Complete Streets Modeling Capabilities and Gaps

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Final Report – May 10, 2024

FHWA-JPO-24-135

U.S. Department of Transportation

Produced by Noblis
U.S. Department of Transportation
Office of the Assistant Secretary for Research and Technology
Intelligent Transportation Systems (ITS) Joint Program Office (JPO)

Notice

Technical Report Documentation Page

1. Report No.
FHWA-JPO-24-135

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
Complete Streets Modeling Capabilities and Gaps

5. Report Date
May 10, 2024

6. Performing Organization Code

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8. Performing Organization Report No.

9. Performing Organization Name and Address
Noblis, Inc.
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Washington, D.C. 20024

10. Work Unit No. (TRAIS)

11. Contract or Grant No.

12. Sponsoring Agency Name and Address
Intelligent Transportation Systems (ITS) Joint Program Office (JPO)
1200 New Jersey Avenue, S.E.,
Washington, DC 20590

13. Type of Report and Period Covered

14. Sponsoring Agency Code
HOIT-1

15. Supplementary Notes
Work Performed for: Hyungjun Park (ITS JPO; TOCOR)

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. sign, and operations. The purpose of this report is to summarize the Complete Streets modeling capabilities and gaps. This report provides a review of existing analytical and modeling approaches at various phases of Complete Streets project development including planning, design, and operations. These analysis, modeling, and simulation (AMS) approaches include but are not limited to travel demand modeling, simulation approaches, multi-resolution modeling (MRM), highway capacity manual (HCM), highway safety manual (HSM), and geographic information system (GIS) methods. The report further identifies gaps in existing modeling approaches, limitations in the applicability of various AMS tools, and data collection and procedural gaps for Complete Streets analysis and modeling. The target audience for this report includes a range of practitioners, tool developers, and other stakeholders involved in urban planning, transportation, and policy development related to Complete Streets.

17. Keywords
Complete Streets, Analysis, Modeling, Simulation, Multimodal, Inter-Modal, Modeling Capabilities, Gaps, ITS

18. Distribution Statement

19. Security Classif. (of this report)

20. Security Classif. (of this page)

21. No. of Pages
39

22. Price

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

Acknowledgements

The authors would like to thank the U.S. Department of Transportation (USDOT) Intelligent Transportation Systems (ITS) Joint Program Office (JPO) for sponsoring this work. Specifically, the authors would like to thank Hyungjun Park (ITS JPO, Task Order Contracting Officer's Representative).

The authors would also like to thank Gene McHale (FHWA Office of Safety and Operations Research and Development, Turner-Fairbank Highway Research Center) and Jeremy Raw (FHWA Office of Planning) for providing valuable feedback.

Table of Contents

List of Tables

List of Figures

No table of figures entries found.

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 the Complete Streets modeling capabilities and outline the gaps in analysis, modeling, and simulation (AMS) methods and techniques. An understanding of the available modeling capabilities can help determine the best approach for analysis of a Complete Streets project. Efficient modeling approaches should be able to handle multimodal analysis and more complex intersection geometries. Most traffic-based AMS tools have been developed to model the type of transportation infrastructure improvement projects common across North America over the last century. The approach for this document included conducting a review of the existing AMS tools and projects that have utilized these tools to analyze a Complete Streets project. This is not an exhaustive list of all AMS tools available, but it covers tools that are currently being used within industry and research to understand their modeling capabilities.

This document first looks at Complete Street use cases and the elements that make up the use cases within Chapter 2. Complete Street use cases are context sensitive to project, location, and end goal. To discuss the existing modeling capabilities, an understanding of the type of use cases needed for Complete Streets is overviewed. These use cases have been outlined by stakeholders, researchers, and practitioners to highlight some of the key elements for Complete Streets. Three major elements noted include pedestrian/bicycle infrastructure, traffic calming strategies, and public transit accommodations. Some examples of Complete Streets use cases include classic road diets, transit-oriented development, and shared used development. These scenarios offer various benefits that enhance mobility options and increase overall safety. Chapter 3 covers the modeling needs to efficiently analyze the Complete Streets use cases. Data, modeling capabilities, evaluation, planning, and operational needs are all reviewed within this chapter before diving into the AMS tools and how they can model Complete Streets.

Chapter 4 includes an overview of the available AMS tools and methods that have been used to analyze Complete Streets projects along with their existing modeling capabilities. This chapter touches on travel demand modeling, simulation approaches (microscopic, mesoscopic, and macroscopic), multi-resolution modeling, deterministic methods, and geographic information systems (GIS). Each AMS tool has strengths and limitations to its analysis, and many can analyze and model Complete Streets and intelligent transportation systems (ITS) related use cases. However, some of the underlying issues of the available AMS tools include the lack of modeling capability regarding interactions amongst various modes of travels, representation of pedestrians, bicyclists, and micro-mobility users, and lack of operational details required for comprehensive Complete Streets analysis.

An assessment of modeling needs or desired modeling capabilities (Chapter 3) and existing modeling capabilities (Chapter 4) revealed significant gaps. These gaps were grouped into three areas highlighting modeling gaps, data collection gaps, and policy/procedural gaps. These gaps are summarized below.

Modeling

- **Model insensitivity**: Current AMS tools are generally insensitive toward various Complete Streets interventions and therefore limited use cases can be analyzed by existing AMS tools.
- **Inadequate representation of pedestrians, bicyclists, and other micro-mobility modes**: Current AMS tools lack adequate representation of pedestrians, bicyclists, and other micro-mobility modes, and lack accurate representation of multimodal transportation networks and facilities utilized for Complete Streets.
- **Limited behavioral research on pedestrians and bicyclists**: Pedestrian and bicyclist traffic flow behavior is an under-researched area and is not adequately reflected in existing AMS tools.
- **Lack of an overall multimodal level of service**: An overall multimodal level of service (MMLOS) is not provided by existing deterministic methods. Instead, a multimodal analysis is applied separate for each mode. Aggregation of results to provide an overall score requires researcher/practitioner judgement in terms of weights for all modes, thus leading to biases.

Data

- **Lack of data collection, requirements, and standards**: General lack of data in context of multiple users and modes as well as lack of standards and requirements especially for non-motorized modes.
- **Limited behavioral data on non-motorized users**: Data scarcity regarding the behaviors of pedestrians, bicyclists, and other non-motorized users poses challenges for developing comprehensive and inclusive transportation models.
- **Difficulty in collecting near-miss and non-motorized collision data**: Near miss incidents greatly impact the perceived safety of a Complete Street project for road users. This data is difficult to collect but important for understanding the user experience.
- **Gaps in data for evaluating Complete Streets**: Lack of consistent, standardized metrics. The varied goals and objectives of Complete Streets projects make it challenging to establish universally acceptable measures.

Procedural

- **Policies favoring certain modes**: Historically many policies have focused on car-centric communities and do not prioritize safe, accessible, connected, equitable, and walkable communities for all users.
- **Lack of evaluation standards**: Lack of evaluation standards for Complete Streets is not only a modeling/data gap but also a procedural challenge. The slow updates of standard and guidance documents complicate the evaluation process, affecting the viability of Complete Streets projects.

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 standards or policies 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.” Federal Highway Administration (FHWA) has begun assessing and revising its policies, regulations, processes, and practices to help State and Local transportation 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 been focused around optimizing the flow of motorized vehicles on the interstate/freeway network, arterial systems, and through traffic intersections. Numerous ITS strategies and deployments have resulted in enhanced safety, mobility, and agency efficiency with a focus on select road user types such as motorists or drivers. 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, the majority of traffic-based analysis, modeling, and simulation (AMS) tools have been developed to analyze traditional transportation infrastructure improvement projects. Examples include adding capacity to an existing roadway, freeway work zone analysis, transportation demand management, operational analysis, transit improvements, etc. While these tools have matured over previous decades and incorporate detailed vehicular/driver behavior such as acceleration/deceleration, car following, lane changing, etc., there are limited capabilities to analyze non-motorized modes of transportation and Complete Streets approaches. Complete Streets enable safe access for all modes and roadway users. In a shared space with multiple modes and users competing for a limited right of way, this becomes a multi-objective optimization problem and includes intricate behavioral interactions between various modes and users, which are not well captured in existing AMS tools. This results in existing AMS tools which have limited applicability to the Complete Streets analysis and modeling. Additional limitations are experienced when there is a desire to account for the growing trend of micro-mobility options such as e-scooters, bike sharing, and use of personal mobility devices in AMS tools as these modes are not fully integrated into the modeling tools. Further, existing AMS tools are not very sensitive to the changes in a built environment, such as Complete Streets infrastructure enhancements, when assessing changes in demand for various modes in response to such changes in road infrastructure [3]. This warrants a comprehensive review of currently available Complete Streets analytical/modeling approaches, assessment of their capabilities, and identification of gaps and challenges. 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.

1.2 Document Purpose

The purpose of this report is to provide a comprehensive review of Complete Streets modeling capabilities and identify gaps/challenges. Once an understanding of these is documented, targeted activities can be initiated to enhance Complete Streets modeling methods and tools to mitigate challenges, fill gaps, and achieve the desired capabilities. This report serves as a resource for transportation planners, engineers, policymakers, and other stakeholders involved in the development and quantitative assessment of Complete Streets projects.

1.3 Document Scope

The scope of this document encompasses a comprehensive exploration of modeling capabilities with a primary focus on accommodating diverse transportation modes and road users including pedestrians, cyclists, and motorized vehicles. It identifies gaps and challenges with existing modeling approaches by considering the context-sensitive design of Complete Streets and other Complete Streets-related policy issues, operational impacts, data collection, driver/pedestrian/cyclist behavior, calibration and validation, and multi-modal network connectivity.

1.4 Organization of Report

This report is organized as follows:

- **Chapter 1 Introduction** – provides the Complete Streets background, purpose, and scope of this report.

- **Chapter 2 Complete Streets Use Cases** – discusses specific Complete Streets use cases covering various Complete Streets elements.
- **Chapter 3 Complete Streets Modeling Needs** – identifies Complete Streets modeling needs from stakeholders’ perspectives.
- **Chapter 4 Complete Streets Modeling Capabilities** – discusses specific Complete Streets analysis and modeling capabilities using currently available analytical and modeling tools and methods.
- **Chapter 5 Gap Identification** – identifies gaps in the existing modeling capabilities, tools, and processes specific to Complete Streets.
- **Chapter 6 Conclusion** – summarizes the key findings from this report.
- **Chapter 7 References** – lists references mentioned in this report.

2 Complete Streets Use Cases

To assess existing Complete Streets modeling capabilities and gap identification, it is essential to first document Complete Streets use cases. User needs from multiple stakeholders' perspectives can then be established in the light of these use cases against which existing AMS capabilities are assessed and modeling gaps are identified. This chapter discusses specific Complete Streets use cases as identified from the literature review and case studies. This chapter also identifies ITS specific Complete Streets use cases using the National ITS Architecture (ARC-IT, Version 9.2) [4] that can be modeled using available tools as well as other ITS application areas specific to Complete Street users which should be incorporated into the AMS methods and tools.

2.1 Complete Streets Use Cases

Complete Streets require a context-sensitive design approach, meaning that designs and implementations vary by location and context. There are many identifiable elements or features of Complete Streets as identified by researchers and practitioners, which can be grouped into three major categories: 1) **pedestrian/bicycle infrastructure** (such as sidewalks, wide-paved shoulders, frequent and safe crossings, accessible pedestrian signals, protected bike lanes, wide raised medians, shared use paths for pedestrians and bicyclists, parallel parking, accessible parking spaces, curb separation and extension, contraflow bike lanes, signing and pavement markings (for non-motorized users), pedestrian/bike signals, etc.), 2) **traffic calming** (such as narrow travel lanes, roundabouts, speed humps and lumps, visibility enhancements, raised crosswalks and intersection, pavement markings and speed display signs (for motorized vehicles), etc.), and 3) **public transit accommodations** (such as special/dedicated bus lanes, comfortable and accessible bus stops, bus stop shelters, floating bus island, etc.) [3], [5], [6], [7], [8]. Depending on the context and project's goals and objectives, Complete Streets elements may also apply to landscaping, provision of green spaces, pavement coloring, parklets, parking, etc. Design choices for Complete Streets projects, like most infrastructure and construction projects, are also largely influenced by regional needs and culture. These Complete Streets use cases and scenarios offer numerous benefits such as enhanced mobility options, increased safety of VRUs, promotion of active mobility, better public health as a result of increased physical activity, environmental friendliness as a result of reduced emissions, increased access to destinations, increased connectivity to transit, increased sense of community, and increased economic activity [9], [10], [11], [12], [13], [14].

Table 1 below contains Complete Streets use cases with their key elements based on a review of Complete Streets projects, literature review, and design manuals. While acknowledging that this is not an exhaustive list of all possible Complete Streets scenarios, the individual elements will be assessed based on existing AMS capabilities in Chapter 4.

Table 1: Complete Streets Use Cases and Corresponding Elements

Complete Streets Use Cases	Elements of Complete Streets
Classic Road Diet – Replacing passing lanes with center turn and bike lanes accommodating a variety of transportation modes [15]	• Reduction of number of through lanes • Left turn lanes • Pedestrian refuge islands • Bike lanes
Transit-Oriented Development – An urban planning approach that is meant or designed to bring people, activities, buildings, and public spaces together, with easy walk and bicycle connections to transit stations [16], [17], [18]	• Walkable design • Transit stations/hubs • Bicycle infrastructure • Bikeshare rental system/network integration • Mixed land uses • Green spaces • Affordable housing • Parking management • High density zoning/urban development
Shared-Lane or Roadway – A roadway that is open to both bicycle and motor vehicle travel [19], [20], [21]	• Bike boulevards • Bus/bike shared use lanes • Clearly marked on street • Road signage to assist in establishing purpose of shared use lane
Shared-Use Paths – Shared-use paths are primarily used by bicyclists and pedestrians, including joggers, skaters, and pedestrians with disabilities, including those who use non-motorized or motorized wheeled mobility devices [20], [21]	• Separated from motorized vehicular traffic • Bike/micro-mobility shared use paths with pedestrians • Road signage to assist in establishing purpose of shared use path
Dedicated and Protected Bicycle Lanes – Dedicated bicycle lanes enabled by removing some parking and/or a general-purpose travel lane to promote bicyclist safety [22], [23]	• Dedicated/protected bike lane • May include removal of general-purpose travel lane • Road signage • Provision of buffer zone • May include removal of on-street parking or shoulder
Dedicated Bus Lanes – Replaces general purpose travel lane to provide exclusive lanes for buses which may be shared with bikes, scooters, and emergency response vehicles, and enforced at certain times of the day [24], [25]	• Generally removes general purpose travel lane, parking, or shoulder • Clear markings on street to establish purpose of lane. • Systematic enforcement of use by non-designated modes and/or vehicle types

Complete Streets Use Cases	Elements of Complete Streets
Pedestrian Infrastructure – Aims to improve the overall pedestrian experience by improving safety, walkability, mobility, capacity, and aesthetics of sidewalks and crosswalks [26]	• Add missing sidewalk segments • Curb ramps • Surface condition improvements • Shade trees • Bus stop improvements • Frequent, safe, high visibility crosswalks • Raised crossings (or crosswalks) • Pedestrian priority areas (or zones) • Accessible pedestrian signals • Street lighting • Pedestrian islands/medians • Interim public plazas
Green/Environmental Spaces – Multifunctional addition of planted areas to promote local flora conservation efforts and improve overall environmental sustainability, aesthetics, air quality, and pedestrian experience [27]	• Street trees, shrubs, grass areas • Landscaping • Conservation landscaping • Runoff collection and treatment
Streetscape Improvements – Aims to increase accessibility, comfortability, connectivity, and appeal of streets for non-motorized users [28], [29]	• Street crossing safety features • Increased street lighting • Increased sidewalk coverage • Connectivity of pedestrian walkways • Addressing gaps in bike infrastructure • Micro-mobility corrals (parking racks) • Street furniture • Street-facing windows • Active street frontages • Parklets • Reduced motorist speed limits • Reduction in number of general-traffic lanes
Light Rail/Streetcar Systems – Aims to promote transit use, tourism, and historical preservation of light rail systems. Light rail systems can enhance access to destinations and serve as a connection to other major transit hubs and stations in the region [30], [31]	• Shared use lanes • Light rail extension • Light rail lanes • Light rail stops
Comfortable and Accessible Public Transit Stops – Promotes transit use by improving transit-users' and other non-motorized travelers' safety and accessibility during wait times, boarding, and alighting [6], [32]	• Protected bus stops • Accessible bus stops • (In-street) transit boarding islands
Street Conversions – Conversion of grid systems from one-way to two-way operations	• Converting one-way streets to two-way streets, and vice versa

Complete Streets Use Cases	Elements of Complete Streets
(to improve local access and to slow traffic), and vice versa (to improve VRU safety and mobility). Other conversion types include transforming highways to boulevards and converting sections of streets into pedestrian promenades [33], [34]	• Highway to urban boulevard • Alley conversion • Pedestrian and bicycle malls/promenade • Contra-flow bike lanes
Traffic Calming Measures – Improves non-motorist safety and mobility by reducing vehicle speeds and/or volumes [35]	• Managing speeds • Improving lighting • Separating users in time and space • Reducing travel lane widths • Changes in roadway geometry, such as roundabouts

2.2 ITS for Complete Streets Use Cases and Application Areas

ITS can complement and help meet the overarching goals of Complete Streets projects including those specific to safety, mobility, equity and accessibility, network connectivity, environmental sustainability, and public health. **Table 2** below contains ITS for Complete Streets use cases based on a review of existing ITS technologies. Some of these technologies are specific to one mode of transportation, but many are multimodal. An analysis of ITS Complete Streets and ITS use cases that can be currently analyzed and modeled using existing AMS tools is presented in Chapter 4.

Table 2: Complete Streets ITS Applications and Descriptions

ITS for Complete Streets Applications	Description
Leading Pedestrian Intervals (LPIs) [36]	Signal timing adjustment made to prioritize pedestrians at intersections. Improves safety of Complete Streets for pedestrians.
Transit or Freight Signal Priority (TSP or FSP) [19]	Gives priority to approaching transit or freight vehicles at signalized intersections to increase transit and freight travel time reliability and decrease delay.

ITS for Complete Streets Applications	Description
Real-time Traveler Information Systems [37]	Systems utilizing sensors, cameras, phone applications, and more to provide accurate and reliable traffic information to multimodal users via applications or changeable message signs. Improves travel time reliability; may affect trips numbers and mode split; can reduce traveler stress and increase satisfaction.
Real Time Adaptive Signal Control [38]	Adjustment of signal timing in response to real-time traffic conditions to decrease multimodal traffic delay and increase mobility and travel time reliability.
Automated Enforcement Systems [39], [40]	Devices, usually cameras, used to enforce speed limits, red light running, and intersection blocking for motorized users, thus improving overall road user safety. Automated enforcement systems can also be used to ensure compliance with regulations prohibiting the obstruction of bike lanes or pedestrian sidewalks.
Bike-Activated Signal Detection [41], [42]	Detection of bicyclists at actuated traffic signals to facilitate safe, comfortable, and convenient crossings at intersections for bicyclists while also minimizing delay.
Accessible Pedestrian Signals (APS) [43]	Devices that communicate pedestrian crosswalk signal information in nonvisual ways to increase accessibility and safety of pedestrian crossings.
Rectangular Rapid Flashing Beacons (RRFBs) [44]	Actuated or manually signaled crossings used to improve pedestrian crossing visibility to motorized vehicles users. Improves safety, mobility, and accessibility for pedestrians.
Pedestrian Detection [44]	Systems that detect waiting pedestrians via push button or sensor, to improve pedestrian safety and accessibility.
Integrated Corridor Management (ICM) [45]	Integrated management of freeway, transit, arterial, and parking systems within a corridor using ITS technologies. It is aimed at managing corridor as a

ITS for Complete Streets Applications	Description
	system rather than individual transportation networks (e.g., bus, rail, arterial freeway, etc.).
Dynamic Curbside Management [46]	Optimization of street curb space based on congestion and street needs (e.g., curb use for parking or loading during off-peak, as an additional driving lane during peak, or as a bike or transit lane).
Dynamic Lane Management (or Lane Grouping) [47], [48], [49]	A traffic management strategy that involves the real-time adjustment of lane configurations on roadways to optimize traffic flow and enhance overall transportation efficiency. Current applications include temporary lane closures for incident management, dynamic speed limits to promote speed harmonization, reversible lanes for freeway/arterials, and part-time shoulder-use. In the future, this functionality could be extended to other modes of transportation such as dedicate bus lane operation during certain time of the day or contra-flow bike lanes.
Traffic Incident Management [50]	Multidisciplinary process to detect, respond to, and clear traffic incidents to efficiently restore traffic flow and reduce the impact of traffic incidents.
Dynamic Parking Management [51]	Management of demand for parking spaces through variable parking rates and the dissemination of real time parking availability information.
Low Emission Zones/Emissions Management [52]	Combining air quality management and traffic capacity management to improve air quality conditions, thus improving safety, mobility, and accessibility for all network users.
Electric Vehicle (EV) Charging Station Management [53]	Space given to electric vehicle charging infrastructure in effort to promote EV use amongst motorized vehicle users.

3 Complete Streets Modeling Needs

This chapter identifies Complete Streets modeling needs from the perspectives of stakeholders including practitioners, AMS tool developers, and transportation agency decision makers. These user needs consider the Complete Streets use cases as presented in Chapter 2 and organize them into various categories. Recognizing that the development and refinement of most AMS tools have centered around motorized traffic, there has been a notable lack of emphasis on modeling non-motorized modes, such as pedestrians and bicyclists [54]. This chapter highlights desired modeling capabilities and related user needs so that existing AMS tools can be assessed against these to determine gaps. User needs representing the following areas are identified in **Table 3**:

- **Data Needs**: such as data collection and standardization
- **Core AMS Desired Modeling Capability Needs**: such as interaction among various modes, and incorporation of travel behavior into AMS tools
- **Evaluation Needs**: such as multi-objective goals areas and metrics for evaluation
- **Planning Needs**: such as AMS tools use for planning
- **Operational Needs**: such as AMS tools use for traffic management and emergency response

Table 3: Complete Streets User Needs and Categories

Need Category	User Need
1. Data Needs	1.1. Transportation agencies need to collect comprehensive multimodal data[1] that encompasses pedestrian and bicyclist information to effectively model and analyze Complete Streets projects.

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[1] Multimodal data refers to a wide array of information including multimodal traffic counts, complete roadway networks, pedestrian/bicyclist infrastructure such as sidewalks, shared use paths, bike lanes, as well as other facilities such as bike corrals, transit stop amenities, and signage and pavement markings.

Need Category	User Need
	1.2. Agencies need to conduct updated travel choice surveys incorporating multiple modes of transportation such as walk, bike, transit (bus and rail), auto, and newer forms of urban micro-mobility to update mode choice models. 1.3. Complete Streets project analysts and modelers need access to historical multimodal traffic and safety data to analyze trends and evaluate the effectiveness of Complete Streets interventions. 1.4. Microscopic simulation tools require behavioral data[2] on multiple roadway users including pedestrian and bicyclists to understand the dynamics of their interactions with each other. 1.5. Agencies need a standardized way to represent multimodal transportation network/facility data to collect, report, share, and exchange data especially on pedestrian and bicyclist infrastructure and access to destinations.
2. Core AMS Desired Modeling Capability Needs	2.1. Practitioners and agency decision makers need AMS tools that can model and analyze multiple transportation modes, such as pedestrians, bicyclists, transit, and cars, to evaluate how Complete Streets interventions will affect safety and mobility of corridor. 2.2. Transportation practitioners and policymakers need AMS tools that can model and evaluate curbside demand management policies to measure their impact. These tools need to be able to account for non-motorized modes. 2.3. AMS tools need to incorporate individual components and design elements[3] of Complete Streets use cases to model their impacts.

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[2] Examples of behavioral data include how pedestrians cross the streets, how bicyclists navigate bike lanes and interact with other roadway users, and how drivers react to various street design features and in the presence of pedestrians and bicyclists.

[3] Examples of design elements include general-purpose lane reductions, lane additions, lane reconfigurations, signing and pavement markings, or pedestrian/bicycle infrastructure improvements (e.g., widening a sidewalk or adding a buffer zone to separate bicyclists and motorists).

Need Category	User Need
	2.4. AMS tools need the capability to model and simulate pedestrian and bicyclist behavior to analyze interactions[4] between various modes such as bicyclist-motorist, motorist-transit, and transit-pedestrian. 2.5. AMS tools need the capability to model and simulate complete trips[5] so that efficiency of multimodal transportation networks can be assessed. 2.6. AMS tools need to be sensitive to the changes in built environment so that the benefits of various Complete Streets implementations can be quantified. 2.7. Multi-objective optimization models are needed for optimal road space allocation to various Complete Streets users in a limited right-of-way with capabilities of reporting multimodal level of service (MMLOS) being responsive to Complete Streets interventions. 2.8. Multi-objective optimization models need to be able to simulate safety impacts and take them into account, along with mobility, in road space allocation and infrastructure design. 2.9. AMS tools need to be able to model mid- and long-term interactions between infrastructure changes, mode choice, and travel behavior by mode, including feedback loops.
3. Evaluation Needs (AMS Tool Outputs)	3.1. AMS tools should provide performance metrics[6] for various transportation modes, encompassing pedestrians, bicyclists, and transit users at the intersection and corridor level of granularity. 3.2. Public agencies, project analysts, and modelers need AMS tools that can evaluate the effectiveness and quantify the

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[4] These interactions refer to the actions performed by users within a potential conflict point or area (e.g., acceleration/deceleration, maintaining a lateral and longitudinal gap distance, lane change maneuvers, etc.)

[5] Complete trips refer to how various modes integrate, and transfers are made e.g., bus to rail transfer, walk or bike to transit, and park-and-ride, etc.

[6] Either as a direct tool output (preferred) or through post-processing/manipulation of the output data.

Need Category	User Need
	benefits of Complete Streets interventions prior to field implementations. 3.3. AMS tools need to encompass a diverse set of performance measures, across the goal areas of safety, accessibility, equity, connectivity, environmental sustainability, and public health, in addition to mobility when evaluating Complete Streets projects.
4. Planning Needs (Demand Modeling AMS Tools)	4.1. Travel demand/long-range forecasting models need to be sensitive to individual Complete Streets elements/components and account for non-motorized trips. 4.2. AMS tools need to be able to quantify the changes in demand for both motorized and non-motorized travel. 4.3. Agencies need to update the travel demand/forecast models by incorporating walk, bike, and other micro-mobility trips in the trip distribution, mode choice, and traffic assignment models for accurate representation of travel choices.
5. Operational Needs (Traffic Operations/Control AMS Tools)	5.1. AMS tools need the capability to model and assess active traffic, demand, and parking management strategies such as dynamic lane management or signal priority. These tools need to be able to account for non-motorized modes. 5.2. Users need tools that can adjust/optimize traffic signal timings to accommodate different modes. 5.3. AMS tools need the capability to model and assess the benefits of various ITS interventions such as leading pedestrian intervals and transit signal priority. 5.4. Traffic operations tools need the capability to model the flow of non-motorized and micro-mobility traffic.

4 Complete Streets Existing Modeling Capabilities

This chapter discusses specific Complete Streets analysis and modeling capabilities using currently available AMS tools and methods. The review of these tools and methods includes Complete Streets modes that can be modeled, behavioral interaction among the road users, and inter-modal effects (impact of improvements made to one or more modes on others such as impact of pedestrian/bike friendly signal timing on passenger vehicle, bus, and commercial vehicle traffic). Further, AMS tools' abilities to analyze Complete Streets use cases (as discussed in chapter 2) are also assessed for various AMS methods.

4.1 Travel Demand Modeling

Travel demand models are used to forecast long-term future travel demand based on current conditions and future projections of household and socio-economic characteristics. Utilizing the traditional four-step modeling approach[7], these models were originally developed to determine the impacts and benefits of major highway improvements in metropolitan areas. The demand is typically forecasted using statistical methods based on household travel and behavioral surveys considering factors such as car ownership, household income, household size and composition, socio-economic indicators, trip purpose, etc. Household surveys are typically conducted every five to ten years to understand the mobility patterns and travel behavior. This data is used to quantify travel behavior (e.g., estimating origin-destination matrices, mode choice models, etc.), analyze changes in travel characteristics over time, and study the relationship between demographics and travel over time [56]. Non-motorized and emerging transportation modes are not well represented in many existing travel surveys and consequently demand models due to limited non-motorized travel survey records, emerging trends in transportation, sample size issues, data collection issues, and tool's modeling abilities [57], [58], [59]. As a result, travel demand models are not very sensitive to Complete Streets enhancements and

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[7] The four steps in this modeling framework include trip generation, trip distribution, mode choice, and route choice/traffic assignment [55].

implementations. Further, many existing demand models only account for limited modes such as walk, auto, and transit in the mode choice and traffic assignment steps. Due to the aggregate nature and regional scope, travel demand models typically do not forecast bicycle or pedestrian trips, which is a major gap in modeling in the context of Complete Streets where multiple modes, road user types, and intermodal interactions have to be modeled [60].

Nonetheless, there are certain Complete Street scenarios such as transit-oriented development [61], [62], land-use modeling [63], dedicated bus lanes [64], parking demand management [65], [66], [67], and other transit improvements [68] which can be modeled and analyzed using travel demand models with varied capabilities. Some of the tools in this AMS category include CUBE, Visum, Aimsun, and TransCAD with capabilities to predict travel behavior changes due to public transport supply enhancements (e.g., adding a new transit line or increasing the bus frequency, etc.) and active mobility/demand management strategies. Visum follows a four-step modeling approach and analyzes multiple modes of transportation including car, freight vehicles, bus, train, motorcycles, bicycles, and pedestrians, however during the traffic assignment step only motorized vehicles are considered (highway and public transport assignment) [69]. This means that during the trip production and trip attraction steps, the number of trips for pedestrians are estimated but not carried over to the traffic assignment and route choice steps, which is a major limitation of many existing demand modeling tools especially in the context of Complete Streets. For bike mode, Visum does have the capability for traffic assignment and user defined attributes can be added as an impedance function affecting the route choice and behavior (e.g., roadway slope, road surface condition, mixed traffic, speed of motorized traffic, high volumes of motorized traffic and number of intersections to pass, etc.) [70]. However, the mode choice in Visum is not sensitive to Complete Street enhancements in terms of predicting or estimating the non-motorized trips (or mode shares) as a result of Complete Streets infrastructure improvements, which is a major desired capability in Complete Streets context. CUBE suite (Voyager, Land, Access, and Cargo) also follows a four-step modeling approach and can analyze walk, auto, and transit as modes with typical applications such as multimodal access to destinations computation, regional demand forecasting, land-use planning, and freight modeling [59], [71], [72]. In CUBE, walk trips are not accounted in the model as a separate mode, rather combined with transit modules. Aimsun also follows a four-step modeling approach and can predict demand levels for car, transit, and bicycle which are then carried over to the traffic and transit assignment models [73]. Aimsun also offers parking demand management scenarios at trip production and attraction levels wherein the capacity at parking facilities is used as an input [73]. As with many other AMS demand modeling tools, the interactions among various modes are not captured adequately (e.g., mixed traffic streams, intermodal transfers, or connections, first and last mile connections, etc.).

Shared and micro-mobility options are also not explicitly modeled and integrated into the demand models (i.e., way people access/egress transit stations and connect to transit services using shared and/or micro-mobility) [68]. Activity-based models, as an alternative to traditional four-step modeling approach offer more flexibility and are more responsive to Complete Streets enhancements. This is due to the fact that activity-based models employ a diverse range of choice models (i.e., discrete choice models, logit models, and experimental designs) that represent travel choices such as mode and route choice in a more effective manner incorporating various travel modes including pedestrian and bicyclists [71]. Activity-based demand models are viewed as an advanced approach with higher fidelity and better policy sensitivity. According to a study conducted in Tampa Bay, FL, four-step models underestimated driving trips compared to activity-based models, which authors attributed to inadequate representation of alternative modes (e.g., taxi and non-motorized) in four-step models [74].

4.2 Simulation Approaches

4.2.1 Microscopic Simulation

Microscopic simulation tools focus on interactions between individual users in a transportation system. These tools are ideal for examining small portions of a network simulating interactions between motorized vehicles. However, in the context of Complete Streets and multimodal traffic simulation, the AMS tools have limited capabilities. The interactions between vehicles and pedestrians at signalized crosswalks are represented in several AMS tools such as Vissim and Aimsun. Vissim does that by defining conflict areas, safety lookup distances, and priority rules (e.g., yield to pedestrians). The pedestrian and bicyclist behavior are not well represented by the AMS tools which, over the last century, have focused on driving behavior such as acceleration/deceleration, lane changing, speed profiles, etc. For pedestrian simulations, PTV Vissim and Viswalk use the social force model from Helbing and Molnár (1985) whose basic principle is to model pedestrian motion based on Newtonian mechanics [75]. AMS tools do not efficiently reflect detailed bicyclist behavior, flow dynamics (e.g., lateral/longitudinal motion, passing, stopping and yielding, etc.), and interactions with pedestrians and traffic streams [76]. Fadhloun et. al., 2022 proposed a bicycle traffic flow dynamics model using naturalistic datasets obtained from experiments which is adapted from the Fadhloun-Rakha car-following model previously developed by the researchers [76]. Vissim simplifies the Wiedemann 1999 car-following model with updated parameters to represent/mimic bicycle behavior, however bicycle simulation in Vissim is limited to dedicated bicycle tracks/lanes [77]. Despite some recent advancements in incorporating pedestrian and bicycle behavior into the AMS tools, these simplified behavioral models do not reflect detailed interactions among and between pedestrian/bicyclist and motorized traffic, and how various enhancements to Complete Streets affect the route choice, level of traffic stress (LTS), pedestrian/bicyclist LOS, and inter-modal impacts among others.

Some of the Complete Streets and ITS related use cases that can be analyzed and modeled using existing microscopic simulation AMS tools include the classic road diet [78], dedicated/protected bus and bike lanes [79], light rail transit, street conversions [33], [78], traffic calming measures [80], traffic incident management [81], variable speed limits [81], dynamic lane grouping [81], integrated corridor management [82], [83], multimodal traffic signal optimization [84], and simulation of connected and automated vehicles [85]. While the microscopic AMS tools offer the highest resolution appropriate for operational analysis, the model outputs are still very auto-centric. As an example, the classic road diet can be analyzed and modeled in majority of the microscopic AMS tools such as Vissim, Aimsun, Paramics, TransModeler, and SUMO, however tool outputs and performance metrics typically include impacts on motorized vehicular traffic such as auto LOS. Limited number of tools such as Vissim and Aimsun have the capability of generating pedestrian outputs such as pedestrian delays, density, walking speed, and travel time. Bicycle measures of effectiveness are typically harder to obtain through microsimulation tools and are highly dependent on the tool's capability to reflect bicyclist behavior into the simulation models.

4.2.2 Mesoscopic Simulation

Another aspect of Complete Streets is the emerging model of shared micro-mobility and mobility-as-a-service (MaaS). The simulation of shared micro-mobility is a complex process given the number of interactions among various modes, technological advancements, and emergence of newer forms of mobility technologies. Although traditional AMS tools do not have built-in capabilities to model and represent these concepts, some mesoscopic agent-based models have added functionalities to represent shared micro-mobility such as Multi-Agent Transport Simulation (MATSim) and POLARIS. A lot of microscopic simulation tools now have the mesoscopic simulation and agent-based modules including Aimsun, TransModeler, SUMO, and CORSIM. The applications range from simulation of bike sharing systems to incorporation of shared taxis/transportation network companies (TNCs) and electric vehicle charging stations management/optimization [86], [87]. Agent-based modeling tools offer more flexibility to incorporate emerging mobility trends due to their disaggregated nature and individual agent-based representation in a simulation. Aimsun provides a framework for modeling MaaS and demand responsive transportation through discrete choice logit models (i.e., mode choice) to represent a wider range of modes [88]. The tool also offers variety of scenarios to be tested including but not limited to route choice, dynamic transit operation, fleet optimization, multimodal journeys, and customization of behavioral parameters [88]. Some of the Complete Streets and ITS specific use cases that can be analyzed and modeled using mesoscopic AMS tools include the classic road diet, street conversions, multimodal traffic simulation (e.g., intermodal connections such as walk to transit, bus to rail, etc.) [89], and traffic management strategies (e.g., traffic calming measures variable speed limits, integrated corridor management, and traffic incident management) [90], [91]. Like demand modeling and microscopic simulation tools, the mesoscopic AMS tools are not particularly sensitive to Complete Streets components (e.g., bike buffer zones, dedicated bike facilities, walkable design, pedestrian refuge islands, signing and pavement markings, etc.) and their impact on pedestrian and bicyclists LOS.

4.2.3 Macroscopic Simulation

Macroscopic simulation tools are based on deterministic relationships of the flow, speed, and density of the traffic stream. These models use aggregated quantities and do not model the individual movements of vehicles on a network, thus presenting some limitations when analyzing Complete Streets projects. Macroscopic tools model traffic movements in a simplistic representation and do not yield the higher fidelity needed to accurately examine Complete Streets. Furthermore, the limited network complexity within these simulation tools may not adequately capture some of the Complete Street use cases. These tools are good for large networks and could be able to evaluate how a Complete Street network affects a larger transportation network. There have been some methodologies set forth to analyze multimodal level of service (LOS) that accounts for pedestrian, bicycle, and transit. However, these methodologies estimate LOS separately for each user class and require extensive local data. A thorough analysis of Complete Streets deployment would require these LOS analyses to be interrelated and measure how changes within one mode affect the other modes. All in all, macroscopic simulation tools such as Visum, FREEVAL, and HCS have their role in transportation analysis, but there are limited capabilities for Complete Street analysis.

4.3 Multi-Resolution Modeling (MRM)

When models of varying temporal and spatial resolutions including macroscopic, mesoscopic, and microscopic models are integrated such that data is shared across the modeling platforms, a multiresolution model/framework is formed [92], [93]. Multiresolution modeling offers the advantage of combining the strengths across the various resolutions to enhance the evaluation of Complete Streets by providing more comprehensive information of the entire network and greater insight into the interaction of individual road users. As such, in a multiresolution modeling framework, the capabilities of the individual modeling approaches (macroscopic, microscopic, and mesoscopic) discussed above complement each other and fill in the gaps where necessary. For example, while macroscopic models are well suited to evaluate how a Complete Street project will affect a large transportation network, they are limited in their ability to analyze detailed improvement to transportation facilities. The microscopic simulation component of the multiresolution model addresses this shortfall by modeling a detailed representation of the traffic network, taking into consideration the characteristics of individual road users.

Nevertheless, there are modeling capabilities and gaps that are associated with the application of multiresolution modeling approach to Complete Streets. A seamless integration of the various components of a multiresolution model framework is key to achieve accurate results. However, due to the absence of standardized data and protocols across the industry, it is difficult for practitioners to effectively integrate tools from different developers. While some developers provide interfaces to integrate their suite of tools (e.g., PTV Visum, Vissim, and Viswalk), only few available AMS tools provide the capability of modeling all the scales of resolution within a single software (e.g., Aimsun). Additionally, large amounts of data, both aggregated and disaggregated, are necessary for multiresolution modeling but are sometimes unavailable, particularly for arterial streets. Newer data sources such as probe data and traffic signal controller data are increasingly accessible. However, their seamless integration into numerous AMS tools poses challenges, requiring significant effort for compilation, cleaning, and conversion into a usable format across various resolution. This challenge is amplified in the absence of standardized data formats.

Furthermore, due to the different approaches used in modeling traffic at the various levels of resolutions, there is the potential to produce inconsistent results. The traffic flow models in a macroscopic or mesoscopic models may produce different link performance results compared to the lane changing and car following models of a microscopic model [94]. This issue arises due to the inconsistency in the definitions of performance measures at different levels of resolution. For example, while microscopic simulation tools like Vissim calculate delay by computing the difference between an individual vehicle's actual travel time and its desired travel time, some dynamic trip assignment procedures compute travel time as the difference between an individual vehicle's travel time when traffic is assigned to the network versus when no traffic is assigned to it. A critical capability of multiresolution modeling is the presence of a feedback loop that is used to fine-tune parameters of lower resolution models based on outputs from higher resolution models. This feature can be particularly useful when evaluating the impacts of various Complete Street alternatives including modal shifts or the introduction of new technologies such as connected and automated vehicles into the network [95].

4.4 Deterministic Methods

The deterministic approach to evaluating Complete Streets involves the use of analytical/empirical/model-based methodologies to predict performance measures (e.g., delay, speed, travel time, crash frequency etc.). Although there are several deterministic methods, this section focuses on the methodologies detailed in the Highway Capacity Manual (HCM) and the Highway Safety Manual (HSM).

4.4.1 Highway Capacity Manual (HCM) Methods

Various methodologies are presented in several chapters of the HCM that support the evaluation of Complete Streets. For example, chapters 16 through 22 present frameworks and methodologies for multimodal evaluation of urban facilities, segments, and individual intersections, taking into consideration the interaction between the modes. The methodologies include motorized vehicle mode, bicycle mode, pedestrian mode, and transit mode [96]. Over the years, the modeling capabilities of the HCM methodologies have improved incrementally, with each latest edition expanding the capabilities of the earlier version. For example, in the latest edition, HCM 7, pedestrian evaluation methods have been enhanced such that the pedestrian LOS at uncontrolled crossing is now sensitive to specific crossing treatment including marked crosswalk, median island, and RRFB, which are typically features of a Complete Street. Also, the method estimates pedestrian delay at multi-leg and multi-stage crossings. The pedestrian methods also estimate the average pedestrian satisfaction making a crossing, accounting for the availability of adequate gaps in addition to the crossing treatment type. Furthermore, all editions since HCM 2010 have methodologies to estimate bicycle performance measure, for example, quality of service, which is a measure of how well bicycle facilities operate from a bicyclist’s perspective and incorporates multiple factors such as bicycle lane width, traffic volume/speed, and pavement quality. Despite these improvements, there are several gaps and limitations which stifle the use of the HCM methodologies for a more comprehensive analysis of a Complete Street. Performance measures such as pedestrian walkability, which measures a facility’s attractiveness to pedestrians, are not addressed in the HCM [97]. This measure takes into consideration the security of the facility, presence of shade, aesthetics, and adjacent land use. Additionally, methodologies for computing bicycle level of traffic stress are not provided in the HCM. This measure assesses the quality of the roadway network for its comfort with various bicycle users [98], [99], [100]. Furthermore, the methodologies for determining the bicycle LOS are not sensitive to intersection treatments such as bicycle boxes, signals, and markings, and always assumes a grade of 2% or less. Also, calibration/validation of models can be labor-intensive [101].

There are several AMS tools that implement the methodologies in HCM. However, some of these tools are limited in the extent to which they fully implement the HCM methodologies. For example, Synchro does not provide analysis for bike lanes when an intersection is unsignalized and does not meet the HCM 2010 criteria [102]. While Synchro does not have built-in capabilities for analyzing several ITS and Complete Streets use cases such as leading pedestrian intervals or transit signal priority, procedures exist to accommodate these scenarios through creation of dummy phases (i.e., updating ring barrier diagrams) [102]. Synchro can also be used for multimodal LOS estimation, minimizing pedestrian delays, and optimizing signalized traffic intersections.

4.4.2 Highway Safety Manual (HSM) Methods

The Highway Safety Manual (HSM) provides information and methods to quantitatively evaluate traffic safety performance on existing or proposed roadways [103]. It integrates quantitative measures of crash frequency and severity into roadway planning, design, operations, and maintenance decisions. However, while it serves as a critical guide utilized by State and Local agencies, the HSM is not without its limitations. While HSM's Part C crash prediction models offer methodologies to quantify the safety impacts of roadway improvements, there are notable exclusions within the HSM Part C framework. For example, it lacks crash predictive models for several roadway facilities such as all-way stop controlled intersections, intersections with more than four legs, one-way streets, and some signalized intersections on rural roads. Also, the methodologies do not offer full consideration of the impacts of non-motorized modes. However, the HSM does incorporate information pertinent to non-motorized road users in Chapters 12 through 14. Chapter 12 provides pedestrian crash prediction methods at signalized intersections and Crash Modification Factors (CMFs) and adjustment factors for stop-controlled intersections and segments. Similarly, it addresses bicycle crash adjustment factors for segments and intersections. Furthermore, Chapter 13 presents CMFs for roadway segments, including treatment impacts related to pedestrians and bicyclists, although with limited information for developing crash modification factors. Meanwhile, Chapter 14 extends this insight to intersections, providing CMFs for specific treatments, such as altering minor-road stop control and installing intersection lighting. However, some treatments critical to pedestrian safety, like narrowing roadways at pedestrian crossings or installing raised pedestrian crosswalks and signal heads at intersections, lack adequate information for CMF development [103], [104].

4.5 Geographic Information System (GIS) Methods

GIS tools enable spatial analysis of transportation systems, facilitating exploration of equity[8], connectivity[9], and access destinations within a transportation system. 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. There are various GIS tools (including but not limited to ArcGIS and QGIS) that can show spatial distribution of transportation burdens, perform buffer analysis to better understand access to destinations, and determine travel shed distances within communities as well as transportation specific tools built on GIS platforms (TransCAD, CUBE). There are a variety of ways in which connectivity, access to destinations, and equity metrics for Complete Streets can been considered or measured, which are context sensitive, but many can be explored using GIS. However, the best way to gauge the effectiveness of these categories of metrics within a transportation system is not always clear. When assessing Complete Streets, GIS is useful in doing spatial analysis to compare how multimodal systems relate to economic status, social equity, and other factors that can contribute to unequal access to destinations or connectivity. The determination of the most useful metrics is dependent on the goals of the project and availability of localized data. GIS can calculate travel time thresholds to analyze travel time and travel distance as well as visualize things such as crash severity and frequency. Several datasets can be overlayed within GIS to understand how they correlate to one another and can effectively analyze the problem to be solved, depending on the overarching goals of the Complete Street project. In general, the visual capability of GIS makes it a useful tool in the early stages of a project, allowing for ideas to be effectively shared with stakeholders and the public. It allows for a clearer picture of before and after concepts for Complete Street projects. This can be particularly useful in the planning stages, especially when determining the best locations for projects. Locations are often selected in areas that present the greatest operational benefits, but GIS can be used to determine where these projects could provide the most equitable benefits for users as well. A study in Massachusetts showed that past Complete Streets projects were ineffective in considering equity factors as operational factors were the focus [105]. This study made use of a multidimensional suitability and fuzzy overlay analyses in

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[8] Equity - the fairness in mobility and ease of access to destinations to meet the needs of all community members.

[9] Connectivity - the measure of access to destinations without regard to distance; the relative degree of connectedness.

GIS to compile datasets relating to income, transit use, presence of service workers, zero-car households, education, and age.

Additionally, GIS can be used to screen areas for walkability and connectivity and address shortcomings within the infrastructure. In Durham, NC there was a large walking and biking population, yet they lacked sufficient infrastructure to support their needs. The Complete Streets approach was determined to be the best solution to the lack of biking and walking infrastructure, while still supporting other modes of travel. GIS was utilized to identify the areas where additional infrastructure was needed the most to focus the approach [106]. Although GIS can be useful in identifying hotspot locations for multimodal facilities, one shortcoming can be the completeness of networks whose routes may not be defined by roadways. Working with a complete network is an essential component of accurate model building. This is particularly true for multimodal networks whose routes may not be thoroughly documented. Furthermore, GIS analysis is limited by the accuracy and completeness of available data needed to complete the analysis. One approach to addressing this problem requires constructing a complete network by compiling various GIS datasets or expanding data collection to create a complete set.

5 Gap Identification

As the paradigm of transportation planning and operations shifts towards embracing Complete Streets, it is crucial to scrutinize the existing modeling capabilities, in terms of tools and methods. This chapter identifies the gaps and challenges identified through the comprehensive, but not exhaustive, review of existing AMS modeling capabilities for Complete Streets (as discussed in Chapter 4), encompassing modeling capabilities, data collection, and procedural gaps/challenges. An assessment of existing AMS modeling capabilities against desired modeling capabilities (as discussed in Chapter 3) reveals significant gaps. First, existing modeling capabilities fall short in providing a holistic and detailed representation of multimodal transportation interactions, non-motorized user behavior, and the impacts of Complete Street interventions. Second, there is a significant gap in meeting the data needs for effective analysis and modeling of Complete Streets. Further, existing AMS tools do not fully meet the diverse multi-objective evaluation needs associated with Complete Streets projects. These gaps are discussed in detail below.

5.1 Modeling Capabilities Gaps

The AMS tools for Complete Streets face critical gaps that hinder comprehensive and accurate representation of multimodal transportation networks and facilities. One fundamental challenge lies in the insensitivity of existing AMS tools to the changes in the built environment (i.e., Complete Streets interventions), particularly changes that significantly influence the demand for non-motorized modes. Pedestrian and bicyclist behaviors, characterized by their unpredictability and complexity, pose a substantial gap in the modeling landscape, especially with limited capabilities to simulate movements beyond defined roadways and crossings. The shared and micro-mobility modes integral to Complete Streets often find inadequate representation in current AMS tools, leading to a deficiency in capturing the diverse range of transportation choices available. Furthermore, the focus on analyzing intersections rather than entire corridors and networks overlooks the broader context of multimodal travel patterns. Macroscopic demand modeling tools often lack the operational detail needed for realistic traffic operation estimation under real-world conditions, while microscopic tools, although offering finer granularity, struggle with capturing long-term changes in multimodal demand. These gaps underscore the need for advancements in AMS capabilities to better address the intricacies of Complete Streets and ensure a more inclusive and accurate representation of diverse transportation modes. A summary of modeling gaps is provided in **Table 4** below.

Table 4: Summary of Complete Streets Modeling Gaps and Challenges

Gap / Challenge ID	Gap / Challenge Category	Gap / Challenge Description
1.	Model insensitivity toward non-motorized trips and Complete Streets scenarios [3], [107], [108], [109]	• Existing AMS tools are generally insensitive to changes in the built environment that can affect demand, especially of non-motorized modes. • Pedestrian and bicyclist behaviors are currently modeled as largely insensitive to variations in delays as well as pedestrian/bicycle infrastructure improvements. • Existing demand models are not sensitive to Complete Streets enhancements (i.e., additional walk or bike trips attracted because of Complete Streets improvements). • Non-motorized modes are not well represented in many existing travel demand models due to limited non-motorized travel survey records, data collection issues, and tool's modeling abilities.
2.	Inadequate representation of shared and micro-mobility options [78], [90], [110], [111]	• Shared mobility options (e.g., ridesharing, bike sharing) and micro-mobility modes (e.g., bike, scooter, personal mobility devices) are not well represented and modeled in existing AMS tools. • Constantly evolving and emerging mobility technologies and availability of newer forms of mobility (such as MaaS) makes it challenging to model intermodal interactions comprehensively.
3.	Limited behavioral research on pedestrian and bicyclists [76], [109], [112]	• Pedestrian and bicyclist traffic flow behavior is an under-researched area and is not adequately reflected in existing AMS tools (i.e., passing, lateral and longitudinal motion, path prediction, etc.). • Pedestrian and bicyclist behaviors (such as movements) are generally difficult to predict, less constrained, and complex. • Limited insights into the travel behavior and traffic flow characteristics of people with disabilities and the elderly population.
4.	Lack of an overall MMLOS output capability and limited representation of diverse range of	• An overall MMLOS is not provided by existing deterministic methods. Instead, a multimodal analysis is applied separately for each mode. Aggregation of results to provide an overall score requires researcher/practitioner judgement in terms

Gap / Challenge ID	Gap / Challenge Category	Gap / Challenge Description
	factors affecting pedestrian, bicyclist, and transit LOS [113], [114], [115]	of weights for all modes, thus leading to biases and inconsistencies. • Pedestrian LOS at intersections is insensitive to increases in delay, not sensitive to curb ramps, crosswalk markings, median refuge islands, and other common treatments. It should be noted, however, that some of the methodologies in HCM 7 do take some of these intersection treatments into consideration. • Pedestrian LOS at the link- or segment-level is insensitive to sidewalk quality or smoothness, landscaping, roadway lighting, improvements to unsignalized intersections, and widening of sidewalks by more than 10 ft. • HCM methodology for bicycle level of service (BLOS) at intersections does not account for bicycle delay or motor vehicle speed, which contribute to a large number of crashes.
5.	Level of resolution and operational detail gaps in macroscopic and microscopic models [3], [94]	• Macroscopic/demand modeling tools do not provide level of operational details and performance measures that can account for realistic estimation of traffic operations reflecting real-world conditions. Microscopic tools provide such level of detail; however, they are computationally intensive and do not consider long term changes in multimodal demand.
6.	Model calibration and validation are often time consuming and complex [97], [116]	• Labor intensive model calibration and validation for pedestrian and bicycle modeling are common due to limited behavioral and counts data on various road user types such as pedestrians, bicyclists, and various micro-mobility users.

5.2 Data Collection Gaps

Another critical hurdle for Complete Streets modeling lies in the realm of data collection, where challenges and gaps significantly hinder the development of accurate and reliable models. These challenges encompass a broad spectrum, ranging from the labor-intensive nature of collecting data for pedestrians, bicyclists, and other micro-mobility users to the limited availability of historical data. Moreover, there is a notable lack of standardized data collection requirements for non-motorized modes, further making it difficult to gather the necessary information for robust model development. There have been some efforts in transit and micro-mobility domains where transit agencies and micro-mobility service providers can utilize a standardized way to represent and disseminate information about transit and bikeshare systems to the riders, such as General Transit Feed Specification (GTFS) or General Bikeshare Feed Specification (GBFS), yet their widescale adoption remains a challenge [117], [118], [119]. The new General Modeling Network Specification (GMNS) provides a common format for representing travel facilities that includes Complete Streets elements (e.g., bike facilities, sidewalks, and road crossings) [120]. As Complete Streets aspire to accommodate a variety of users, including those with disabilities, the existing data collection methods fall short in capturing the nuanced experiences of all individuals. A summary of gaps and challenges related to data collection for Complete Streets modeling is presented in **Table 5** below.

Table 5: Summary of Complete Streets Data Gaps and Challenges

Gap / Challenge ID	Gap / Challenge Category	Gap / Challenge Description
1.	Lack of data collection, requirements, and standards for Complete Streets [121], [122], [123], [124], [125], [126], [127]	• General lack of data in context of multiple users and modes. • Lack of requirements and standards on data collection for non-motorized modes. • General lack of requirements to analyze safety impacts of Federally funded projects especially in the context of VRUs. However, there is a proposed rule by FHWA to update the Highway Safety Improvement Program (HSIP) that will require safety improvements (focusing on the safe systems approach) to be incorporated into projects funded by the federal-aid program [128]. • Lack of standardized ways to represent Complete Streets facility data (e.g., sidewalks, bicycle racks, etc.). • Data collection for bicyclists and pedestrians is often very labor intensive to perform.
2.	Limited behavioral data on non-motorized road users [76], [109]	• Data scarcity regarding the behaviors of pedestrians, bicyclists, and other non-motorized users poses challenges for developing comprehensive and inclusive transportation models. • Household travel surveys do not always capture shared and micro-mobility mode choice preferences. • Incorporating non-motorized users in travel demand models requires extensive data collection efforts including but not limited to socio-economic data,

Gap / Challenge ID	Gap / Challenge Category	Gap / Challenge Description
		household travel surveys, travel/mode preference and choice surveys, etc.
3.	Difficultly in collecting near-miss and non-motorized collision data [123]	• Near-miss incidents greatly impact the perceived safety of a Complete Street project for road users. This data is difficult to collect but important for understanding the user experience. • Crashes involving pedestrians and bicyclists are often underreported.
4.	Gaps in evaluation data for Complete Streets [109], [115], [124]	• The varied goals and objectives of Complete Streets projects make it challenging to establish universally acceptable measures. • Evaluation decisions are often subjective with an emphasis on LOS that prioritizes congestion over safety and environmental goals. • Historical Complete Streets data is often difficult to obtain, making it challenging to track the long-term evolution of projects and understand their impacts and outcomes.

5.3 Procedural Gaps

In addition to modeling and data collection challenges, procedural gaps pose another obstacle to the seamless integration of Complete Streets principles into modeling and subsequently practice. For the last century in the United States, road transportation infrastructure has been focused almost exclusively on automobiles. While Complete Street projects attempt to rectify this, many stakeholders and institutionalized policies/procedures in the transportation field have not updated their priorities to reflect those of Complete Streets. As a result, the effectiveness of Complete Streets projects is diminished when other projects still work to prioritize motorized vehicle mobility without sufficient regard for other road users/modes. Policies biased towards certain transportation modes create a significant procedural hurdle to Complete Streets as they prioritize traditional approaches over the diverse needs of multimodal users. Zoning and building codes play a crucial role in shaping urban environments. However, their variation across jurisdictions often inhibits the uniform implementation of Complete Streets principles, affecting walkability and transportation inclusivity. The slow pace at which standards and guidance are updated at the Federal level poses challenges, leaving State and Local transportation departments with outdated frameworks that hinder innovation.

Many planning organizations and evaluators have noted the lack of evaluation standards for Complete Streets as a significant gap. This gap is difficult to address given the context-specific nature of Complete Streets projects. Not only will project goals differ, but social and cultural values in each region may influence road user behavior and project goals. All these factors make producing standardized methods for evaluation difficult. The procedural gaps have significant implications for Complete Streets modeling. Historically, these gaps in policies, procedures, development decisions, and evaluations have consistently favored the advancement of auto-centric transportation within the framework of AMS tools. A summary of procedural gaps and challenges are presented in **Table 6** below.

Table 6: Summary of Complete Streets Procedural Gaps and Challenges

Gap / Challenge ID	Gap / Challenge Category	Gap / Challenge Description
1.	Policies favoring certain modes [78], [126], [129]	• Many policies exhibit bias towards motorized modes of transportation, particularly auto. • Lack of a project prioritization framework often means that projects are prioritized based on ease of implementation. • Increase in suburban sprawl, homogenous suburbs far from city/urban centers, freeways dividing the city's neighborhoods, and racial and income segregation has led to decline in walkability and accessible streets/neighborhoods.
2.	Development decisions often made in silos [130]	• Zoning codes, building codes, and street standards can influence how livable or walkable a community is. • The siloed approach can lead to suboptimal outcomes as decisions are made without considering the broader impact to community (e.g., transportation decisions might be disconnected from housing or environmental considerations).
3.	Lack of consistent standards and practices across jurisdictions [122], [124], [125]	• Lack of evaluation standards for Complete Streets is not only a modeling/data gap but also a procedural challenge. The slow updates of standard and guidance documents at the Federal level complicates the evaluation process, affecting the success of Complete Streets projects.
4.	Lack of consistency in measuring equity, access to destinations, and	• Another significant procedural gap is the absence of consistent and standardized metrics for measuring equity, access to destinations, and connectivity in Complete Streets projects.

Gap / Challenge ID	Gap / Challenge Category	Gap / Challenge Description
	connectivity [122], [131]	

6 Conclusion

This report provides a comprehensive exploration of Complete Streets modeling using existing AMS tools and methods, covering background information, specific use cases and needs, and the existing modeling capabilities. The analysis has revealed notable gaps and challenges in various aspects, including modeling capabilities, data collection, and procedural gaps. Key findings include the scarcity of bicycle and pedestrian behavioral data, limited modeling capabilities for non-motorized travelers/road users, and challenges in evaluating the effectiveness of Complete Streets initiatives. The lack of standardized metrics, slow updates in evaluation standards, and the subjective nature of assessment present additional hurdles for Complete Streets modeling. Bridging these gaps will require efforts in standardizing data collection practices, improving modeling tools, updating evaluation metrics, and fostering collaboration across stakeholders. As Complete Streets continue to play a pivotal role in shaping the future of mobility, addressing these identified modeling and related gaps is essential for creating transportation systems that are safe, accessible, equitable, and sustainable for all users.

7 References

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