory).

Robinson, L. A. (2024, November 19). *Assessing Distribution and Equity*.

Ross, C. L., Boston, T. D., Golshani, N., Rao, A., & Adebola, O. (2020). *Phase III: Transportation Investment Act—Benchmark: Assessment and Benefit–Cost Analysis, 2013–2018*.

Rutgers. (2010). *Cost/Benefit Analysis of NJDOT Route 30/130 Reconstruction Project*.

Salling, K. B., & Leleur, S. (2011). Transport appraisal and Monte Carlo simulation by use of the CBA-DK model. *Transport Policy*, *18*(1), 236–245. https://doi.org/10.1016/j.tranpol.2010.08.007

Sallman, D., Flanigan, E., Jeannotte, K., Hedden, C., & Morallos, D. (2012). *Operations Benefit/Cost Analysis Desk Reference*.

Sartori, D., Catalano, G., Genco, M., Pancotti, C., Sirtori, E., Vignetti, S., & Bo, C. D. (2015). *Guide to cost-benefit analysis of investment projects: Economic appraisal tool for cohesion policy 2014-2020*. European Union.

Searle, G., & Legacy, C. (2019). Australian Mega Transport Business Cases: Missing Costs and Benefits. *Urban Policy and Research*, *37*(4), 458–473. https://doi.org/10.1080/08111146.2019.1663727

SFMTA. (2015). *TIGER Benefit Cost Analysis: 22 Fillmore Transit Priority Project*.

Sound Transit. (2015). *Benefit-Cost Analysis Methodology Report*.

Strategic Research and Analysis Division. (2023). *Transport Appraisal Framework: Appraisal Guidelines for Capital Investments in Transport | Module 8—Detailed Guidance on Appraisal Parameters*.

STV. (2022). *Benefit-Cost Analysis Technical Memorandum*.

Tartaglia, M. (2024, November 21). *Extending BCA in Italy to a wider impact appraisal*.

Thomopoulos, N., Grant-Muller, S., & Tight, M. R. (2009). Incorporating equity considerations in transport infrastructure evaluation: Current practice and a proposed methodology. *Evaluation and Program Planning*, *32*(4), 351–359. https://doi.org/10.1016/j.evalprogplan.2009.06.013

URS. (2006). *Benefits Analysis for the Georgia Department of Transportation NaviGAtor Program*.

USDOT. (2023a). *Benefit Cost Analysis Guidance 2024 Update*. https://www.transportation.gov/sites/dot.gov/files/2023-12/Benefit%20Cost%20Analysis%20Guidance%202024%20Update.pdf

USDOT. (2023b). *Benefit-Cost Analysis Guidance for Discretionary Grant Programs*. https://www.transportation.gov/sites/dot.gov/files/2023-12/Benefit%20Cost%20Analysis%20Guidance%202024%20Update.pdf

Van Den Bijgaart, I., Klenert, D., Mattauch, L., & Sulikova, S. (2024). Healthy climate, healthy bodies: Optimal fuel taxation and physical activity. *Economica*, *91*(361), 93–122. https://doi.org/10.1111/ecca.12497

Van Wee, B. (2012). How suitable is CBA for the ex-ante evaluation of transport projects and policies? A discussion from the perspective of ethics. *Transport Policy*, *19*(1), 1–7. https://doi.org/10.1016/j.tranpol.2011.07.001

Victoria Transport Policy Institute. (2022). *Transportation Cost and Benefit Analysis II*. https://www.vtpi.org/tca/tca02.pdf

Wang, G., Macera, C. A., Scudder-Soucie, B., Schmid, T., Pratt, M., & Buchner, D. (2005). A Cost-Benefit Analysis of Physical Activity Using Bike/Pedestrian Trails. *Health Promotion Practice*, *6*(2), 174–179. https://doi.org/10.1177/1524839903260687

Wangsness, P. B., Rødseth, K. L., & Hansen, W. (2017). A review of guidelines for including wider economic impacts in transport appraisal. *Transport Reviews*, *37*(1), 94–115. https://doi.org/10.1080/01441647.2016.1217283

Weisbrod, G. (2024, November 21). *Benefit-Cost Analysis: Past, Present, Future*.

Weisbrod, G., & Duncan, C. (2016). Integrating Multiple Economic Analysis Methods for More Effective Decision Making: Three-Dimensional Framework. *Transportation Research Record: Journal of the Transportation Research Board*, *2597*(1), 99–107. https://doi.org/10.3141/2597-13

Weisbrod, G., & Grovak, M. (1998). Comparing Approaches for Valuing Economic Development Benefits of Transportation Projects. *Transportation Research Record: Journal of the Transportation Research Board*, *1649*(1), 86–94. https://doi.org/10.3141/1649-11

Weisbrod, G., Mulley, C., & Hensher, D. (2016). Recognising the complementary contributions of cost benefit analysis and economic impact analysis to an understanding of the worth of public transport investment: A case study of bus rapid transit in Sydney, Australia. *Research in Transportation Economics*, *59*, 450–461. https://doi.org/10.1016/j.retrec.2016.06.007

Williges, C., & Mahdavi, M. (2008). Transportation Benefit–Cost Analysis: Lessons from Cal-B/C. *Transportation Research Record: Journal of the Transportation Research Board*, *2079*(1), 79–87. https://doi.org/10.3141/2079-11

Zahed, S. E., Shahandashti, S. M., & Najafi, M. (2018). Lifecycle Benefit-Cost Analysis of Underground Freight Transportation Systems. *Journal of Pipeline Systems Engineering and Practice*, *9*(2), 04018003. https://doi.org/10.1061/(ASCE)PS.1949-1204.0000313