Complete Streets Evaluation Best Practices

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16. Abstract

Complete Streets are a set of transportation policies, planning approaches, design practices, and operational strategies focused on improving safety, accessibility, and mobility for all road users regardless of their age, ability, and mode of transportation. The purpose of this report is to summarize Complete Streets evaluation best practices using analysis, modeling, and simulation (AMS) approaches. Evaluation of Complete Streets projects requires a diverse set of target performance metrics given the multi-modality of Complete Streets for roadway users such as pedestrians, cyclists, motorists, public transit users, people with disabilities, children, and micro-mobility users. This report identifies potential goal areas for Complete Streets evaluation, suggests target performance metrics within each goal area, and documents best practices for evaluation of projects in planning, design, or operational stages. Existing AMS approaches are also identified with sets of performance metrics that can be obtained by using existing AMS tools and methods. The target audience for this report includes a range of practitioners, tool developers, researchers, and other stakeholders involved in urban planning, transportation, and policy development related to Complete Streets.

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Executive Summary

Complete Streets are a set of transportation policies, planning approaches, design practices, and operational strategies focused on improving safety, accessibility, and mobility for all road users regardless of their age, ability, and mode of transportation. The purpose of this report is to summarize evaluation best practices for Complete Streets using analysis, modeling, and simulation (AMS) approaches. Evaluation of Complete Streets requires a diverse set of target performance metrics due to diverse array of users, encompassing pedestrians, bicyclists, motorists, public transit users, people with disabilities, children, older adults, as well as users of emerging transportation modes like ride-hailing and micro-mobility. This report identifies common goals for Complete Streets evaluation, suggests target performance metrics within each goal area, and summarizes best practices related to the application of AMS tools to evaluate Complete Streets. This report is not an exhaustive search of all evaluation methods related to Complete Streets but is meant to capture a high-level picture of common approaches used in both research and practice using currently available AMS tools. This report is meant to be complementary to the "Complete Streets Modeling Capabilities and Gaps" report. Both reports will be used to identify priority research areas as part of the ITS JPO's AMS for ITS Program. The target audience for this report includes a range of practitioners, researchers, tool developers, and other stakeholders involved in urban planning, transportation, and policy development related to Complete Streets.

Approach

An in-depth literature review was conducted to gather Complete Streets evaluation best practices both from research and practice settings. Specific attention was giving to studies that leveraged AMS tools to evaluate various impacts for Complete Streets projects. A review of current AMS tools was also performed to identify capabilities relevant for Complete Streets evaluation tasks. These findings serve as foundational knowledge and are further explored in the "Complete Streets Modeling Capabilities and Gaps" report.

Goal Areas for Complete Streets

The wide-ranging goals and objectives of Complete Streets require an evaluation approach that is holistic and focused on a diverse set of users and stakeholders. Based on the literature, six goal areas were identified and are listed below with a few representative examples.

- **Mobility** – E.g., travel time, travel delay, lane blockage, multi-modal level of service
- **Safety** – E.g., crash frequency/rate, near misses, speed compliance, pedestrian cross time
- **Equity and Accessibility** – E.g., transit supply/level of service, number of cutouts/ramps
- **Network Connectivity** – E.g., route directness, network quality, network/intersection density

- **Environmental Sustainability** – E.g., CO_2 emissions, criteria pollutants, tree coverage
- **Public Health** – E.g., bicycle/walking trip share, social interaction, air quality

Other important considerations for evaluation were also identified related to stakeholder engagement, community outreach, and evaluation plan development. In general, Complete Streets projects involve diverse stakeholder and user groups that require extensive coordination. Therefore, the co-development of project goals and evaluation plans are integral as they set expectations and ensure that diverse project goals are measurable and quantifiable. It is also important to distinguish between *output* and *outcome* metrics within the evaluation plan to determine the relative importance of various design considerations on overall Complete Street impacts. *Outputs* are specific design considerations utilized to influence positive impacts, such as number of bike lanes or curb cutouts. *Outcomes* are the impacts of the Complete Street as experienced by users, such as air quality or multi-modal level of service. AMS tools are integral during the design and evaluation plan development process to evaluate impacts of various design components, communicate findings using visualizations, and iterate with diverse stakeholder groups.

AMS Tools for Complete Streets Evaluation

In the past, AMS tools have focused on automobile traffic and its optimized movement through the network, which limits their capabilities when it comes to holistic evaluation of Complete Streets projects. A few of the key challenges identified for evaluating Complete Streets impacts using AMS tools are as follows:

- **Scale/Resolution**: Complete Street trips often originate/terminate outside of the transportation infrastructure facility boundary, which means that modeling efforts need to consider multiple levels of resolution to capture both local and aggregate impacts.
- **Context specific**: Complete Street outcomes are dependent on local population, network, and built environment characteristics. This means that local data collection is required to inform modeling efforts beyond typical inputs for AMS tools.
- **Multi-modality**: Overall impacts/outcomes are heavily tied to mode shift and mode split through the Complete Street corridor. To model this using AMS tools requires multi-resolution modeling and/or statistical methods to inform multi-modal demand inputs.

Despite these inherent challenges for evaluating Complete Streets, many AMS tools have specific capabilities that can be leveraged to evaluate certain Complete Streets metrics at pre-defined resolutions, which can provide valuable insights when combined with other data sources and analysis techniques. In general, all current AMS tools have significant shortcomings for modeling pedestrian/bicyclist movement compared to their ability to model motorized vehicular traffic. The analysis and modeling suggested best practices for Complete Streets evaluation are as follows based on a review of current AMS tool capabilities:

- ***Use activity- and agent-based modeling/simulation approaches to model newer forms of mobility*** such as shared micro-mobility, MaaS, MOD, and electric vehicle charging stations management.

- ***Use multiresolution modeling to obtain performance metrics at various scales of resolution***. Use macroscopic and mesoscopic models to capture mode shift and system-level impacts coupled with microscopic models to evaluate corridor level interactions and operational decisions. It is recommended to tune parameters for all three levels of resolution (macroscopic, mesoscopic, and microscopic) to increase model accuracy.
- ***Deterministic methods (HCM methods) are simple and quick approaches for estimating multi-modal level of service*** through a Complete Street corridor and are generally preferred when resources are limited.
- ***Leverage microscopic models to gain deeper insights into the interactions of multi-modal road users***. Numerous tools exist with different capabilities. Commercially available examples include Synchro/SimTraffic for modeling/evaluating traffic signal operations, Vissim for modeling/evaluating multi-modal modeling capabilities, Viswalk for pedestrian simulation and their interaction with each other, among others—which can provide insights into broader impacts through aggregated results. Multi-modal demand scenarios are typically used to quantify a range of potential outcomes and sensitivity.
- ***Use GIS-based tools*** to analyze connectivity, equity, and multi-modal facility coverage to inform optimal locations for Complete Street upgrades.
- ***Leverage statistical methods to fill gaps in AMS tools for more realistic assessments of Complete Street projects***. Most high-resolution traffic simulation tools do not directly model mode shift caused by different Complete Street configurations and/or design components. Statistical methods that leverage previous studies or findings from local survey data can help quantify modal behavior for improved modeling results.
- ***Utilize multimodal automated traffic signal performance measures (ATSPM) data*** to assist with multimodal traffic operations decision-making.
- ***Utilize system dynamics models (both qualitative and quantitative) to explain the dynamic interactions*** among infrastructure, policy adjustments, and user response. System dynamics modeling can be used to capture feedback loops, which are essential for understanding how Complete Streets interventions and user behaviors interact over time.
- ***Use available analytical tools to evaluate safety of Complete Streets.*** Most AMS tools are generally capable of outputting many mobility measures but limited in their ability to produce safety performance measures. Deterministic methods outlined in Highway Safety Manual (HSM) such as Crash Modification Factors (CMF) or Crash Reduction Factors (CRF) can be utilized to incorporate safety measures into the planning, development, and evaluation processes.

1 Introduction

1.1 Complete Streets Background

Complete Streets refer to transportation policies, planning approaches, design practices, and operational strategies that aim to enhance safety, accessibility, and mobility for all roadway users regardless of their age, ability, or mode of transportation. A Complete Street is safe, and feels safe, for all users [1]. The Bipartisan Infrastructure Law (BIL) [2] defines Complete Streets as “standards or policies that ensure the safe and adequate accommodation of all users of the transportation system, including pedestrians, bicyclists, public transportation users, children, older individuals, individuals with disabilities, motorists, and freight vehicles.” The Federal Highway Administration (FHWA) has begun assessing and revising its policies, regulations, processes, and practices to help state and local agencies advance and build Complete Streets [1]. These initiatives address five overarching opportunity areas including improving data collection and analysis to advance safety for all users, supporting safety assessment during project development and design to prioritize safety outcomes, accelerating adoption of standards and guidelines, reinforcing the primacy of safety for all users, and making Complete Streets the FHWA’s default approach for funding and designing non-access-controlled roadways [1]. The Safe Streets and Roads for All (SS4A) Grant Program established by the BIL provides funding opportunities to regional, local, and tribal initiatives for transforming a roadway corridor on a high-injury network into a Complete Street with safety improvements [2].

Over the last century, the United States’ transportation infrastructure has prioritized the efficient movement of motorized vehicles on the interstate/freeway network, arterial systems, and through traffic intersections. Additionally, numerous Intelligent Transportation Systems (ITS) strategies and deployments have resulted in enhanced safety, mobility, and agency efficiency for motorized modes. For example, the adaptive traffic signal control or ramp metering applications are focused on minimizing motorized traffic delays. Consequently, typical performance measures, such as traffic throughput or intersection delay, which are intended to account for maximizing vehicular traffic or throughput at a signalized intersection, may need to be reconsidered in the context of Complete Streets. Furthermore, most traffic-based analysis, modeling, and simulation (AMS) tools were developed to analyze traditional transportation infrastructure improvement projects such as adding capacity to an existing roadway, freeway work zone analysis, transportation demand management, optimizing operations, transit improvements, etc. While these tools have matured by incorporating detailed vehicular/driver behavior such as acceleration/deceleration, car following, lane changing, etc., they have limited capabilities when it comes to analyzing non-motorized modes (e.g., bicycle, walk, scooter) and evaluating different Complete Streets design/management approaches. Up to this point, Complete Streets evaluation approaches have been limited to qualitative or descriptive analysis comparing before-and-after data using a combination of sensors and survey methods [3]. Less attention has been paid to quantitative assessment and performance measurement of Complete Streets projects and analyzing the effects of various design components and operational strategies on traffic and travel behavior [4]. This lack of guidance related to quantitative Complete Streets evaluation motivates this comprehensive review of currently available analytical methods and approaches for effective Complete Streets evaluation including the identification of multiple objectives and associated performance metrics that are needed to evaluate all travel modes.

For this report, traffic analysis tool definitions in alignment with the Federal Highway Administration’s Traffic Analysis Tools Program [5] are the focus, and include travel demand models, deterministic tools (i.e., Highway Capacity Manual methods), traffic signal optimization tools, and macroscopic/mesoscopic/microscopic simulation models. GIS software and statistical methods were also included due to their prevalence in the Complete Streets literature.

1.2 Why do Complete Streets Evaluations Warrant a Different Approach?

While effective Complete Streets should integrate seamlessly into existing roadway networks, they require a different set of tools and methods to measure their performance. This is largely due to the historical tendency of both roadway design and evaluation to focus solely on automobiles and their movement through the transportation network. Therefore, traditional performance measures and analysis methods do not fully capture the overall performance of Complete Streets projects. Understanding what differentiates the task of evaluating a Complete Streets project from a traditional roadway improvement project is an important step before evaluation best practices can be identified.

1.3 Document Purpose

The purpose of this report is to serve as a resource for practitioners, researchers, and other stakeholders involved in Complete Streets project evaluation. It offers a comprehensive review of the existing literature to identify Complete Streets evaluation best practices using AMS tools. Common goals and performance metrics for Complete Streets will also be discussed along with AMS approaches to quantify impacts.

1.4 Document Scope

The scope of this report encompasses a wide array of roadway users, such as pedestrians, cyclists, motorists, public transit users, people with disabilities, children and older adults, and micro-mobility[1] users. The report identifies key goal areas for evaluation, recommends performance metrics for each, and demonstrates how some of these measures can be obtained using currently available AMS tools and methods. Additionally, it highlights best practices for evaluating Complete Streets projects in various stages, from planning and design to operations, including the existing analytical and modeling approaches for assessing performance.

1.5 Organization of Report

This report is organized as follows:

- **Chapter 1 Introduction** – provides Complete Streets background, document purpose, and scope.
- **Chapter 2 Complete Streets Evaluation Methods and Techniques** – explains how to establish a structured evaluation framework using available AMS tools and discusses the importance of defining clear goals for evaluation and utilizing appropriate performance metrics.
- **Chapter 3 Evaluation Best Practices** – summarizes the key best practices for Complete Streets evaluation.
- **Chapter 4 Conclusions** – summarizes key findings from report.
- **Chapter 5 References** – lists references mentioned in this report.

[1] In this report, many references to pedestrians and bicyclists also include micro-mobility modes such as scooters, e-bikes, hover boards, wheelchairs, and other personal mobility devices.

2 Complete Streets Evaluation Using AMS Tools

This chapter explains how to establish a structured evaluation framework using available AMS tools and discusses the importance of defining clear goals for evaluation and utilizing appropriate performance metrics. The specific steps involved include stakeholder collaboration and community engagement, outlining Complete Streets goals and objectives, developing performance metrics for each goal area, identifying corresponding evaluation methods and techniques, and re-evaluating goals, design, and evaluation methods. This chapter also provides an overview of various AMS tools used in the Complete Streets context.

2.1 Stakeholder Collaboration and Community Engagement

Stakeholder collaboration and community engagement are essential elements for all transportation projects and Complete Streets are no exception. Engaging stakeholders early in the planning process is important to accommodate the needs of all Complete Street users and to ensure that their needs are considered during evaluation [6]. While we have placed this step at the beginning of the evaluation approach, collaboration and engagement is an ongoing process throughout planning, design, and evaluation phases of the project.

Complete Streets projects require a diverse set of stakeholders due to the numerous design components and holistic set of objectives. To illustrate the complexity of the Complete Streets stakeholder group, the Minnesota Department of Transportation published a list of stakeholders within the State DOT and their responsibilities under their Complete Street policy [7], which includes:

- Project Sponsors (e.g., district engineers)
- Planners
- Project Managers
- District and Office/Modal Public Engagement and Communications Professionals
- Office of Project Management and Technical Support
- Office of Transportation System Management
- Modal Offices
- Traffic Engineers, Landscape Architects, and Designers
- Resident Construction Engineers and Project Engineers

- Maintenance Engineers/Superintendents/Supervisors
- Director – Office of Sustainability and Public Health

Other stakeholder groups may also include:

- Local Government (e.g., elected officials, planning, public works, police, and fire departments)
- Metropolitan Planning Organization (MPO)
- Transit Agencies
- Neighborhood Associations
- FHWA Division Office (if funded by the federal government)

Complete Streets also require continuous community engagement and outreach to ensure the project is meeting the needs of all potential users. The following outreach strategies—adapted from the U.S. DOT's report titled "Promising Practices for Meaningful Public Involvement in Transportation Decision-Making" [8]—are designed to gather diverse community responses respectfully and equitably.

- Use initial outreach activities to identify and understand community demographics, wants, and needs. Listen and incorporate feedback into project decisions.
- Work with community leaders (community-based organizations, non-profits) and build relationships with community members. Leverage these relationships to reach populations often left out of the engagement process.
- Work with community members who have already established trust with disadvantaged communities to gain support (such communities have long history of outsider interference).
- Educate community members on project goals, community costs, and benefits.
- Meet people where they are—in their neighborhoods and homes, over meals, at already established community events, weekdays/weekends, evenings.
- Provide decision-making authority to community members. Establish a framework for co-creation.
- Be sensitive to local norms and culture. Use preferred engagement techniques.
- Track participation—demographics, backgrounds, location of residence—to help inform future outreach activities.

The process of gathering feedback related to community needs and goals from diverse stakeholder groups is integral in establishing expectations and developing an overall evaluation plan supported by all. During this process, it is also important to educate various groups about AMS tools and to leverage these tools to provide feedback and visualizations. This iterative process will help bolster community support through co-creation. The trust built during this process will also be beneficial during the project evaluation phase, when diverse community feedback is needed to assess performance from various user perspectives.

2.2 Goal Areas for Evaluation / Goal Identification

Complete Streets serve a wider range of users than traditional roadways. Consequently, the goals of Complete Streets projects will also be more varied. An effective Complete Street should address specific needs in a community meaning that each project will have context-specific goals. Identifying community-specific goals and adopting a framework to prioritize the various (and potentially competing) goals is a crucial step of the planning stage [9]. Identifying project goals early in the process allows organizations to choose performance measures that best match their unique objectives. Additionally, since funding and evaluation capacity are often limited, adopting a prioritization framework allows evaluators to focus their efforts efficiently and evaluate tradeoffs. The approach proposed in this report is a generalized framework, but the specifics of how an evaluation is carried out should be informed by the project goals.

Benefits of Complete Streets can be far-reaching from increasing active transportation to reducing roadway collisions and severity by decreasing vehicle speed [10]. To properly evaluate the benefits of Complete Streets, clear goals with corresponding performance metrics and indicators need to be established. Specific goals for Complete Street projects may differ, given that a one-size fits all approach for evaluation is insufficient due to the uniqueness of locations and current conditions for each project [11]. Goal areas, however, may be similar across projects. Common goal areas identified in the literature include safety, mobility, equity and accessibility, connectivity, environmental sustainability, and public health [3], [4], [10], [12], [13]. Motivations and definitions for each goal area are provided in the following section (Section 2.3). **Figure 1**. shows potential Complete Streets performance measurement areas that reflect the needs of all roadway users.

Figure 1: Complete Streets Goal Areas for Evaluation (Source: Noblis, 2024)

2.3 Identifying Performance Metrics

Once the goals of a Complete Streets project have been identified, it is important to select performance metrics that are well suited to assess progress towards those goals. Below, common goal areas and corresponding performance metrics were identified for several Complete Streets projects. Many of the metrics listed will be familiar but those that are not have descriptions provided. Additionally, many performance metrics could, and often do, address multiple goals. The fact that they are listed under a certain goal area does not necessarily mean that is the only area to which they are relevant. However, to avoid unnecessary repetition, metrics were grouped with their most commonly identified goal area. Presenting information in this way is meant to mirror the practice of choosing performance measures based on project goals. Currently available AMS tools are also presented for each performance metric grouping along with a brief description of the tools' capabilities and references to gather further information. Strengths and weaknesses of the various AMS tools for evaluation are further discussed in **Table 7**. This section does not represent an exhaustive list of possible goal areas and accompanying performance metrics for Complete Streets, but rather a summary of the most notable ones from the reviewed literature.

2.3.1 Mobility

Measures in this performance area demonstrate how easily and effectively users can move through a roadway or network. Many typical measurements of performance (e.g., total travel time, total delay) fall into this category. Each of these measures can be broken down by individual mode. Example performance metrics under the mobility goal area and how they can be obtained from existing AMS tools are shown below in **Table 1**.

Table 1: Summary of Mobility Performance Metrics and Currently Available AMS Tools

Performance Metrics	Assessment	Applicable AMS tools with descriptions of capabilities
• Travel time (Multi-modal) • Travel distance (Multi-modal) • Travel delay (Multi-modal) • Transit headway • Transit person throughput • Total person throughput • Transit travel time reliability and on-time performance • Mode share	• Most of the mobility metrics can be obtained from existing AMS tools (primarily auto and transit). • Pedestrian and bicyclist measures are dependent on tool's capability to model pedestrian interactions and are generally hard to obtain. • Transit-specific measures can typically be obtained from macroscopic/ mesoscopic travel demand models. • Mode shares are usually obtained from travel demand models/forecasts. Most of existing demand modeling AMS tools are not sensitive to Complete Streets enhancements and generally do not estimate emerging mobility options such as shared micro-mobility.	• Multi-modal (auto, transit and pedestrian) performance metrics using PTV Vissim (in conjunction with Viswalk) and Visum [14], [15] ○ Travel time, travel speed, travel delay, travel distance, transit headway, transit ridership, throughput, public transport waiting times, number of stops, pedestrian density. • Deterministic tools such as Synchro allow for computation of pedestrian and bicyclist delays at signalized intersections [16]. • CUBE, TransCAD, and EMME can generate transit specific measures (e.g., headway, ridership, person throughput, transit travel time reliability, and travel time) [17], [18], [19], [20] • Other microsimulation tools that generate multi-modal performance metrics include Aimsun, Paramics, CORSIM, and TransModeler

• Multi-modal Level of Service (LOS): An aggregate measure which assigns letter grades based on magnitude of use, user experience, ability to reach destinations (i.e., access to destinations), and capacity.	• Auto LOS is captured in majority of the AMS tools.
	• Transit LOS is captured in many AMS tools.
	• Pedestrian and bicyclist LOS cannot be obtained directly from AMS tools' outputs.
	• HCM methods allow calculation of pedestrian, bicyclist, and transit LOS.
		• HCM [13], [21], [22] – Multi-modal LOS (auto, pedestrian, and bike modes)
		  ○ Synchro
		  ○ Highway Capacity Software (HCS)
		• Bentley's LEGION [23] and PTV Viswalk allows computation of pedestrian specific measures at transit facilities (e.g., ingress/egress time, pedestrian crowdedness, pedestrian density, hotspots, flow and occupancy levels, waiting times, queueing time, etc.)

• Lane blockage and utilization rate (bus stops, parking, etc.)	• Lane blockage rate is usually obtained from surveys, field observations, and operational data. AMS tools typically do not report lane blockage or utilization rates as an output.	• Deterministic tools use lane blockage and utilization rates as an input for calculating LOS [16].

2.3.2 Safety

One of the primary objectives for Complete Streets projects is to improve safety outcomes for all road users, including pedestrians, cyclists, motorists, and public transit users. Enhancing safety often necessitates optimizing space allocation for different modes and minimizing interactions between users of different modes [24]. Therefore, a comprehensive Complete Streets safety assessment should include a holistic and systemic approach, considering the needs and safety concerns of all road users. It is crucial that safety measures evaluate both the factors related to injury collisions and those linked to perceptions of safety. Metrics associated with collisions include *frequency*, *severity* (e.g., property damage only, injury, fatal), and *crash rates* over a specific period. These metrics serve to identify and prioritize locations with heightened safety issues, guiding the allocation of resources. Additional indicators like *Post-Encroachment Time (PET)* and the *count of near-miss incidents* can be used to evaluate the risk of crashes occurring within a Complete Street facility, offering valuable insights into potential safety risks. Safety perception measures can be acquired through community feedback regarding their sense of safety and comfort while using Complete Streets. Quantitative data, such as reported collisions, safety incidents, and volume of service calls, also provide valuable insights into perceived safety levels of Complete Streets facilities. Another significant measure associated with the perception of safety is the presence of adequate lighting in low light conditions. Additionally, the visibility of signs and road markings along a Complete Street facility during both daytime and nighttime conditions can serve as indicators of safety. Furthermore, shifts in mode preferences can offer an indication of the safety conditions within a Complete Street. For instance, an increase in active transportation modes such as walking and cycling can signify an enhancement in safety for these modes.

While most AMS tools are limited in their ability to model and simulate safety, there are analytical tools and methods available to evaluate safety. The Highway Safety Manual (HSM) provides methodologies that can be used to quantitatively evaluate traffic safety performance on existing or proposed roadways. To support the implementation of the HSM methodologies, the FHWA has developed supporting tools such as the Interactive Highway Safety Design Model (IHSDM), the Crash Modification Factors (CMF) Clearinghouse, HSM Spreadsheets, and the Systemic Safety Project Selection Tool that help practitioners to incorporate safety measures into their planning, development, and evaluation processes [25]. Most microsimulation AMS tools do not offer the capability to model crashes. However, tools such as the Surrogate Safety Assessment Model (SSAM) can be used to automatically identify, classify, and evaluate traffic conflicts with vehicle trajectory data output from microscopic traffic simulation models. SSAM is capable of identifying traffic conflicts on all types of road facilities and produces measures such as conflict frequency and severity which can be used to assess the relative safety performance among alternative road facilities [26]. Sample safety performance metrics, along with descriptions and currently available AMS tools, are shown below in **Table 2**.

Table 2: Summary of Safety Performance Metrics and Currently Available AMS Tools

Performance Metrics	Assessment	Applicable AMS Tools with descriptions of capabilities
• Crash Frequency/Severity: Number and severity of crashes occurring within a specific jurisdiction, on a roadway segment, or at an intersection. • Post-crash emergency access/response times (incident clearance and response time, time to return to normal flow of traffic)	• Multiple crashes occurring at the same location over a period may be an indication of a safety issue and should be investigated and addressed appropriately. • A breakdown of the number of crashes by mode, age, gender, income, race, ethnicity, and disability status is desirable for effective crash analysis in Complete Streets. • Crash severity should be classified by the degree of injury including fatal, incapacitating, non-incapacitating, possible injury, no injury or a property damage-only (PDO). • Post-crash emergency access/response times are typically obtained from public safety computer-aided dispatch (CAD) system time	• HSM Methodologies based tools: ○ AASHTOWare Safety Analyst ○ HSM Spreadsheets ○ Enhanced Interchange Safety Tool (ISATe) ○ IHSDM ○ Crash Modification Factor Clearing House. • GIS-based Traffic Crash Analysis tools [27] ○ Crash frequency, severity, and hotspots. • SSAM ○ Crash frequency and types

Performance Metrics	Assessment	Applicable AMS Tools with descriptions of capabilities
	stamps, law enforcement traffic crash reports, safety service patrol logs, and transportation management centers (TMCs).	
• Crash rates: Measures the relative safety of a segment or intersection considering exposure data such as traffic volumes or roadway mileage.	• Crash rates provide an effective comparison of similar locations with safety issues. • Complete Streets can also use crash rates to prioritize locations when considering safety improvements with limited resources.	• HSM Methodologies ○ Crash rates, predicted and expected frequencies
• Number of near-miss crashes	• Near-miss crashes can be used to supplement police-reported crashes and may be used as surrogate of actual crashes to identify crash hotspots [28]	• Video camera based detection tools such as the Auto Incident Recording System [29]
• Speed and Compliance with Speed Limits	• The percentage of vehicles adhering to posted speed limits can indicate if speed limits are being observed, which is crucial for pedestrian safety.	• Vissim: average vehicle speed, speed heatmaps, • Synchro/SimTraffic: average speed • HCS [30] • NHTSA FARS [31]
• Pedestrian Cross Times	• Pedestrian cross time is the time that pedestrians take to cross the crosswalk.	• Aimsun Next pedestrian simulator: Pedestrian Travel Time, Pedestrian Walking Time [32] • PTV Vissim (in conjunction with Viswalk)
• Lighting and Visibility	• Adequate lighting helps improve visibility, especially during low light conditions or at night. • Presence of reflective materials in road markings and signage can enhance visibility and improves safety.	There are no AMS tools for assessing lighting and visibility, however there are guidelines for measuring appropriate lighting, including: • AASHTO Roadway Lighting Design Guide Warranting System [33] • AASHTO Green Book • FHWA Lighting Handbook [34]

Performance Metrics	Assessment	Applicable AMS Tools with descriptions of capabilities
• Mode Share and Shift • Pedestrian and Cyclist Volumes	• Mode share measures the proportion of trips taken by different modes of transportation (e.g., walking, cycling, driving) • Increases in walking and cycling mode shares can indicate improved safety for these modes. • Level of exposure of non-motorized modes such as pedestrians and bicycle can provide an indication of the safety of Complete Streets facilities. • The likelihood that a given person walking or bicycling will be struck by a motorist varies inversely with the amount of walking or bicycling [35]	• Activity and Tour-Based Models (e.g., San Francisco Chained Activity Modeling Process [36] • Demand Forecasting Models • GIS Spatial Tools (e.g., Active+, MoPeD) • Network Simulation Tools (e.g., Space Syntax) [37]
• Post Encroachment Time (PET): Measured as the time difference between the time when an offending road user leaves an area of potential collision and the moment of arrival of a conflicted road user possessing the right of way [37]. • Time to Collison (TTC): Measured as the time remaining prior to a collision if the path and speed of road users are maintained as a constant [38].	• PET is usually used to assess pedestrian vehicle conflict and right-angle collisions. • TTC can be used to assess potential collision risk. Higher TTC values indicate more time for vehicles or individuals to react and avoid collisions, contributing to safer intersections	• Vissim • SSAM [38]
• Bicycle Level of Traffic Stress (LTS): Quantifies the level of stress or discomfort one may feel when biking close to traffic.	• Bicycle LTS scores range from 1 (low stress) to 4 (high stress) based on user inputs by facility type	• Bicycle Level of Traffic Stress Calculator [39]

2.3.3 Equity and Accessibility

Equity is a broad term with a definition that varies between different stakeholders and project types. In the Complete Street context, equity is generally defined as the ability for the facility to meet the transportation mobility and access needs for all user groups across the demographic spectrum and for all modes of travel (walk, bike, transit, auto, etc.) [10], [40], [41].

Equity metrics for Complete Streets projects fall into two general categories: 1) outputs and 2) outcomes. Outputs are design decisions that are intended to impact user experience and travel behavior, such as the *number of curb cutouts/ramps*, *audible pedestrian signals*, *transit stop location and design*, *sidewalk width*, *length/type of bike lanes*, among others. Outcomes are direct measures of facility level of service, usage characteristics, and travel behavior changes. Public transit level of service is particularly important because 55% of public transit rider households in the United States earn less than $50,000/year and 60% of transit riders are non-white [42].

The terms *access to destinations* and *accessibility* are often used interchangeably. However, the purpose of this report, the term *accessibility* is reserved for accessible facility design to accommodate people with disabilities. Many AMS tools have built in capabilities to evaluate access to destinations and public transit level of service. One common approach to compute access to destinations is to sum up opportunities (e.g., places of employment, education, social gatherings, healthcare, among others) that can be reached within a pre-defined travel time threshold (e.g., 30 minutes). This process relies on various data sources but can be directly computed using GIS software. Detailed routable network encompassing pedestrian and bicycle facilities is generally required for computing multimodal access to destinations especially when accommodating first-and-last mile connections. Transit level of service using General Transit Feed Specification (GTFS) data, which provides stops, frequencies, routes, and schedules, can be analyzed using current AMS tools (e.g., TransCAD [43]). Predicting the demographic makeup of facility users requires high-resolution, agent-based tools, which are computationally expensive and difficult to interpret. The stochastic nature of such tools and the need to model the broader network to capture travel patterns across population groups creates interpretability issues when trying to extract detailed behaviors at specific locations. For these reasons, standard survey design and statistical analysis is most often used because socioeconomic/demographic feedback can be collected directly from current and future users. Equity and accessibility performance metrics, along with descriptions and currently available AMS tools, are shown below in **Table 3**.

Table 3: Summary of Equity and Accessibility Metrics and Currently Available AMS Tools

Performance Metrics	Assessment	Applicable AMS Tools with descriptions of capabilities
• Community connections (access to destinations)—job opportunities, transit stops,	• Static assessment of how the facility improved non-driving access to desired destinations.	• GIS-based tools (ArcGIS, QGIS)

Performance Metrics	Assessment	Applicable AMS Tools with descriptions of capabilities
micro-mobility hubs, grocery, childcare, etc. that are within 0.5-mile walking distance or 3-mile biking distance.	• This metric usually requires land use and population demographic layers with spatial information along with the physical network. • Usually measured as a sum of opportunities by different modal options and travel time budgets.	• Travel Demand Models (TransCAD, CUBE, Visum, EMME)
• Sidewalk width, number of cutouts/ramps, storefront access • Rate of accessible sidewalk/curb ramp intersection improvements • Bikeway surface condition (roughness index) • Presence of marked crosswalks • Total miles of bike paths in a given locality or jurisdiction • Number of on-street (and accessible) parking spaces • Number and distribution of on-street loading zones per mile • Quality (potholes, uneven surfaces, slope) • Sidewalk/bike lane blockages	• Accessibility for travelers with disabilities, people pushing strollers, people pulling suitcases, and deliveries. • Can be obtained through existing inventories of multimodal transportation infrastructure and facilities. • Some measures such as roughness index and lane blockages require field observation.	• GIS-based tools
• Transit supply/LOS (number of transit stations, average frequency, number of routes, bus travel time reliability, bus blockages) • Transit demand (access/egress counts in corridor) • First/last mile connections (count of bikeshare stations, micro-mobility hubs, curbs for pickup/drop-off) • Count of reachable opportunities based on travel time threshold by transit (e.g., 30 minutes)	• Modeling/predicting transit use behavior for different demographic groups and across modes is important for assessing overall project equity. • Complete Streets can also reduce transit delay through corridor with priority signals, dedicated lanes. Network level access to destinations might also improve depending on the scale of the project.	• GIS-based tools. • Travel demand models (TransCAD, CUBE, MATSim, Visum, EMME)

Performance Metrics	Assessment	Applicable AMS Tools with descriptions of capabilities
• Mode split across population groups (gender, income, race, etc.) • Modal shift toward transit	• Measurable metric to assess equity across demographic groups and modes. • Mode choice in majority of AMS tools is limited to walk, auto, and transit. Micro-mobility modes are not typically well represented in the demand models.	• Survey/statistical methods • Travel demand models (TransCAD, CUBE, Aimsun Next, EMME, Visum, MATSim)
• Distribution of people at local businesses/events • Community participation	• Potentially a way to measure inclusivity. Would require surveys. No AMS tools to model community participation along demographic lines.	• Surveys/statistical methods

2.3.4 Network Connectivity

Network Connectivity is a measure of how well the Complete Street is connected to the greater transportation network. In most cases, Complete Streets projects are limited in size based on a variety of reasons (budget, land use, neighborhood goals, zoning, and transportation needs). While some proportion of trips will both begin and end within the facility boundary, most trips will require use of the greater network beyond the Complete Street corridor. For this reason, and to maximize the potential impacts of Complete Street projects, connectivity must be considered during the planning and design process. Many of the metrics discussed in the following paragraphs are described further in the U.S. DOT guidebook for "Measuring Multimodal Network Connectivity" [44].

The first set of metrics are borrowed from graph theory and network science as ways to describe a network based on physical characteristics. Each mode will have a *network completeness* score that measures the total number of links within modal facilities (e.g., bike lanes) compared to the greater automobile network. *Network density* is a measure of how many different routes a traveler can take between an origin and destination. *Intersection density* (number of intersections per unit area) and *link-node ratios* (number of links divided by number of nodes) have also been proposed as connectivity metrics based on the idea that higher intersection density results in more direct routes and increased route options [45]. Finally, *betweenness centrality* measures the importance of any one node within the network. In other words, how many shortest paths pass through a specific node of interest. The betweenness centrality metric is more relevant for transit planning tasks [46]. The overall benefits of a Complete Street project will depend on where the facility fits within the greater network, and how well it improves network-level connectivity metrics because most trips will not originate and terminate within the facility boundary.

The second set of metrics are more context specific and rely on additional sources of data, such as land use and travel survey data. *Route directness* is a measure of how well the corridor serves through traffic. This could be based on the number of shortest origin-destination paths that traverse the corridor, or a metric that measures the detour required when using the Complete Street as a percentage of overall travel time (or distance). *Access to destinations* is often the count of reachable opportunities within a given travel time budget with closer points of interest weighted more heavily. This metric is usually calculated for each mode separately because travel speeds vary across modes. Finally, *network quality* measures facility quality for different modes. For example, dedicated or separated bike lanes are of higher quality than shared lanes due to lower levels of traffic stress.

The following metrics listed in **Table 4** are static in nature meaning that each metric's respective score is primarily based on the network layout except for level of traffic stress (LTS), which can change based on traffic flows. Therefore, standard GIS-based or transportation specific tools built on GIS platforms (CUBE, Visum, EMME) are sufficient to analyze most connectivity metrics. It is important to note that the definition of connectivity varies for different communities and stakeholders, and the following list is only meant to be a guide.

Table 4: Summary of Connectivity Performance Metrics and Currently Available AMS Tools

Performance Metrics	Assessment	Applicable AMS Tools with descriptions of capabilities
• Network completeness • Network density • Betweenness centrality • Intersection density • Link-node ratio	• Metrics borrowed from graph theory and network science to describe a network based on its physical characteristics.	• Network-based metrics available in most GIS-based tools. • Numerous network analysis packages available using open-source software (python, R, etc.) • CUBE, Visum, TransCAD, EMME
• Route directness • Access to destinations • Network quality	• Transportation focused metrics that are more direct measures of service performance and quality. • Dependent also on land use, points of interest, and quality of infrastructure.	• GIS-based tools (ArcGIS, QGIS, TransCAD)

2.3.5 Environmental Sustainability

The transportation sector is the largest greenhouse gas (GHG) emitting economic sector in the United States responsible for one third of total GHG emissions [47] and accounts for 28% of total U.S. energy consumption [48]. The transportation sector also contributes 45% of total NO_x

emissions, and about 10% of both volatile organic compounds and particulate matter ($PM_{2.5}$ and PM_{10}) emissions [49]. A large-scale, multi-pronged approach will be needed to decarbonize the transportation sector that includes large investments in public transit, rail, and active transportation infrastructure (infrastructure designed for human powered modes, such as bicycles, walking, scooters, among others). [47]. The Complete Street framework integrates many of these ideas, thus resulting in significant environmental benefits if adequately connected to desired locations.

The potential environmental benefits of Complete Streets are largely due to mode shift away from private vehicles to cleaner, more energy-efficient modes of travel (e.g., walking, cycling, public transit) [50]. Therefore, modeling tools that consider destination and mode choice are required to accurately capture environmental benefits. Traffic simulation tools (macroscopic, mesoscopic, and microscopic) quantify CO_2 emissions, energy consumption, and criteria pollutant emissions, however, mode choice isn't directly modeled, thus limiting their ability as a standalone tool for Complete Street evaluation.

A different approach to estimate mode shift more locally is through the bicycle/pedestrian environmental quality index (BEQI/PEQI) [51]. *BEQI/PEQI* is a metric designed to evaluate active transportation infrastructure in terms of safety, street design, land use, and vehicle traffic characteristics. The score is determined through observation by a trained professional based on a scoring system developed from a previous survey of bicycle experts. The scoring system and respective weights are based on individual scores across the following metrics: intersection safety, vehicle traffic, street design, safety, and land use. While BEQI/PEQI are not direct measures of environmental impact, higher BEQI/PEQI scores for a Complete Street that is sufficiently connected with the greater bicycle network will likely result in higher use of active transportation modes, thus helping inform multi-modal demand inputs for various simulation tasks.

Supply-side tools, such as the National Renewable Energy Laboratory's (NREL) Mobility Energy Productivity (MEP) metric [52], can also evaluate environmental benefits of Complete Streets projects by quantifying gains in access to destinations for low-carbon modes. More specifically, each area (or grid cell) within a region is assigned a score based how many opportunities (jobs, healthcare, grocery, etc.) can be reached for each mode (car, bus, walk, bike) within a given amount of travel time (e.g., 30 minutes). Transit, biking, and walking networks are used to calculate travel times. The overall MEP score is then weighted by travel time, energy intensity, and monetary cost. The downsides of MEP are related to computational requirements, no direct access to the tool for transportation decision makers (studies are run in-house), and the inability to directly measure environmental impacts.

Performance metrics to evaluate environmental impacts fall into two general categories: 1) facility design and 2) operations and travel behavior. Examples of facility design metrics are *sustainable sourcing of materials*, *percentage of greenspace*, *number of rainwater gardens*, *use of reflective surfaces*, among others [53]. While some of these metrics can influence traveler mode/route choice, facility design decisions are largely static with minimal interaction with intelligent systems. On the other hand, corridor usage and operational characteristics (i.e., *mode split*, *transit ridership*) can vary significantly based on the use of intelligent systems with varying impacts on the environment. **Table 5** first summarizes metrics related to operations and travel behavior followed by metrics related to design choices that can positively impact environmentally friendly travel behavior.

From an AMS tools perspective, transportation planning tools (e.g., travel demand models, agent-based models) model *mode shift* and estimate *network level energy consumption* and *emissions*. However, attributing macro-level behavioral changes to corridor-level interventions is difficult because the modeling resolution for planning applications does not consider the detail needed to accurately quantify impacts at higher resolutions (e.g., street, corridor, neighborhood). On the other hand, microsimulation tools can estimate energy use and emissions impacts at the corridor level, however, multi-modal demand must be assumed as a simulation input. Therefore, to holistically capture environmental sustainability for a Complete Street retrofit, multiple tools are typically needed with support from real-world data (e.g., surveys to evaluate mode shift, multimodal count data, air quality sensors). In most cases, data specific to Complete Street evaluation is not standard, and would require one-off strategies to accurately capture direct impacts.

Table 5: Summary of Environmental Sustainability Metrics and Currently Available AMS Tools

Performance Metrics	Assessment	Applicable AMS Tools with descriptions of capabilities
Corridor usage/operations metrics – direct evaluation of mobile emissions/energy use		
• CO_2 emissions (kg) • Criteria pollutants (SO_2, NO_x, CO, PM2.5, ground-level O_3) • Transportation energy consumption • Access to electric vehicles charging facilities	• AMS tools can estimate energy/emissions impacts based on network demand and fleet mix inputs with emission model integration (EPA MOVES, EPA Community Line) • Travel demand models can estimate regional mode shift (auto and transit) but not local active transportation mode shift. • Most AMS tools do not consider emerging modes (transportation network companies or TNCs, micro-mobility, on-demand transit)	• TransCAD with EPA MOVES integration, CUBE. • Microscopic models (SUMO, Vissim) can model corridor-level impacts under various roadway configurations and ITS solutions. • Travel Demand/Macroscopic Models (TransCAD, Visum, CUBE, EMME) • Network level activity- and agent-based models (Aimsun and MATSim) can measure regional impacts including mode shift, however model calibration/validation is challenging due to limited behavioral data on non-motorized users • RouteE: Vehicle-level/route-level energy estimation

Performance Metrics	Assessment	Applicable AMS Tools with descriptions of capabilities
• Bicycle/Pedestrian environmental quality index (BEQI/PEQI) - Holistic measure of active transportation environment that includes safety, vehicle traffic, street design, and land use [51]	• Higher BEQI/PEQI scores lead to better environments for bicyclists and pedestrians leading to mode shift.	• Statistical methods/GIS tools: ratings are determined from observational surveys.
• Mobility Energy Productivity	• Energy-consumption weighted scores can be calculated for regions to evaluate access to opportunities using low-carbon modes.	• MEP: quantifies access to goods and services accounting for travel time, travel cost, and energy consumption.
Facility-based metrics – design choices with impacts to sustainability		
• Trees retained/newly planted, lighting, water conservation/runoff	• Trees store CO_2 and mitigate urban heat island. • Vegetation improves active transportation experience. • Many low-energy technologies (e.g., high-efficiency bulbs, brightness control systems) can improve environmental sustainability. • Improved lighting impacts safety (increased visibility) and perception of safety for vulnerable users. • Permeable pavements, rain gardens, vegetation, xeriscaping impact water related environmental impacts and improve corridor operations	• Direct impacts (CO_2): sequestration rates & building heating/cooling energy effects from trees estimated using CUFR Tree Carbon Calculator [54] • Direct impacts (lighting): Many tools to estimate efficiency gains with new lighting technologies [55], [56]

2.3.6 Public Health

A safe and inclusive environment that facilitates active and multi-modal travel for all users can have significant public health benefits through increased physical activity, improved air quality, and safer interactions between motorists and vulnerable road users. Early studies have shown

Complete Streets to increase walking and bicycle counts [57], [58], [59] and improve air quality [59]. However, the ability to accurately model these outcomes remains difficult due to the variety of design options, user preferences, and the influence of local population and infrastructure characteristics (e.g., connectivity to the greater network, population demographics, land use, existing public transit network). Potential metrics to evaluate public health impacts are listed in **Table 6**. Safety impacts are omitted from this section due to a dedicated section for safety-related performance metrics (see Section 2.3.2).

AMS tools to estimate public health outcomes from Complete Street projects are limited because inputs only consider a limited subset of transportation network features (road lanes, bike lanes, sidewalks, intersections, traffic lights, etc.) and land use. However, Complete Streets integrate a variety of design components that affect travel behavior and mode choice that are not currently considered in most transportation modeling software packages. Some examples include lighting, vegetation, shade, covered bus stops, presence of benches, dining platforms, parklets, and public art. This shortcoming will negatively impact the accuracy of mode choice models, which will impact public health metrics related to the use of active transportation modes.

Table 6: Summary of Public Health Performance Metrics and Currently Available AMS Tools

Performance Metrics	Assessment	Applicable AMS Tools with descriptions of capabilities
• Criteria pollutants (SO_2, NO_x, CO, PM2.5, ground-level O_3)	• AMS tools can estimate energy/emissions impacts based on network demand and fleet mix inputs with emission model integration (EPA MOVES, EPA Community Line) • Travel demand models can estimate regional mode shift (auto and transit) but not local active transportation mode shift. • Most AMS tools do not consider emerging modes (transportation network companies [TNCs], micro-	• TransCAD with EPA MOVES integration, CUBE. • Microscopic models (SUMO, Vissim) can model corridor-level impacts under various roadway configurations and ITS solutions. • Travel Demand Models (TransCAD, Visum, CUBE, EMME) • Network level activity- and agent-based models (Aimsun and MATSim) can measure regional impacts including mode shift, however model calibration/validation is challenging due to limited behavioral data on non-motorized users. • RouteE: Vehicle-level/route-level energy estimation

Performance Metrics	Assessment	Applicable AMS Tools with descriptions of capabilities
	mobility, on-demand transit)	
• Bicycle trip share • Walking trip share • Transit ridership	• Greater use of active transportation modes will positively impact public health. • Studies show that transit use contributes between 8-33 minutes of daily physical activity [4].	• Travel Demand Models for regional mode share considering auto and public transit (TransCAD, CUBE, EMME, Visum)
• Number of social interactions (as a proxy for social connectedness)	• The benefits of social connectedness are context specific and an on-going area of research [60]. The value of this will have to be assessed on a case-by-case basis.	• PTV Viswalk, Paramics Discovery
• Health metrics (BMI, weight gain/loss, incidence of cardiovascular disease, diabetes, asthma, etc.)	• This is a measurable downstream outcome metric that can be improved with physical activity and/or cleaner air.	• Survey methods and statistical models that link individual attributes and physical activity levels/pollution exposure to health outcomes.

2.4 Subjective Measures

Several of the performance metrics presented above are flexible in how they are defined. For example, multi-modal equity and racial equity are two different equity metrics that are both applicable to Complete Street evaluation. Therefore, it is important to clearly define goals and measures during initial stakeholder collaboration and outreach.

For the most part, Complete Streets studies reviewed in the previous sections agree in terms of methods used to calculate mobility level of service, environmental impacts, and public health. Connectivity is not well-studied in the Complete Street literature; however, it is anticipated that definitions used will be similar to the broader network science and connectivity community. The definitions of safety, equity, and access to destinations vary between projects and communities and need to be carefully defined during the development of the evaluation framework.

In the following paragraph, several examples of how metric definitions can change in the Complete Streets context are presented. From a safety perspective, collisions, crash rate, and fatalities are common metrics used for general transportation improvement projects. In contrast, Complete Streets also focus on performance metrics for non-motorized modes, such as perceived safety while walking [61], bicycle/pedestrian crash rates [61], traffic calming measures [13], personal security, and number of crashes not involving a vehicle [53]. Next, access to destinations is often calculated by summing all opportunities that a given household or neighborhood can access within a given travel time budget. This approach is less valuable for one-off Complete Street projects but will play a larger role in evaluation tasks as projects grow in scope and expand their footprints through connections with other Complete Street projects. Gains in access to destinations can also be inferred by evaluating outcomes, such as mode share or bus boardings within the Complete Street facility. Finally, from an equity perspective, many different metrics have been proposed for Complete Street projects, such as health equity [61], improved access and performance of affordable modes [62], and improved connections to public transit [53]. More general measures of equity have also been used, such as mode split as a function of age, income, gender, race, and disability status [53].

In conclusion, traditional definitions for various transportation performance metrics might not apply to Complete Streets projects. Therefore, it is important to clearly define all metrics during early stakeholder engagement to set expectations and measure outcomes appropriately in line with community goals and objectives.

2.5 Identifying Evaluation Methods and Approaches

After identifying performance measures for Complete Streets projects, organizations must also identify which approach and tools are best suited to evaluate the chosen measures. Some measures can be best quantified using before-and-after data collection methods or through surveys while others can be obtained by modeling Complete Streets scenarios using AMS tools. This section will introduce and define several traffic analysis tools and methodologies along with their most common applications. Discussion will then be provided about how each approach can be applied to Complete Streets evaluation supported by specific examples identified in the literature. A summary overview of evaluation methods and approaches, along with assessment of key strengths and weaknesses is shown in **Table 7** below.

Table 7: Summary of Evaluation Methods and Approaches

Evaluation Method	Capabilities	Gaps/Limitations
Travel Demand Modeling	• Ability to forecast long-term future travel demand and mode shifts. • Many models only account for walk, auto, and transit modes in the mode choice and traffic assignment steps. • Suitable for obtaining networkwide mobility measures for auto and transit modes (e.g., headway, ridership, person throughput, transit travel time reliability, and travel time). • Some demand modeling tools have built-in GIS capabilities to obtain equity, access to destinations, and connectivity metrics.	• Travel demand models are not very sensitive to Complete Streets enhancements and implementations. They are more tailored for evaluating benefits and impact of major highway/transit improvements in metropolitan areas. • Micro-mobility modes are generally not well represented in mode choice sets.
Microscopic Simulation	• Ability to model individual road users in a transportation network. • Suitable for obtaining mobility measures for motorized vehicles at the microscopic scale (e.g., vehicle speed, delay, and travel time). • Some tools can produce pedestrian related measures (e.g., pedestrian counts, walking time, waiting time, speed). • Simulation outputs may be used to obtain safety measures using other tools such as the SSAM (e.g., crash severity and frequency).	• Need for more resources (time, skills, data, and money) to develop, validate, and calibrate the models. • Most tools are limited in their ability to model interaction between non-motorized modes.
Mesoscopic Simulation	• Mesoscopic simulation tools can take many forms with some having more microsimulation capabilities than macrosimulation capabilities and vice versa. • Suitable for obtaining mobility measures for motorized vehicles at the network, segment, and corridor level (e.g., travel times, congestion levels, delays, mode shares, and transit specific measures).	• Require greater level of effort and resources and do not consider long-term changes in multi-modal demand. • Micro-mobility modes are generally not well represented.
Macroscopic Simulation	• Suitable for evaluating how a project will affect a large transportation network. • Suitable for obtaining mobility measures at the network or corridor level (e.g., total vehicle-miles and average pedestrian delays).	• Tools are not sensitive to Complete Streets infrastructure improvements (pedestrian and bicycle infrastructure enhancements).

Evaluation Method	Capabilities	Gaps/Limitations
Multiresolution Modeling (MRM)	• Integrates models of varying temporal and spatial resolutions including macroscopic, mesoscopic, and microscopic models, and enables data to be shared across modeling platforms. • Multimodal modeling capabilities are based on the tools that are used and how the tools are integrated with one another. • Mobility measures can be obtained at various levels of resolution (e.g., total vehicle-miles, total travel time, and vehicle hours of delay, delay per node, link travel time/speed).	• Need for more resources (time, skills, data, and money) to develop, validate, and calibrate the models. • Integrating models from different resolutions may encounter interoperability challenges. • The accuracy of one model at a specific resolution can influence analyses conducted at other resolutions (e.g., error propagation).
Deterministic Approaches (HCM/HSM Methodologies)	• Quicker and more cost-effective for evaluations compared to other AMS methods such as microsimulation. • Ability to report multimodal level of service (LOS). • Can be used to obtain mobility measures for transit, pedestrian, and bicycle modes (e.g., link- or segment-based LOS). • Safety measures can be obtained using analytical methods outlined in the HSM and implemented in tools such IHSDM, and HSM spreadsheets.	• Limited ability to analyze network or system effects. • Simplified assumptions to model traffic flow and safety, which may not fully capture the complexities of the real-world.
GIS-based Analysis	• Suitable for evaluating connectivity, equity, and access to destinations measures both visually and computationally. • Suitable for obtaining equity, access to destinations, and connectivity metrics by aggregating and analyzing data from multiple sources (e.g., land use, employment locations, socio-demographic, transportation supply, etc.)	• Limited in the ability to model interactions between the various road users. • Relies heavily on the availability and quality of input data. • Analyzing large datasets may require additional computational resources.
Statistical Analysis and Modeling	• Can be used to estimate multimodal demand based on local characteristics and population groups. • Can be used to quantify impacts from Complete Streets design approaches using before-and-after data/collected survey data.	• Accuracy of statistical models relies heavily on input data, which is often time consuming and expensive to collect.

Evaluation Method	Capabilities	Gaps/Limitations
	• Broad and flexible tools to answer a variety of questions at different levels of resolution. • Suitable for obtaining multimodal demand that can be used as inputs for other AMS tools.	• Requires a high level of expertise to tease out causal factors and accurately quantify the influence of various design parameters.

2.5.1 Travel Demand Modeling

Travel demand models forecast long-term future travel demand based on current conditions and future projections of household and socio-economic characteristics. Travel demand models were originally developed to determine the benefits and impacts of major highway improvements in metropolitan areas. As a result, travel demand models are not very sensitive to Complete Streets enhancements and implementations. Furthermore, many existing demand models only account for limited modes such as walk, auto, and transit in the mode choice and traffic assignment steps. However, travel demand models can be used to predict how travel patterns and mode choices change after the implementation of certain Complete Streets scenarios such as transit-oriented development, dedicated bus lanes, or other transit improvements. Given the multi-modal nature of transportation networks coupled with the increased penetration of emerging transportation services such as use of transportation network companies (TNCs), mobility on demand (MOD) or mobility-as-a-service (MaaS), and micro-mobility options, some of the AMS tools have been updated to account for multi-modality [63]. There are several commercial and open-source AMS tools such as CUBE, Visum, Aimsun, MATSim, TransCAD, and Emme that can be used for travel demand modeling to obtain Complete Streets performance metrics. For example, CUBE, TransCAD, and EMME can generate transit specific measures such as headway, ridership, person throughput, transit travel time reliability, and travel time [18]-[21]. While these tools typically implement the traditional four-step process (trip-based) which includes trip generation, trip distribution, mode choice and route assignment [64], updated versions of the tools have incorporated relatively recent methodologies such as tour and activity-based modeling, as well as discrete choice methods [18], [19], [65]. Also, other tools have been integrated with GIS applications that are particularly useful in Complete Streets evaluation [19]. In [4], researchers developed a multi-modal mode choice model that can be used to enhance the traditional trip-based transportation models to account for nonmotorized trips. Using this approach, the researchers were able to measure the resultant non-motorized mode shares due to lower levels of traffic stress (which is a common outcome from Complete Streets projects) [4].

2.5.2 Microscopic Simulation

Microscopic simulation is the modeling of individual road user movements at short time intervals (e.g., per second) for the purpose of assessing the traffic performance of highway and street systems. Thus, microscopic simulation focuses on interactions between individual users in the transportation system. These models provide a detailed representation of the traffic process, taking into consideration the characteristics of individual road users and simulating vehicle interactions in the traffic stream based on car-following and lane-changing models [66], [67]. In the context of Complete Streets, microscopic models are ideal for examining the interactions of multi-modal road users and can be used to estimate several mobility and environmental performance measures. It is worth noting that while most microsimulation tools have matured capabilities in simulating the interaction between vehicles, their ability to simulate interactions with and between non-motorized modes is limited. There are tradeoffs that come with the use of microsimulation for analysis. These include the need for more resources (time, skills, data, and money) to develop, validate and calibrate the models. The FHWA has identified seven key steps to the process for developing and applying a microsimulation model to traffic analysis problems [67]. These steps can be used in any traffic analysis project and are therefore applicable to (though not fully adequate for) the evaluation of Complete Streets. The first step is the determination of the scope and purpose of the evaluation. This involves the identification of project objectives, available resources, assessment of verified and available tools, quality assurance plan, and identification of the appropriate tasks to complete the evaluation. The second step is the collection and preparation of all the data necessary for the microsimulation analysis. Data required for Complete Street evaluation using microscopic simulation will typically include segment and intersection geometries, traffic control data, existing traffic volumes (turning movement counts and origin-destination (O-D) table), travel times and queues data for calibration, as well as data for other modes such as transit, bicycle, and pedestrians. The third step is the development of a base model and involves the coding of links and nodes and their associated traffic controls and link operations. The existing traffic volumes, traveler behavior, and simulation run parameters are also added to the basic network. The fourth step is to identify and correct coding errors in the model. Errors in coding can result in inaccurate calibration of the models. The fifth step is the calibration of the base model. Parameters are adjusted to ensure that the base model matches specific field conditions which are usually not modeled. Due to the time intensive nature of calibration, it is important to document this process to allow other reviewers to understand the basis of the various parameter changes made. The sixth step is where the calibrated model is applied to evaluate various project alternatives. At this stage the relevant performance measures are gathered, and the model is run for each alternative to generate the necessary output. Some output may need further post-processing to obtain certain performance measures. The last step involves summarizing and reporting the analytical approach and results.

There are several AMS tools which can be used for microsimulation modeling of Complete Streets. Examples include Vissim, Synchro/SimTraffic, AIMSUN, SUMO, Paramics, and TransModeler. Various state and local agencies provide frameworks for selection of tools based on factors such as the required performance measures, level of detail, scope, and resources available for the project [68], [69], [70], [71]. While microsimulation tools are capable of outputting a plethora of performance measures for the goal areas discussed in Section 2.3, safety measures are rarely obtained as direct outputs. However, some microscopic simulation tools can provide data which are then fed into other safety assessment tools to evaluate safety. In [72], researchers evaluated the effect of a protected intersection design (PID) for bicyclists on traffic operational performance and safety. A PID provides physical roadway features such as corner islands and road markings to improve pedestrian and bicyclist visibility and reduce their exposure to vehicles. Trajectory data was obtained as an output from a Vissim model and fed into the SSAM to analyze and estimate the number of potential conflicts, type of conflicts, maximum TTC and PET. A similar approach was adopted in [73] and [74].

Researchers in [75] evaluated the operational and safety effects of a Complete Streets network in Atlanta, Georgia using microscopic simulation. A base model of the existing condition was modeled in Vissim and calibrated using travel time data. The model was then modified to include connected bike lanes and increased bicycle demand (assuming a modal shift from automobiles to bicycles), to create two alternate scenarios. Operational performance measures such as average speed, delay, number of stops, and stop delay were obtained as direct outputs from the Vissim microsimulation tool. SSAM was then used to evaluate safety impacts from the Complete Streets network. Trajectory files, which were outputs from the Vissim model, were used as inputs in the SSAM to estimate the number and types of conflicts within the network. The conflict types evaluated included crossing, rear-end, and lane change. Through this evaluation approach, researchers found that Complete Streets resulted in fewer conflicts between vehicles and bicycles, while not adversely affecting vehicular travel time. Similarly, in [66] researchers used a microscopic simulation model to evaluate the networkwide impacts of Complete Streets. A base model of a selected area of downtown San Jose was developed in Vissim and calibrated using travel time data and adjusted driving behavior parameters. Various alternate scenarios which included the conversions of some streets from one-way to two-way streets and adjustment of vehicular volumes to mimic modal shifts were evaluated. Networkwide performance measures obtained from this evaluation include total travel time, distance, and delay. Link level performance measures include average speed, delay, and number of stops.

2.5.3 Mesoscopic Simulation

Mesoscopic simulation tools operate at a level of detail between microscopic and macroscopic simulation, making them a good fit for analyzing Complete Streets projects. Macroscopic simulation and demand modeling tools do not provide the level of operational details and performance measures which can account for realistic estimation of traffic operations reflecting real world Complete Streets scenarios [76]. Microscopic simulation tools on the other hand provide operational-level details, however, they require a greater level of effort and resources and do not consider long-term changes in multi-modal demand [76]. Mesoscopic simulation tools can take many forms with some having more microsimulation capabilities than macrosimulation capabilities and vice versa [77], [78]. There are several mesoscopic simulation tools with capabilities to analyze and model some Complete Street scenarios, such as the classic road diet example (the conversion of a four-lane road to three lanes with a center turn lane). A number of these tools, though primarily built for microsimulation analysis, do have methodologies for mesoscopic simulation, such as TransModeler, Paramics, CORSIM, SUMO, and Aimsun. Typical performance metrics that can be obtained from mesoscopic tools include network, segment, and corridor level travel times, congestion levels, delays, mode shares, and transit specific measures (see Section 2.3 for further details regarding matching AMS tools to specific metrics of interest).

2.5.4 Macroscopic Simulation

Macroscopic simulation involves the use of deterministic relationships of flow, speed, and density of a traffic stream to model transportation networks. Unlike microscopic simulation models which account for the individual interactions of vehicles, macroscopic modeling takes place on a section-by-section basis [79]. Macroscopic simulation is suited to evaluate how a

Complete Street project will affect the larger regional network. The tradeoff is that macroscopic tools are not sensitive to detailed Complete Streets infrastructure improvements (pedestrian and bicycle infrastructure enhancements) since they have fewer capabilities in modeling bicycle/pedestrian interactions. Thus, the decision to use a macroscopic simulation tool as opposed to a microscopic simulation tool depends on the type of metrics desired and availability of resources. For example, if only networkwide or corridor level performance measures such as total vehicle-miles or average pedestrian delays are required, then macroscopic simulation tools are suited for a Complete Streets evaluation. Examples of AMS tools for macroscopic modeling are Visum, FREEVAL, and HCS. Like microscopic traffic simulation, macroscopic traffic simulation does not provide safety metrics as direct outputs. However, some tools have built-in customized GIS-based models (e.g., GIS interface add-on module in Visum) that allow for the geo-location and analysis of safety hotspots and crashes [76]. In [80], researchers used a macroscopic simulation tool (Visum), a GIS-based tool, and other external models to develop a map showing the spatial distribution of metrics including emissions, noise level, safety, and congestion on a transportation network. Such analysis can be used to evaluate and visualize networkwide impacts of Complete Streets.

2.5.5 Multiresolution Modeling (MRM)

Multiresolution modeling is the integration of models of varying temporal and spatial resolutions including macroscopic, mesoscopic, and microscopic models, by enabling data to be shared across modeling platforms to solve a single question or set of questions. When two or more independent models are combined such that the output of one model is used as input to another, a multiresolution model structure is formed. There are two types of multiresolution model structures: full multiresolution and partial multiresolution modeling. In full multiresolution modeling, the macroscopic, mesoscopic, and microscopic models are all integrated into one modeling framework. In partial multiresolution modeling, trip tables produced by regional demand models at a macroscopic level are used as input for either a mesoscopic or microscopic model [81]. A typical multiresolution approach for Complete Streets is to utilize macroscopic modeling to develop and analyze long-term travel demand forecasting scenarios, and to use microscopic analysis to investigate the impacts of operational strategies on individual road users [76]. Multiresolution modeling enhances the evaluation of Complete Streets by providing more comprehensive information about the entire network and greater insight into the interaction of individual road users. However, using multiresolution modeling for Complete Streets typically requires greater budget and time. Proper planning and scoping of activities—geographic/temporal scope, data needs, availability assessment, etc.—should be conducted to determine whether multiresolution modeling is required.

A seamless model integration is necessary to successfully use multiresolution modeling for Complete Streets evaluation. Model integration is the process of combining different traffic models of different resolutions and scales to create a more comprehensive and accurate model of traffic behavior. The simplest way of integrating different multiresolution models is to input the same data into different models. Since this can be time consuming, there are commercial and open-source automated model integration tools to support this process. Some commercial tools automatically import the networks and demands from macroscopic models and convert them to mesoscopic models and then to microscopic models. The resultant model can then be fine-tuned by entering additional microscopic simulation-level details. Other commercial tools have an integration interface feature wherein a single coded network provides the required level of detail across all resolutions. Lastly, unified model integration tools which utilize open data specifications are available.

In multiresolution modeling, consistency is needed between the various levels of resolution. This can be achieved by establishing a feedback loop where information from lower resolution levels informs adjustments in higher resolution levels. For instance, the feedback loop can use outputs from microscopic simulation tools to fine-tune parameters in mesoscopic and macroscopic models. For example, in [82], the DynusT mesoscopic tool was integrated with the Vissim microscopic tool. The researchers converted a regional travel demand model (macroscopic) into a DynusT network. Subsequently, a subarea was extracted from the calibrated larger DynusT network. To facilitate this process, the researchers used a tool called DVC (Dynus-T Vissim Converter). This tool enabled the conversion of DynusT inputs and outputs into Vissim inputs. The following paragraph discusses an example to illustrate how multiresolution modeling was used to evaluate Complete Streets.

A Salt Lake City (SLC) Central Business District (CBD) case study sought to assess the streets that constitute the SLC CBD network and determine the needed improvements to convert them to Complete Streets [76]. Three scenarios were considered: 1) existing (base case), 2) all streets converted to Complete Streets, and 3) partial conversion that supports multi-modality only on portions of the CBD network. Using a multiresolution modeling approach, a macroscopic model of the entire city was developed in Visum, while the downtown area of SLC was modeled in Vissim (a microscopic simulation tool). The macroscopic model allowed for evaluating broad, metro-wide impacts of the proposed scenarios. The team adopted an existing model of the SLC CBD network which was then modified to match current field observations. This was necessary to ensure consistency between micro and macro models. The model was then calibrated by comparing traffic volumes from the field with traffic volumes from the Visum outputs after the traffic assignment procedure was executed. Using the travel times, the macroscopic model was further validated by comparing travel time collected from open-source map applications (Google maps and Waze) with the travel times extracted from the macroscopic model. The microscopic simulation in Vissim focused on modeling the more detailed field operations in the three scenarios. For this purpose, more granular data such as intersection signal timing and intersection turning movement counts, which include vehicular traffic, pedestrians, and bicyclists were used. The microscopic model was also calibrated by comparing field average daily traffic (ADT) data with Vissim volumes validated using field travel times (measured from the middle of an intersection to the middle of the next intersection). To ensure consistency between the microscopic and macroscopic models, volumes and travel time outputs from Vissim and Visum were compared. At the macroscopic scale, the Visum model provided overall mobility measures such as total vehicle-miles, total travel time, and vehicle hours of delay for motorized modes. Using a GIS-based module in Visum, the research team was able to geo-locate and analyze safety hotspots and individual crashes to compute the number of crashes in the network. At the microscopic scale, the Vissim model provided mobility measures such as average vehicle delay/travel time/speed (per vehicle type and average person delay) for motorized modes. The SSAM was used to evaluate the safety performance of the three Complete Streets scenarios at the microscopic scale using SSAM and simulated with desired traffic conditions. The measures obtained from the SSAM included conflict types (e.g., crossing, rear-end, and lane change) and frequency. Note that mesoscopic scale performance measures such as delay per node and link travel times and speeds were also obtained from the Vissim model.

2.5.6 Deterministic Approaches (HCM Methodologies)

The deterministic approach to evaluating Complete Streets involves the use of analytical/empirical/model-based methodologies to predict measures such capacity, density, speed, delay, and queuing on a variety of transportation facilities. While these tools are effective in analyzing the performance of isolated or small-scale transportation facilities, their ability to analyze network- or system-level impacts are limited [70]. In most cases, these tools implement the procedures of the Highway Capacity Manual (HCM). As such, this section focuses on the HCM methodologies that support the evaluation of Complete Streets. Chapter 16 of the HCM [21] provides a multi-modal evaluation framework that considers urban street travel modes and their interactions with other modes. The framework can be used to evaluate the LOS of each travel mode on an urban street. The purpose for which this framework methodology is used determines the level of detail required in relation to input data, default values, and accuracy of the results. The three main purposes identified by the HCM include operational, design, and planning & preliminary engineering. Regarding the spatial scope, while the methodologies are used to evaluate entire facilities, they can be used for selected segments or intersections. The methodologies that comprise this framework include motorized vehicle mode, bicycle mode, pedestrian mode, and transit mode. The main output of these methodologies is LOS. For urban street facilities, the LOS criteria for motorized vehicle mode are based on through-vehicle travel speed. LOS for the pedestrian travel mode is based on three factors: 1) the pedestrian LOS score, 2) the average pedestrian space (ft^2/person), and 3) pedestrian travel speed (ft/s). Similarly, the bicycle and transit LOS are based on bicycle and transit travel speeds and LOS scores. Chapter 18 provides methodologies for evaluating the quality of service of motorized vehicle, pedestrian, bicycle, and transit travel modes along an urban street segment. The performance measures obtained from these methodologies are link- or segment-based LOS. Furthermore, the motorized vehicle, pedestrian, and bicycle methodologies in Chapter 19 can be used to evaluate individual intersections within a facility. The performance measures applicable to the motorized vehicle travel mode include volume-to-capacity ratio, control delay, LOS, and queue storage ratio. The performance measures applicable to the pedestrian travel mode include corner circulation area, pedestrian delay, and pedestrian LOS score. The performance measures applicable to the bicycle mode are bicycle delay and LOS score. Additionally, the procedures in Chapters 20, 21 and 22 can be used to evaluate two-way stop, all-way stop control intersections, and roundabouts, respectively [21].

The methodologies in the HCM are computationally intensive and require the use of software to implement. There are several AMS tools that implement the methodologies in the HCM.

Examples include the HCS, Synchro, Sidra Intersection, and Traffic Engineering Applications Package (TEAPAC) (see Appendix E in [70] for complete list of tools). In Berkeley, California, the HCM methodology was used to evaluate the before and after implementation of a Complete Street on an urban facility consisting of five intersections. The methodologies were implemented using HCS. The 'after' conditions included design changes to facilitate pedestrian and bicycle movement, including new separated bicycle lanes, painted bicycle lanes, buffer areas, signal timing modifications, and the installation of new traffic signals. The performance measures obtained through this evaluation approach were LOS for motorized vehicles, pedestrians, and bicycles [83]. Also, authors in [84] used the HCM methodologies to evaluate the impacts of a Complete Streets as compared to auto-oriented streets. Using bicycle and pedestrian LOS as the performance measures, the results showed that a Complete Street design improves bicycle and pedestrian LOS with no significant impact to auto LOS. It is important to note that the capabilities of the HCM have improved over the years, with the latest versions of the HCM increasing becoming more sensitive to the needs of non-motorized modes including pedestrian crossing treatments and interactions between modes. However, the HCM is still limited when it comes to evaluating safety, which is addressed more by the HSM.

2.5.7 GIS-based Analysis

This spatial organization of various data types makes GIS a powerful tool for a variety of transportation analyses and evaluation tasks because the transportation network is essentially a spatial-temporal optimization problem—connecting people to opportunities across space and time. From a Complete Streets perspective, the types of evaluation most suited for GIS-based tools are related to connectivity, equity, and access to destinations because spatial information has high influence on the specific metric's performance (e.g., the spatial location of the Complete Street corridor within the greater network will significantly impact connectivity).

Starting with connectivity, the exact location of the Complete Street facility within the greater network is extremely important. Dedicated bike lanes that are not connected to the greater bicycle network provide little value for bicyclists with origins or destinations outside of the Complete Street boundary. GIS based analysis enables decision makers to evaluate connectivity both visually and computationally based on network and spatial features, provided a routable network is available and links are properly connected. The U.S. DOT guidebook for "Measuring Multimodal Network Connectivity" [44] provides numerous approaches to evaluate connectivity of walking and cycling networks using GIS-based tools. Connectivity metrics developed specifically for Complete Streets applications are limited, however, a few researchers have analyzed specific components (e.g., bicycle corridor) from a connectivity standpoint using GIS tools. [85] used ArcGIS to measure how well origins and destinations are connected in Seattle using low-stress bike routes based on network and land use data. [86] used ArcGIS to evaluate bike network completeness and directness for 74 cities in the United States. Follow on statistical analysis revealed that completeness and directness were important factors for predicting bicycle commuting.

Access to destinations and equity metrics are also highly dependent on the spatial distribution of people and opportunities and the underlying transportation network. The calculation of these metrics requires various types of information (land use, employment locations/types, socio-demographic data, among others) in addition to spatial information (opportunity locations, work/home locations). GIS tools allow for numerous data types aggregated by spatial location, which is a powerful tool when evaluating transportation system effectiveness for different neighborhoods and population groups. The overall transportation access to destinations literature is rich and often relies on GIS tools to calculate the number of opportunities available in a region within a given travel time budget (e.g., 30 minutes). Similar approaches can be used for Complete Street evaluation (regional changes under proposed design changes); however, the overall size of the retrofit might warrant more local methods to measure access to destinations. Best practices have yet to be established for Complete Streets projects simply due to the variation in project types, but several studies have developed walkability [87] or bikeability [88] metrics more generally using GIS tools.

Many different types of GIS tools exist ranging of core GIS tools (ArcGIS and QGIS) to transportation specific tools built on GIS platforms (TransCAD, CUBE). The core GIS tools are more flexible for defining and calculating metrics. GIS-based tools generally provide improved visualization compared to other AMS tools based on the spatial organization of data. TransCAD, for example, has a transportation focus where GIS is used to answer specific transportation-related questions. Both the core GIS and transportation specific GIS-based tools are used often in the transportation access to destinations and equity literature.

2.5.8 Statistical Analysis and Modeling

Statistical analysis and modeling encompass a wide range of mathematical tools that identify trends and patterns in collected data. In the Complete Streets context, three general statistical approaches have been observed in the literature to answer various questions about mode shift, facility use, and near- and long-term benefits including environmental, public health, and safety. The following section summarizes these approaches and discusses how statistical modeling can help complement more traditional AMS modeling efforts.

First, statistical methods can be used to estimate multimodal demand—which are required inputs for many traffic simulation tools—based on local characteristics (Complete Street design details, population characteristics, build environment, modal access/availability, etc.). The standard approach is to use a discrete choice modeling framework to quantify the influence of local characteristics/design details on mode choices using stated and/or revealed preference survey data. The fitted statistical model (usually Multinomial Logit) can then be used to estimate multimodal demand based on a variety of design scenarios. In some cases, findings from previous Complete Street evaluation studies can be leveraged to estimate multimodal demand in new locations. For example, [4] quantified the influence of Level of Traffic Stress (LTS) on non-motorized mode choice and used the Maryland Statewide Transportation Model to evaluate statewide impacts due to active infrastructure investment to reduce LTS for bicycle and walking modes.

Next, other forms of statistical models can be used to gather specific insights about Complete Street designs, and their effects on travel behavior. For example, one study used active transportation counts and meter-scale landcover characteristics to find positive associations between walking/bicycle counts and street tree cover [89]. A different study used negative binomial regression models and found that dedicated bike lanes improved safety outcomes for all roadway users [90]. The advantage of this approach is that experiments can be designed to answer specific questions to help stakeholders understand Complete Street impacts. However, the large number of design considerations and the uniqueness of each Complete Street implementation creates challenges with respect to transferability of results. The key takeaway from this approach is that statistical models are versatile tools that can be used to answer a variety of questions. However, the accuracy of statistical models relies on the quality of input data, which is often time consuming and expensive to collect. Informative models also require a high level of expertise to tease out causal factors and accurately quantify the influence of various design parameters.

Finally, statistical methods commonly used to assess Complete Street impacts using before-and-after data are briefly discussed due to their prevalence in the existing literature [59], [91], [92]. The general approach is to collect data both before and after Complete Street implementation for the various evaluation metrics of interest. In addition, data must also be collected to control for situations that might create bias. For example, a new electric bike rebate program that is implemented during the data collection period could bias the results by overestimating the magnitude of the effect of the Complete Street itself on bicycle counts. Numerous statistical tools—event-based studies, difference-in-differences, regression discontinuity in time, among others—can be used to evaluate the effect of Complete Streets on various performance metrics. However, careful experimental setup is required to ensure accurate results.

2.6 Confounding Factors

The first step in quantifying the effects of Complete Street projects using modeling and simulation tools is network calibration. Real-world data is collected throughout the network using various sensors and is used to inform modeling parameter adjustments until some pre-defined accuracy threshold is met. Any bias present during data collection or input process will be replicated in the modeling results. Careful consideration is needed when defining the calibration data set to produce accurate results in alignment with the desired metrics.

For analysis tasks, especially for before-and-after studies, controlling for all confounding and omitted variables is a difficult task due to the long durations of data collection that are required and the inability to foresee all possible changes (e.g., pandemic). In essence, one would have to control for all variables in time throughout the full data collection period that may affect the metrics one is trying to measure. Numerous statistical methods have been developed to help aid in identifying issues with statistical models or methods, however, it is incredibly difficult to satisfy all modeling requirements to eliminate bias from omitted and/or confounding variables.

Some potential confounding and/or omitted variables (though not exhaustive) that can affect results are as follows:

- **Policy/regulatory changes that impact behavior change on the network**: This is a broad category that includes numerous travel demand management strategies that can result in shifting travel behaviors. Examples of such strategies include infrastructure pricing (e.g., tolls, parking, congestion), incentives to use alternative modes (e.g., free/subsidized bus pass, employer commute programs), or other public policy programs that might shift travel behavior (e.g., public health programs that award points for using active modes).
- **New investment in infrastructure**: Investments in active transportation infrastructure, public transit systems, or automobile infrastructure will impact mode share and travel behavior. For example, an improved, more connected bicycle network will likely lead to higher bicycle use.
- **Behavior shifts due to emerging technologies:** New modes and service models are changing the way travelers use and interact with the transportation system. The introduction of shared micro-mobility options or the construction of a new pickup/drop-off zone for ridehailing services will impact local travel behaviors. Emerging connected and automated vehicle technologies may also impact travel behavior and mode share.
- **Adoption and use of other influential technologies:** Smartphones and new technologies to aid travelers with various disabilities are enabling new types of travel for specific population groups. For example, the Aria app provides blind and visually impaired travelers with a “second set of eyes” for navigating large, complex airport settings.

The above groupings are only a subset of potential factors that can influence travel behaviors in an increasingly complex transportation system. When evaluating the impacts of Complete Streets projects, it is important to think about all potential factors that can impact travel behavior in the area during the evaluation phase of the project and control for such factors to ensure reliable results.

2.7 Context Sensitive Approach

The goal areas of Complete Streets projects may all be similar, but specific prioritized needs of each project may not be. Therefore, the goals of Complete Streets should be assessed based on the needs of the user population. The safety needs of a dense urban city block will vary from that of a rural corridor, as they have vastly different land uses, population densities, connectivity demands, environmental needs, equity needs, etc. As previously stated, the evaluation of the effectiveness of Complete Streets requires the initial input of community stakeholder needs, including surveys and local data. Stakeholder input speaks to current and future land use priorities, as well as community-specific priorities such as tourism, historical preservation, or communities with high concentrations of vulnerable road users (i.e., children, elderly, users with disabilities).

Context sensitive design evaluations require the understanding of trade-offs. In cities where pedestrian traffic positively correlates to revenue, stakeholders will advocate for wider sidewalk space to increase pedestrian capacity, thus increasing potential revenue for street facing shops. Resulting trade-offs may be between dedicating space for sidewalk, dedicated bus lanes, dedicated bike lanes, or on-street parking. There will likely also be trade-offs between pedestrian safety/perceived safety and automobile mobility. Local data and relevant stakeholder input are crucial to these decision-making processes.

Similarly, in areas with many schools and families with young children, safety, connectivity, and local air quality might be priorities, which could have negative implications for automobile and public transit level of service. Speed limit regulations, pedestrian and bike signal phases, pedestrian infrastructure and motorized traffic calming measures, and the analysis of these strategies/applications would be paramount. Evaluations of travel time reliability and public transit level of service, for example, should still be considered but should be weighted according based on local priorities.

Evaluation must begin with a clear understanding of these priorities. Quantitative measures of desired outputs should also be sought after but may not always be available. Examples of this are the preservation of landmarks or environmental elements, some aesthetic measures, and user satisfaction.

3 Evaluation Best Practices

This chapter summarizes the best practices for evaluating Complete Streets projects, encompassing data collection, performance measures and prioritization, and modeling techniques using currently available AMS tools.

3.1 Evaluation Plan Development

Like any transportation project or investment, there is a need to track metrics to evaluate various policies and initiatives to inform current and future actions. Complete Streets are no different. However, the all-encompassing design philosophy and set of potential impacts extends well beyond automobile-centric transportation improvement projects and requires teams of diverse stakeholders with priorities that can be in competition. Therefore, a systematic evaluation plan is needed to balance the various goals and priorities of different stakeholder groups to establish expectations and ensure widespread support [61].

When developing a Complete Streets evaluation plan (a structured framework used to document methods, criteria, and strategies to determine if goals and objectives are achieved), the first step is to identify all potential stakeholders for collaboration. Early collaboration is integral to identify metrics across diverse perspectives and garner support. Gathering feedback from these interactions will help define community needs and desires, which will then inform potential metrics and performance measures. Best practices related to the evaluation plan development process are as follows:

- ***Define the project geographic scope*** (block, corridor, network). Appropriate metrics and data collection strategies will vary based on the scale of evaluation tasks [13], [53].
- ***Separate outputs and outcomes*** in the evaluation framework. Outputs are decisions made during design with the intention to improve the corridor in ways to meet predefined objectives (e.g., crossing distance, protected bike lanes). Outcomes are the actual impacts of the design (e.g., crash counts, mode share). The two forms of metrics are needed to determine the cause and effect [53], [61], [93].
- ***Complete Streets designs and anticipated impacts are context specific***. Review local policies, active projects, and long-range transportation plans to help define metrics and overall success. Impacts from one Complete Street project may not be transferrable to others, even with similar designs. Be flexible and leverage results to inform future designs, even if the benefit was less than expected [13], [93].
- ***Identify appropriate and cost-effective data collection strategies*** that align with objectives and initiate any collection tasks that might be unique to the Complete Street project prior to

implementation. In most cases, both before and after data are needed for evaluation model development, calibration, and validation.

- ***Use both quantitative and qualitative data*** for evaluation. The combination of data types provides a richer narrative and deeper understanding of Complete Street impacts. Additionally, different stakeholders are interested in different types of outcomes, which might require support from qualitative data [53].

Evaluation plans require flexibility, interpretability, and compromise (e.g., traffic calming measures might improve corridor safety at the expense of vehicle travel time). The transportation system is one component of an extremely complex urban environment, although not all Complete Streets projects are confined to urban areas. Efforts should be made to simplify the evaluation approach, such as choosing metrics that can easily be collected/calculated and interpreted by the public. A holistic approach is also required to think outside the box and not be blinded by the data. For example, the lack of cyclists after a retrofit might be due to the proximity of the Complete Street to the greater bike network and have nothing to do with the presence of protected bike lanes. Finally, develop a holistic set of metrics focused on community objectives, and do not be constrained by return on investment. Such a framework can negatively affect transportation equity goals [53].

From an AMS perspective, a similar thought process is required to evaluate modeling and simulation results. It is also important to select the appropriate AMS tool to answer questions that are in alignment with the evaluation plan. For example, a highly accurate modeling result for traffic delay may not be necessary for projects with primary objectives related to mode shift. AMS tools can be powerful means of communication if aligned with project goals and objectives.

3.2 Data

This section consists of two subsections regarding data. Section 3.2.1 37 covers data for AMS tools and Section 3.2.2 covers data for before and after studies.

3.2.1 Data for AMS Tools

Complete Streets aim to improve facility performance and experience for all modes including walking, bicycling, micro-mobility, on-demand mobility, and public transit. Therefore, the ability to estimate mode shift and simulate modal interactions is paramount for Complete Streets evaluation. While no current tools exist to holistically evaluate Complete Street projects, strategic data collection efforts can help inform impacts, bound uncertainty, and calibrate models using currently available AMS tools.

Starting with microsimulation, inputs include road geometry, traffic control, multi-modal demand, traffic volumes, and turning movement data for calibration. The first step is to define the network and calibrate the model based on real-world observations. Therefore, the model is only as good as the data that is being collected, which in most cases, is heavily focused on traffic movements and motor-vehicle level of service. The most common microsimulation approaches for Complete

Streets evaluation focus on the impacts of reconfiguration on traffic level of service (LOS). Various demand scenarios have been estimated and simulated to gather broad insights (e.g., delay impacts of increased traffic demand by 5% under new configuration) [66], [94]. A different study fixed multi-modal origin-destination demand inputs for vehicles, pedestrians, and bicycles and simulated different infrastructure scenarios (e.g., removing motor-vehicle lanes to better accommodate bicycles). All data including bicycle and pedestrian counts were obtained from the Swedish Traffic Authority [95]. For the most part, data inputs required for microsimulation are collected by local jurisdictions and include traffic volumes, turning movements, parking capacity and locations, traffic signal timing information, on/off-ramps, among others. Active transportation counts have been shown to be less reliable and were often estimated from travel surveys [96]. However, new low-cost ITS sensors reduce the costs associated with multi-modal data collection, which have allowed cities and jurisdictions to expand non-motorized data collection efforts for analysis and visualization [96]. This same data can be used to help improve the accuracy of microsimulation models using real-world multi-modal count data.

Other studies have leveraged macroscopic frameworks to estimate mode shift resulting from Complete Streets. First, [76] used a macrosimulation model to estimate multi-modal demand inputs for microsimulation tasks along the Complete Street corridor. Macroscopic origin-destination demand data was provided by local MPOs. [4] conducted a discrete choice survey to evaluate the importance of LTS on bicycle and pedestrian demand. Findings were then used to modify input origin-destination demand tables for more realistic simulation results. This approach allowed modelers to leverage existing studies to improve demand estimations. For example, the odds travelers will use active modes are 1.39 times higher with 10% greater sidewalk tree cover [89], or higher levels of traffic stress reduced willingness to use active modes [97]. If prior research is not available, specific Complete Street design components can be assessed prior to implementation through outreach and statistical modeling for improved location-based results.

Best practices related to data collection for AMS tools are as follows:

- ***Utilize ITS sensors to collect multimodal transportation data.*** These are embedded sensors (e.g., video cameras, radar, inductive loop sensors, ultrasonic sensors, active/passive infrared) used to collect real-time transportation data, which can passively collect most standard operational data including traffic counts/speeds, bicycle counts, pedestrian behavior, emissions, among others, that are used to inform various modeling efforts from base model development to model calibration and validation tasks [96], [98], [99], [100]. The continuous collection process also eliminates bias that arises with manual field counts (difficult to capture day-to-day or season-to-season variation) and reduces data collection costs. ***Placement of ITS sensors should be carefully chosen*** so that data is not mixed between modes (e.g., vehicles mistaken for pedestrians or bicyclists) [101]. ***Calibrating ITS sensors*** is also crucial for ensuring the accuracy of the traffic data collected [101].
- ***Advanced sensors (e.g., LiDAR) or cameras with automated detection and classification algorithms*** that can identify emerging modes, such as micro-mobility, ride hailing, and on-demand transit, can ***further support microsimulation efforts to capture corridor-level conditions*** more accurately (although, it is important to mention that current microsimulation

tools do not model specific behaviors associated with the different emerging modes) [102]. The accuracy of such machine-vision based detection/classification systems has improved with recent research advancements in this domain. An accuracy of up to 97% has been reported, for instance, for automated pedestrian counting systems based on LiDAR data [103]. According to another study by Carnegie Mellon University [104], 95% accuracy was achieved using machine vision-based counting of pedestrians and bicyclists. Despite these results, several considerations should be made while leveraging artificial intelligence and machine learning approaches such as ***validating data using other sources such as manual counts or surveys, mitigating model bias and misrepresentation, model generalization, and incorporating human-in-the-loop*** validation mechanisms.

- ***Ensure data quality*** by defining clear data requirements, developing a comprehensive data collection and management plan, implementing quality assurance and control procedures, cleaning data to remove errors, outliers, and duplicates, and documenting all aspects of the data collection process including assumptions and/or limitations [44]. Once the data quality is assessed, identify specific performance metrics especially for projects covering multiple regions [105].
- ***Use consistent and standardized metrics and data collection protocols*** so that benchmarks can be used for comparisons within and between projects. Studies have also suggested that transportation agencies should use consistent data standards to represent multimodal transportation facilities and network data attributes [44], [106]. Data standardization also facilitates interoperability, enabling efficient data sharing among agencies involved in projects spanning multiple jurisdictions.
- ***Conduct travel behavior and choice surveys*** sensitive to multiple Complete Streets contexts and inclusive of emerging modes of transportation to realistically account for realistic mode choice modeling. A study suggests that findings from updated surveys should be used to update AMS tools such as macroscopic demand models [4]. Other studies have suggested increasing the survey sample size, diversification of survey samples representative of population segments, and conducting sensitivity analysis of acceptable walking and biking distances to transit for multi-modal coordination [66], [107], [108].
- ***Build comprehensive databases of Complete Streets infrastructure facilities.*** Multiple studies have identified the need for transportation agencies to collect, update, and maintain GIS datasets and inventories of various Complete Streets facilities such as bike lane widths, roadway slopes, pavement and sidewalk conditions, signing and pavement markings, crosswalks, etc. [1], [100], [109]. These datasets can help develop Complete Streets implementation plans and project prioritization frameworks based on the critical infrastructure gaps, as well as be used as inputs for AMS tools.

3.2.2 Data for Before-After Studies

Finally, and most prevalent in the literature, are before-and-after studies [3], [10], [83], [107]. While such studies are context specific and provide limited information about the influence of specific design considerations on observed outcomes, their broader level impacts can help inform future modeling tasks when many studies (and findings) are aggregated. Best practices related to data collection for before-and-after studies are as follows:

- For field data collection, ***plan several collection periods to capture different traffic conditions*** (peak vs non-peak), travel days (weekday vs weekend), and seasons (winter vs summer). If variation is high, and one collection day has a high influence on the overall findings, plan to increase the number of data collection days to reduce overall influence of any one observation.
- A toolkit for Complete Streets evaluation developed by Broward Metropolitan Planning Organization suggests establishing working relationships with partner agencies to ***collaborate on data collection*** for evaluation, ***establishing baseline data*** collected prior to the implementation of project, ***being clear about measuring outputs versus outcomes***, and creating metrics that are tied to ***community goals and are obtainable*** [13].
- Different metrics require different data collection time periods. Longer time periods are needed for rare events, e.g., collisions. The National Association for City Transportation Officials recommends ***safety data to be collected for 3-5 years prior and at least 1-3 years*** after transit improvement projects [110]. For other metrics, it is recommended to collect at least 1 year of data before and 1-3 years after retrofit construction [53].
- ***Collect data beyond the Complete Street corridor*** to gain broader insights and reduce bias.
  - E.g., traffic data collection on adjacent streets to capture changes in routing behavior.
  - E.g., placing emissions sensors away from roadway to control for base-level regional air quality.
- ***Collision data can often be collected through state and local data portals*** (online platforms that municipal authorities used to store and share collected/generated data) when a vehicle is involved. However, near misses and/or pedestrian/bicycle crashes with no car involved are often not reported. Several methods and technologies exist using computer vision algorithms to analyze traveler trajectories, which can all be collected using low-cost or existing closed-circuit television (CCTV) surveillance cameras. According to a report by Iowa State University [111], model accuracy for vision-based traffic congestion and incident detection ranged between 85% to 91.2% for motor-vehicle conflicts. The applications for identifying vehicle conflicts and near-missed incidents involving other roadway (e.g., pedestrians and bicyclists) are limited and more work should be carried out in this domain. A study on the use of crowd-sourced data suggests that near-miss incidents should be included in the scope of safety data collection for pedestrians and bicyclists in order to get a complete picture of incident hotspots [112].
- National Highway Traffic Safety Administration's (NHTSA's) ***Fatality Analysis Reporting System (FARS) databases*** and associated toolkit can be used to access historic data (1975 to present) regarding fatal injuries and crashes involving motorists and non-motorists by location (e.g., state, county, city, corridor, intersection, or other user-defined criteria) [113]. The tool also allows to calculate fatality rates per 100 million vehicle miles traveled or per 100,000 population. This can be a useful resource for collecting baseline statistics for before-and-after comparisons of Complete Streets projects.
- ***Mode shift data can be directly measured through surveys or inferred by analyzing multi-modal count data***. However, specific controls are needed when inferring mode shift using count data because vehicle travel routes can move to adjacent streets, making it difficult to determine without expanding the data collection boundary if the vehicles are simply rerouting or if mode shift is occurring. A study suggests that ***non-motorized shares obtained from stated-***

preference choice surveys should be validated against census data and regional/national household travel surveys [4].

- Automobile level of service metrics can be ***analyzed using third party and crowdsourced data providers*** [114], [115], [116]. Some companies provide vehicle data for purchase that includes link-level travel times and speeds for any period. This option might be preferred when access to installed sensors is restricted. Further, the capabilities have been extended to provide multimodal counts and behavior data including pedestrians and bicyclists [117].

The long duration of data collection required for before-and-after studies creates challenges when calculating the causal effects of Complete Streets. Data collection strategies mentioned above help reduce possible bias, however, it is difficult to control for situations that might influence observations during the collection period. Different studies have used various statistical approaches, such as G-Computation [118], differences-in-differences [92], hierarchical Poisson models controlling for time period, seasonal effects, and random effects [91], empirical Bayes [119], among others. The key takeaway here is that additional (and often complex) statistical analysis is required to accurately measure the effect size of Complete Streets project using before-and-after data.

Lastly, documenting data collection methods and known gaps/limitations is extremely important for study transferability. All sources of error and data cleaning/filtering processes should be made explicit for transparency and reproducibility.

3.3 Analysis and Modeling Techniques

Complete street projects have wide ranging goals that are impacted by travel behavior, mode choice, and network design. The analytical methods to model these different aspects of the transportation system are distinct, which makes it difficult to holistically model impacts with one set of AMS tools. A review of the Complete Street literature shows that most studies that leverage existing AMS tools focused on one or a few metrics (e.g., traffic delay, mode shift). The studies that analyzed Complete Street impacts more holistically tended to use statistical methods informed by before-and-after data to draw broader conclusions [10]. Overall, studies that used AMS methods were sparse in comparison to before-and-after studies. Nonetheless, the use of AMS tools for Complete Streets evaluation provides unique insights into the impacts of Complete Streets such as traffic operational metrics and interactions between the various road users, that may not be obtained through statistical methods. The objectives of a Complete Street evaluation would inform the types of AMS tools or techniques to be used. While a specific AMS tool may be suitable for obtaining metrics of a specific goal area, it may not necessarily be appropriate for other goal areas. In that regard, to achieve the full potential of AMS tools, it is likely necessary to use more than one AMS tool or technique to obtain metrics for multiple goals. Complete Streets literature provide several best practices, some of which are summarized below.

- ***Use activity- and agent-based modeling/simulation approaches to model newer forms of mobility*** such as shared micro-mobility, MaaS, MOD, and electric vehicle charging stations management. Agent-based models can be applied by simulating the actions and interactions of autonomous individuals with a view to assessing their effects on the system as a whole [120]. Due to their disaggregate nature, agent-based models can account for complex interactions and heterogeneous behaviors in a multi-modal transportation context utilizing a bottom-up approach. Agent-based models can generate link-level estimates of travel time, delay, speed, queue lengths, capacity utilization, network access to destinations measures, emission factors, energy consumption, and noise pollution in addition to capturing mode shift by modeling individual behaviors [121]. Additionally, agent-based modeling for transportation applications has seen exponential growth in recent years as new modeling frameworks are introduced as a result of increased computing power [122]. An agent-based model in New York City was developed to support walk and bicycle infrastructure investment decisions [123]. The model included active transportation modes (e.g., walk and bicycle) in the mode choice steps to answer critical questions, such as, how many agents walk or bike to work? Other applications of agent-based models include bus network redesign alternatives, MOD scenarios, and simulating bike-sharing systems and TNCs [124], [125], [126].

- ***Use a multiresolution modeling approach to obtain performance metrics at various scales of resolution***. Multiresolution modeling provides more comprehensive output information and greater insight into the interaction effects of individual road users as well as networkwide traffic characteristics. However, using multiresolution modeling requires greater resources (budget and time). In that regard, effective planning and scoping of activities should be done to determine whether multiresolution modeling would be efficient in a specific context. Furthermore, close collaboration is essential in multiresolution modeling to maintain consistency in traffic performance estimations across levels of resolution, and ensure accurate coded network geometry, precise demands, and appropriately calibrated traffic flow models. It is recommended to fine-tune parameters for all levels of resolution (macroscopic, mesoscopic, and microscopic) to improve model accuracy. Using tools that automate the conversion of networks between the macroscopic, mesoscopic, and microscopic levels greatly reduce the level of effort required.
- ***Deterministic methods (HCM methods) are simple and quick approaches for estimating multi-modal level of service*** through a Complete Street corridor and are generally preferred when resources are limited. However, when using such methods, specific considerations, assumptions and/or techniques are needed to minimize errors. First, analysis periods exceeding one hour are not advisable due to the steady traffic condition assumption. Next, HCM methods are not appropriate for short urban street segments due to complex interactions between traffic movements and traffic control devices at boundary conditions. Finally, to evaluate Complete Streets at the facility level, performance measures along individual links must be aggregated.
- ***Microscopic models can be used to gain deeper insights*** into the interactions of multi-modal road users. However, they require greater resources (time, data, money, and skills) to develop, validate, and calibrate compared to other models. It is advisable to use at least two key performance measures when calibrating microscopic models. One measure could be either speed or travel time, while the other measure could be bottleneck throughput or duration [127]. Note that the available commercial and open-source microscopic simulation tools have varying capabilities. For example, some tools (e.g., CORSIM) do not have extensive multi-modal functionality. Other tools such as Synchro/SimTraffic are effective in optimizing traffic signal operations. Also, some tools such as Vissim provide multi-modal modeling capabilities however they do not provide HCM outputs, which may be a requirement of some state and local agencies [66].

- ***Macroscopic simulation approaches and travel demand models*** are best suited for Complete Streets evaluation if network- or link-level performance metrics (e.g., total vehicle miles traveled, average pedestrian delays) are desired [76]. These tools can also be used to forecast the impact of transit improvements projects at a network-level on mode choice, ridership, and transit LOS. While there are limitations in terms of available modes that can be analyzed using existing AMS tools (macroscopic demand models), a study conducted in Baltimore-Washington Area recommended ***developing a data-driven mode choice modeling approach to estimate both motorized and non-motorized mode shares*** [4]. The study also suggested to update travel demand models based on updated mode choice preferences as indicated by surveys and experimental designs.
- ***Use GIS-based tools to analyze connectivity*** [128], ***equity*** [129], and ***multi-modal facility coverage*** [13] to inform optimal locations for Complete Street upgrades. These analyses can provide valuable insights to determine the most suitable locations for implementing Complete Street projects.
- ***Leverage statistical methods to fill gaps in AMS tools*** for more holistic assessments of Complete Street projects. Most high-resolution traffic simulation tools do not directly model mode shift caused by different Complete Street configurations and/or design components. Statistical methods that leverage previous studies or findings from local survey data can help quantify modal behavior for improved modeling results. For example, previous studies have found higher rates of walking on streets with increased tree cover. These findings can be used to estimate mode split based on proposed tree cover for the Complete Street project.
- ***Utilize multimodal automated traffic signal performance measures (ATSPM) data to assist with multimodal traffic operations decision-making.*** ATSPM refer to a suite of performance metrics, data collection, and data analysis tools to support objectives and performance-based approaches to traffic signal optimization [130]. Many state and local DOTs have implemented these systems to measure and display signalized intersection performance. Depending on the type of traffic signal controller and associated set of sensors and detectors, the tool may be able to report pedestrian demand, pedestrian delays, and sensors on top of many auto-centric performance metrics [131], [132]. These metrics can not only be used to optimize multimodal traffic but also provide a valuable input to AMS tools (e.g., signal optimization tools, micro-simulation tools, etc.). Studies [131], [132], [133], [134] have reported that ATSPM can show real-time and historic functionality at signalized intersections, help identify vehicle and pedestrian malfunctions, identify operational deficiencies, optimize traffic signal timing for multiple modes, and are a cost-effective solution.
- ***Utilize system dynamics models (both qualitative and quantitative) to explain the dynamic interactions*** among infrastructure, policy adjustments, and user response. System dynamics modeling can be used to capture feedback loops, which are essential for understanding how Complete Streets interventions and user behaviors interact over time. These models can incorporate behavioral factors such as mode choice preferences, safety perceptions, context sensitivity, as well as social interactions. By capturing these dynamics, the model can provide insights into the factors driving user behavior and inform strategies to encourage sustainable and safer transportation choices. System dynamics modeling has been used by researchers and practitioners for various applications such as quantifying the impacts and locations of road icing [135] and measuring the benefits of active modes of transportation [136].

- ***Use available analytical tools to evaluate safety of Complete Streets projects.*** Most AMS tools are generally capable of outputting many mobility measures but limited in their ability to produce safety performance measures. It is recommended to use available analytical tools such as IHSDM, CMF, HSM Spreadsheets and the Systemic Safety Project Selection tool for safety evaluations. Additionally, SSAM can be used alongside microsimulation tools to identify traffic conflicts and obtain measures such as conflict frequency and severity.

4 Conclusions

In summary, this report surveyed the existing Complete Streets literature and identified common goal areas and modeling techniques used for evaluation. Within each goal area, specific performance metrics were matched with appropriate AMS tools based on data requirements and software capabilities. A discussion and literature review then followed focused on AMS tool groupings, their most common applications, and how they have been applied to Complete Streets evaluation tasks. Finally, best practices were identified related to data collection, evaluation plan development, and evaluation using AMS tools.

The key takeaway from this effort was that the complexity of Complete Streets designs and the diversity of outcomes create challenges when using AMS tools for evaluation. Many AMS tools have numerous capabilities which can be applied to different Complete Streets components, yet they tend to focus on one goal area or set of metrics (e.g., traffic level of service), thus limiting their ability to capture the potentially broad set of positive impacts. Moving forward, more flexible and holistic modeling tools that are sensitive to Complete Streets infrastructure improvements and that consider multiple modes of transportation and their interactions with other users/modes are needed to realistically model Complete Streets.

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