Analysis, Modeling, and Simulation (AMS) Testbed Framework for Dynamic Mobility Applications (DMA) and Active Transportation and Demand Management (ATDM) Programs

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16. Abstract

Both the Dynamic Mobility Applications (DMA) and Active Transportation and Demand Management (ATDM) Programs have similar overarching goals to improve surface transportation system efficiency and individual traveler mobility. However, each program has a unique research approach seeking to meet these goals. The DMA Program focuses on exploiting new forms of data from wirelessly connected vehicles, travelers, and the infrastructure to enable transformative mobility applications. The ATDM Program focuses its research efforts on accelerating the pace of dynamic control within transportation systems management through operational practices that incorporate predictive and active responses to changing operational conditions.
In order to explore potential transformations in transportation systems performance, both programs require an Analysis Modeling and Simulation (AMS) capability. AMS tools and methodologies offer a cost-effective approach to addressing complex questions on optimization of longer-range investments, shorter-term operational practices, and overall system performance. Both programs have invested significant resources in the development of advanced concepts and foundational research, but the potential impacts from deployment are uncertain and poorly quantified. The two programs must identify the technologies, applications, and operational approaches that work cost-effectively in concert with each other in order to justify large-scale demonstrations and pilot deployments.

A capable, reliable AMS Testbed provides a valuable mechanism to address this shared need by providing a laboratory for the refinement and integration of research concepts in a virtual computer-based AMS environment prior to field deployment. An AMS Testbed as envisioned here refers to a set of computer models that can replicate the effects of public agencies and private sector in a region implementing concepts, bundles, and strategies associated with the DMA and ATDM Programs. The purpose of this document is to provide a high-level framework for AMS Testbeds that recognizes both technical risk and the primary evaluation needs of the DMA and ATDM Programs. Four technical approaches that are consistent with the AMS framework are also presented.

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Executive Summary

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In order to explore potential transformations in transportation systems performance, both programs require an Analysis Modeling and Simulation (AMS) capability. AMS tools and methodologies offer a cost-effective approach to addressing complex questions on optimization of longer-range investments, shorter-term operational practices, and overall system performance. Both programs have invested significant resources in the development of advanced concepts and foundational research, but the potential impacts from deployment are uncertain and poorly quantified. The two programs must identify the technologies, applications, and operational approaches that work cost-effectively in concert with each other in order to justify large-scale demonstrations and pilot deployments.

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1 Introduction

1.1 Background

Effective congestion management involves a systematic process that enhances mobility and safety of people and goods, and reduces emissions and fuel consumption through innovative, practical, and cost-effective strategies and technologies. In response, the Federal Highway Administration (FHWA) Office of Operations initiated the Active Transportation and Demand Management (ATDM) Program to seek active, integrated and performance based solutions to improve safety, maximize system productivity, and enhance individual mobility in multi-modal surface transportation systems [1]. ATDM is the dynamic management, control, and influence of travel demand, traffic demand, and traffic flow of transportation facilities. Through the use of available tools and assets, traffic flow is managed and traveler behavior is influenced in real-time to achieve operational objectives, such as preventing or delaying breakdown conditions, improving safety, promoting sustainable travel modes, reducing emissions, or maximizing system efficiency. Under an ATDM approach, the transportation system is continuously monitored. Using historical and real-time data, predictions of traffic conditions are generated and actions are performed in real-time to achieve or maintain system performance. The ATDM Program is intended to support agencies and regions considering moving towards an active management approach. Through ATDM, regions attain the capability to monitor, control, and influence travel, traffic, and facility demand of the entire transportation system and over a traveler's entire trip chain. This notion of dynamically managing across the trip chain is the ultimate vision of ATDM. ATDM builds upon existing capabilities, assets, and programs and enables agencies to leverage existing investments - creating a more efficient and effective system and extending the service life of existing capital investments. All agencies and entities operating transportation systems can advance towards a more active management philosophy.

While active management can be applied to any part of our transportation system (such as implementing dynamic pricing on a facility to manage congestion, or informing travelers of specific or compatible transit operations for their trip), it is most beneficial when the relationships and synergies to other parts of the system are considered. For example, an agency could apply adaptive ramp metering to improve freeway traffic flow. However, if the effect of ramp metering on connecting arterials is not considered or if dynamic actions to manage overall demand are not implemented, some of the system-wide performance gains from the ramp metering system may be compromised. The ATDM Program has identified 23 strategies that fall under three major categories (Active Demand Management, Active Traffic Management, Active Parking Management) are documented in the ATDM Analysis, Modeling, and Simulation (AMS) Concept of Operations [2]. These strategies (Table 1-1) are not intended to be inclusive, but are intended to demonstrate how the ATDM concept of dynamically managing the entire trip chain can be manifested in individual strategies.

Figure 1-1 illustrates the five stages in a trip chain that represent a series of decisions that affect demand and utilization of the network.

Table 1-1: List of ATDM Strategies

Active Demand Management	Active Traffic Management Strategies	Active Parking Management Strategies
Dynamic Fare Reduction	Adaptive Ramp Metering	Dynamic Overflow Transit Parking
Dynamic HOV/Managed Lanes	Adaptive Traffic Signal Control	Dynamic Parking Reservation
Dynamic Pricing	Dynamic Junction Control	Dynamic Wayfinding
Dynamic Ridesharing	Dynamic Lane Reversal or Contraflow Lane Reversal	Dynamically Priced Parking
Dynamic Routing	Dynamic Lane Use Control	
Dynamic Transit Capacity Assignment	Dynamic Merge Control	
On-Demand Transit	Dynamic Shoulder Lanes	
Predictive Traveler Information	Dynamic Speed Limits	
Transfer Connection Protection	Queue Warning	
	Transit Signal Priority	

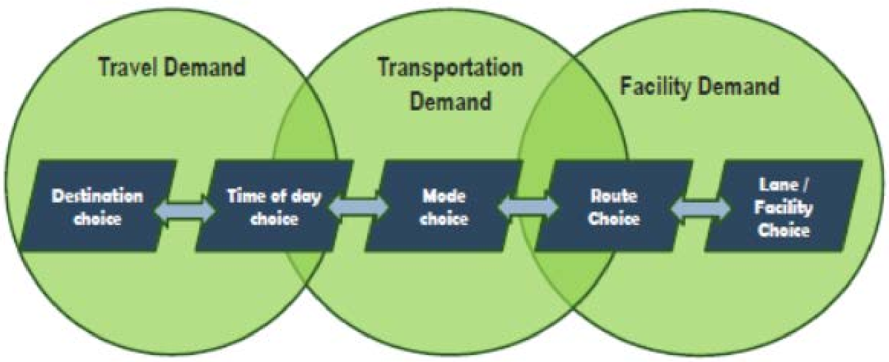

Figure 1-1: Trip Chain and Relation to Demand Activities [2]

Simultaneously, the USDOT initiated connected vehicle research to evaluate the merit of applications that leverage connected vehicles, travelers, and ITS infrastructure to enhance current operational practices and transform future surface transportation systems management. According to the USDOT, "Connected vehicles refer to the ability of vehicles of all types to communicate wirelessly with other vehicles and roadway equipment, such as traffic signals, to support a range of safety, mobility and environmental applications of interest to the public and private sectors. Vehicles include light, heavy and transit vehicles. The concept also extends to compatible aftermarket devices brought into vehicles and to pedestrians, motorcycles, cyclists and transit users carrying compatible devices, which could make these vulnerable users more visible to surrounding traffic." This research program is a collaborative initiative spanning the Intelligent Transportation Systems Joint Program Office (ITS JPO), Federal Highway Administration (FHWA), the Federal Transit Administration (FTA), the Federal Motor Carrier Safety Administration (FMCSA) and the National Highway Traffic Safety Administration (NHTSA). One foundational element of the connected vehicle research is the Dynamic Mobility Applications (DMA) Program [3]. The DMA Program seeks to create applications that fully leverage frequently collected and rapidly disseminated multi-source data gathered from connected travelers, vehicles and infrastructure, and that increase efficiency and improve individual mobility while reducing negative environmental impacts and safety risks. The objectives of the DMA Program include:

- Create applications using frequently collected and rapidly disseminated multi-source data from connected travelers, vehicles (automobiles, transit, freight) and infrastructure;
- Develop and assess applications showing potential to improve the nature, accuracy, precision and/or speed of dynamic decision making by both system managers and system users;
- Demonstrate applications predicted to improve the capability of the transportation system to provide safe, and reliable movement of goods and people; and
- Determine required infrastructure for transformative applications implementation, along with associated costs and benefits

In 2011, the DMA Program identified seven high priority bundles of transformative mobility applications that have the potential to improve the nature, accuracy, precision and/or speed of dynamic decision making by system managers and system users (Table 1-2). As a first step, the DMA Program partnered with the research community to further develop six of these high-priority transformative concepts (i.e., EnableATIS, FRATIS, IDTO, INFLO, MMITSS, and R.E.S.C.U.M.E.), and identify corresponding data and communications needs. The seventh bundle on Next Generation ICM (Integrated Corridor Management) may be developed at a later date.

Table 1-2 List of DMA Bundles

Bundle Acronym	Objective
EnableATIS	*Enable Advanced Traveler Information System* seeks to provide a framework for multi-source, multimodal data to enable the development of new advanced traveler information applications and strategies.
FRATIS	*Freight Advanced Traveler Information System* seeks to provide freight-specific route guidance and optimizes drayage operations so that load movements are coordinated between freight facilities to reduce empty-load trips.
IDTO	*Integrated Dynamic Transit Operations* seeks to facilitate passenger connection protection, provide dynamic scheduling, dispatching, and routing of transit vehicles, and facilitate dynamic ridesharing.
INFLO	*Intelligent Network Flow Optimization* seeks to optimize network flow on freeway and arterials by informing motorists of existing and impending queues and bottlenecks; providing target speeds by location and lane; and allowing capability to form ad hoc platoons of uniform speed.
MMITSS	*Multi-Modal Intelligent Traffic Signal System* is a comprehensive traffic signal system for complex arterial networks including passenger vehicles, transit, pedestrians, freight, and emergency vehicles.
R.E.S.C.U.M.E.	*Response, Emergency Staging and Communications, Uniform Management, and Evacuation* is an advanced vehicle-to-vehicle safety messaging over DSRC to improve safety of emergency responders and travelers.
Next Gen ICM	*Next Generation Integrated Corridor Management* seeks to optimize corridor mobility through a system-wide integration of enhanced operational practices and information Services.

The DMA Program is currently sponsoring several efforts to develop a prototype and conduct a small-scale demonstration for each of the six bundles to test if the bundles can be successfully prototyped and deployed in the future. The DMA Program is also sponsoring separate, multiple efforts (one for each bundle) to conduct an independent assessment of the impacts of the prototype as well as the impacts of the bundle when deployed at various levels of potential future market acceptance in the region where a small-scale demonstration of the prototype will be conducted. The data and findings from the small-scale demonstrations and impacts assessments will help USDOT make more informed decisions regarding the technical feasibility and potential impacts of deploying the bundles more widely. Both DMA and ATDM Programs have similar overarching goals. However, each program has a unique research approach seeking to meet these goals. The DMA Program focuses on exploiting new forms of data from wirelessly connected vehicles, travelers, and the infrastructure to enable transformative mobility applications. The ATDM Program focuses its research efforts on accelerating the pace of dynamic control within transportation systems management through operational practices that incorporate predictive and active responses to changing operational conditions[1]. While on the surface, these two research agendas may seem independent, the DMA and ATDM research approaches are really two sides of the same research coin. The more active forms of control envisioned by the ATDM Program will rely on new forms of data from connected vehicles, travelers, and infrastructure to hone predictions and tailor management responses. Likewise, the transformative applications developed in the DMA Program must be incorporated within current and future dynamic system-wide management practices in order to realize their full potential.

In order to explore potential transformations in transportation systems performance, both programs require an AMS capability. AMS tools and methodologies offer a cost-effective approach to addressing complex questions on optimization of longer-range investments, shorter-term operational practices, and overall system performance. Both programs have invested significant resources in the development of advanced concepts and foundational research, but the potential impacts from deployment are uncertain and poorly quantified. Each program recognizes the need to test these concepts, applications, and operational practices as a key next step in the process of moving research from concept towards deployment. The two programs must identify the technologies, applications, and operational approaches that work cost-effectively in concert with each other in order to justify large-scale demonstrations and pilot deployments.

A capable, reliable AMS Testbed provides a valuable mechanism to address this shared need by providing a laboratory for the refinement and integration of research concepts in a virtual computer-based AMS environment prior to field deployment. An AMS Testbed as envisioned here refers to a set of computer models that can replicate the effects of public agencies and private sector in a region implementing concepts, bundles, and strategies associated with the DMA and ATDM Programs. The AMS Testbed will be implemented in a laboratory setting in that the modeling conducted will not be directly connected to the systems, algorithms, or Traffic Management Center (TMC) operators that make real-time traffic management decisions. However, it is the intent to make the AMS Testbed as closely based in reality as possible by modeling an actual metropolitan region’s transportation system (e.g., road, transit, and parking networks), transportation demand (e.g., persons, vehicles, transit), and DMA and ATDM concepts, bundles, and strategies.

[1] Operational conditions describe the frequency and intensity of specific travel conditions experienced by a traveler over the course of a year. Operational conditions are identified by a combination of specific travel and traffic demand levels and patterns (e.g., low, medium or high demand), weather (e.g., clear, rain, snow, ice, fog, poor visibility), incident (e.g., no impact, medium impact, high impact), and other planned disruptions (e.g., work zones).

A joint DMA-ATDM AMS Testbed can make significant contributions in identifying the benefits of more effective, more active systems management, resulting from integrating transformative applications enabled by new data from wirelessly connected vehicles, travelers, and infrastructure. To this end, the DMA and ATDM Programs have jointly sponsored the planning of multiple AMS Testbeds to support the two programs in evaluating and demonstrating the system-wide impacts of deploying application bundles and strategies in an AMS environment.

This planning effort has resulted in a series of reports, including:

- AMS Testbed High Level Requirements for DMA and ATDM Programs [4]
- AMS Testbed Preliminary Evaluation Plan for DMA Program [5]
- AMS Testbed Preliminary Evaluation Plan for ATDM Program [6]
- AMS Testbed Framework for DMA and ATDM Programs (this report)
- AMS Testbed Initial Screening Report [7]

It is envisioned that multiple AMS Testbeds will be developed to both mitigate technical risk and enable a more rigorous evaluation of the impacts and benefits of applying DMA and ATDM approaches, given differences in regional characteristics and varying combinations of bundles and strategies. As mentioned previously, it is the intent to make these AMS Testbeds as closely based in reality as possible by modeling actual metropolitan region's transportation systems (e.g., road, transit, and parking networks), transportation demand (e.g., persons, vehicles, transit), and DMA and ATDM concepts, bundles, and strategies.

1.2 Purpose

The purpose of this document is to provide a high-level framework for AMS Testbeds that recognizes both technical risk and the primary evaluation needs of the DMA and ATDM Programs. Four technical approaches that are consistent with the AMS framework are also presented.

2 Hypotheses and System Description

This section presents a description of the system and some preliminary key hypotheses, which will be modified with input from stakeholders. First, we present a set of primary hypotheses for the DMA and ATDM Programs that an AMS Testbed will test. Overlapping and divergent elements of these key hypotheses are explored. Next we present a system description based on the intersection of the two programs key hypotheses. The description that can be utilized to describe alternative deployed systems relevant to the overarching experimentation required in each program. The AMS Testbed Framework is developed based on this representation of the transportation system.

2.1 Key Hypotheses

An AMS Testbed is essentially a complex experimental apparatus created to test specific research hypotheses. It is not an operational system, but must represent and evaluate alternative operational systems. The DMA and ATDM Programs have differing but overlapping visions on investments in technologies and enhanced operational practices can result in more effective systems management, and a transportation system with improved mobility, safety and reduced environmental impacts.

In the ATDM Program, the focus is on quantifying the value of more active and predictive systems management:
"…to conduct business in a new way, by proactively managing transportation systems and services to respond to real-time conditions while — at the same time — providing realistic choices for managing travel demand… ATDM is the dynamic management, control, and influence of travel demand, traffic demand, and traffic flow of transportation facilities. Under an ATDM approach, the transportation system is continuously monitored, and through the use of available tools and assets, traffic flow is managed and traveler behavior influenced in real time to achieve operational objectives" [2]

Translating this vision to a hypothesis statement that could be tested in an AMS Testbed:

ATDM Program Hypothesis: *Incorporating predictive (compared to reactive) and more active (reduced latency) dynamic transportation system management considering the full spectrum of potential traveler decision-making in response to changing operational conditions yields cost-effective gains in system efficiency, and safety and reductions in negative environmental impacts.*

Such a hypothesis might be misrepresented as a truism – that in fact prediction and more active and comprehensive management must in fact be cost-effective or at least effective in yielding gains in system efficiency. However, it is not clear that all investments in improving prediction or reducing the latency of decision-making are cost-effective in all cases. More specifically, not all ATDM-related investments can be *equally* effective or cost-effective. Therefore, an ATDM Testbed must address both the ATDM Program hypothesis as well as its corollary ATDM Testbed hypothesis:

ATDM Testbed Hypothesis: *An AMS Testbed can be developed that can accurately quantify the potential cost and benefits of system improvements incorporating predictive, active, and comprehensive responses to changing operational conditions, and effectively differentiate between* *more and less effective alternative system improvements within the resource and schedule constraints of the ATDM Program*.

Note that the differentiation among alternative approaches is not the same as designing, prototyping or perfecting methods of prediction and active management. The ATDM Testbed hypothesis is focused on the value of prediction and active management as represented in alternative systems that attempt to address the ATDM Program hypothesis, rather than representing and refining a single ATDM master prototype system.

In the DMA Program, the focus is on exploiting new forms of data from wirelessly connected vehicles, travelers, and infrastructure to enable transformative mobility applications.

"The vision of the Dynamic Mobility Applications Program is to expedite the development, testing, commercialization, and deployment of innovative mobility applications, fully leveraging both new technologies and federal investment to transform transportation system management, to maximize the productivity of the system and enhance the mobility of individuals within the system." [8]

Translating this vision to a hypothesis statement that could be tested in an AMS Testbed:

DMA Program Hypothesis: *Compared to legacy systems, the introduction of applications based on new forms of wirelessly-connected vehicle, infrastructure, and mobile device data yields cost-effective gains in system efficiency, and safety and reductions in negative environmental impacts.*

This hypothesis is not an accepted truism within the transportation community. Enabling the capture, distribution and processing of new forms of data will certainly incur additional costs, but whether the associated benefits are actually transformative, or even cost-effective, is an open question. However, similar to the ATDM Program, some applications are likely to be cost-effective or at least effective in yielding gains in system efficiency. However, it is not clear that the collective investment in enabling new forms of data capture to support some or all of the transformative applications is cost-effective in all cases. More specifically to the core of DMA Program, not all DMA-related investments will be *equally* effective or cost-effective. Therefore, the AMS Testbed must address both the DMA Program hypothesis as well as its corollary DMA Testbed hypothesis:

DMA Testbed Hypothesis: *An AMS Testbed can be developed that can accurately represent new forms of wireless data capture and defined mobility applications, quantify the potential cost and benefits associated with enabling these applications, and effectively differentiate between more and less cost-effective alternative systems incorporating differing forms of systematic data capture and the deployment of some or all mobility applications within the resource and schedule constraints of the DMA Program*.

The two Program and AMS Testbed hypotheses, although they focus on different aspects of a larger problem, are complementary forms of research regarding the broader surface transportation system improvement and investment planning decision. In the next section, we present a transportation system description that attempts to reflect all of the key hypotheses of the two programs.

One benefit of addressing the ATDM and DMA hypotheses jointly is to provide an analytical method of comparing alternative systems that are in fact combinations of the visions of both programs. For example, is the most cost-effective predictively-managed system more cost-effective than a reactive system with some collection of near-term mobility applications? We might also posit a less competitive research question with a complementary one: does the incorporation of some new forms of wirelessly connected vehicle and traveler data inherently enable the most cost-effective forms of predictive management? Therefore, while the two programs are asking relevant research questions in isolation of each other, a decision-maker contemplating system investments is likely more interested in identifying the most effective combination of legacy/new technology and associated predictive/active management.

Studies utilizing a joint DMA-ATDM AMS testbed will analyze the regional mobility impacts of various combinations of DMA Applications, deployed in isolation or combination. For the ATDM Program, analyses will test various combinations of ATDM strategies based on an active management approach to demonstrate the system-wide and localized impacts and benefits of taking an ATDM approach to transportation management. Cost-effectiveness is a critical aspect to justifying demonstration and early deployment and therefore the hypotheses reflect the importance of cost-effectiveness. One part of that includes trying different sub-alternatives with improvements swapped in and out, and applications deployed in isolation and in combination. The testbed is intended to focus on the impacts or benefits of deployment, but the alternatives tested will also have an associated cost, calculated outside of the testbed.

The testbed need not seek most the complex or detailed method of emulation in every aspect of modeled system entities or user behavior. The intent of this effort is to systematically manage technical risk, and seeking ways of separating risk so that we are not completely dependent on single points of failure in any technical approach.

The testbed concept developed here is intended as an off-line test-bed, not a predictive tool to be integrated within an operational system. Therefore, the test bed is not intended to be a real-time predictor, although findings from the development of one or more test beds may be useful in the development of improved prediction systems. Rather, the focus of the effort is on the projected value of a range of prediction techniques (simple, faster and less precise versus complex, slower and more precise) rather than on the development of a single highly precise prediction technique. Other concurrent FHWA research efforts are tackling the problem of developing complex and highly precise prediction methods, and findings from these efforts will be useful in correctly representing these approaches within an AMS testbed.

Testbed development is intended to leverage open source and open data concepts where practical, to both engage potential analysts and to foster rapid adoption of analytical approaches developed in this effort. Availability of analysis plans, test bed development progress, algorithms and methodological statements, as well as input files and output data are expected to be broadly shared through the USDOT Open Source Portal (www.its-forge.net) and the USDOT Research Data Exchange (www.its-rde.net).

2.2 System Description

A system description is as an abstraction of the overall transportation system that can serve to highlight both the hypotheses posited by the two programs as well as be used as a building block to devise and document alternative system deployments evaluated within an AMS Testbed. The system description utilized in this document is shown in Figure 2-1. On the far left side of the figure, there is a column of **System Users**, who represent the travelers, drivers and workers who directly utilize the transportation system. System Users are humans, who make a range of strategic decisions regarding their travel. These decisions may be whether to travel, what mode of travel to use, when to take a trip, what route to travel on within a mode, where to park, and finally, how a collection of trips (tour) within a day will meet a variety of obligations and desired outcomes. Further there are tactical decisions that must be made, particularly as a driver, regarding how fast to travel, in what lane, and how to maneuver effectively and safely in a variety of situations. A traveler (upper left) may transition between multiple states while planning and executing travel, starting from a pre-trip state and passing through one or more combinations of pedestrian, cyclist, passenger, driver, or transit rider states prior to completing a trip. Each state will have a different set of potential decisions that collectively influence the operational status of the overall transportation system.

At the far right of the figure are the **System Managers**, who control a particular aspect of the system and are responsible for ensuring the safe and efficient operation of their element of the complete system. Note that while System Managers are humans, some aspects of system management may be automated and do not require human intervention or decision-making on a regular basis. In between the users and the managers there is a natural gap to be bridged. An isolated system user, without any technological assistance, can only perceive or understand the state of the system in their immediate locality. A system manager, without any technological assistance, has even a more limited view of system performance or the likely actions of the system users. One thought experiment we might consider is a *pervasive omniscient* system ideal, where all users and all managers are collectively aware of all other users' and managers' current status and anticipated future behavior. This concept represents one upper bound on the limits (and benefits) of any system to optimize joint decision making by users and managers. Reality is not ideal, however, so our system description must include delineating the underlying capabilities and limitations of both system users and system managers to make informed decisions based on the quality, latency, reliability and scope of information available to them.

The subtitle of the system description is "System Users, Managers, and Intermediary Technologies and Entities". Between the System Users and the System Managers in the diagram are the existing and potential technologies to bridge the gap and supply information to both Users and Managers. One way of understanding a system is to trace how messages from System Users (and their associated vehicles and devices can combined and integrated and used in conjunction with predictive tools to support decision-making by System Managers.

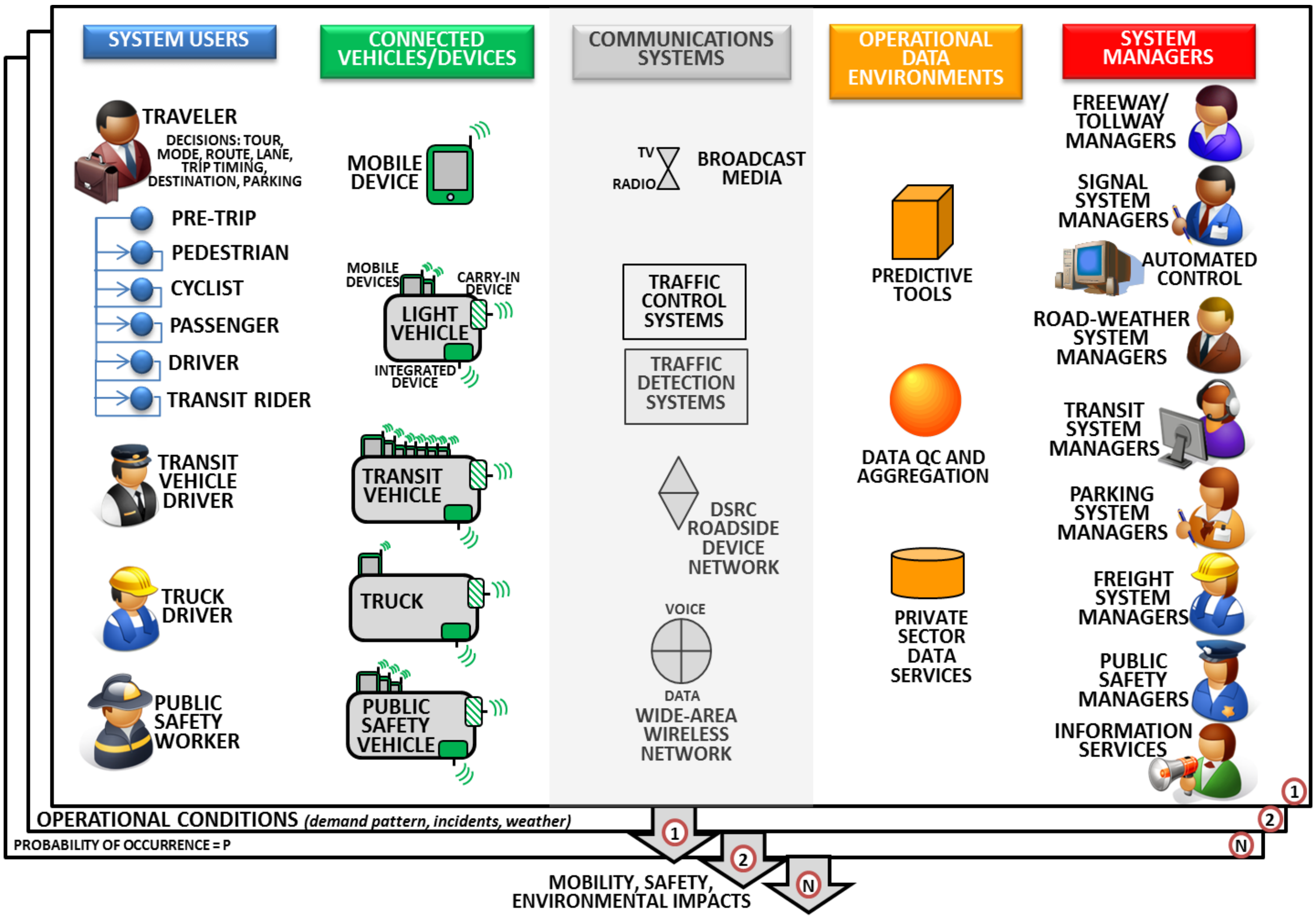

Figure 2-1: System Description: Transportation System Users, Managers, and Intermediary Entities

This left-to-right path represents the data-to-information chain for System Managers. A path extending from the right to the left can also be constructed indicating how control messages and advisory information generated by System Managers are realized in traffic control systems or other communications systems to inform System Users and influence their decisions. A right-to-left path represents the control-to-information chain for System Users.

Adjacent to the System Users on the left side of the diagram are an array of **Connected Vehicles and Devices** which are capable of sending messages through one or more communication systems over and above being passively detected by deployed traffic detection systems. These include mobile devices carried by individual system users, devices carried into and mounted within a vehicle, and devices permanently integrated into vehicles. Note that a vehicle may have multiple devices in it at any one time, including mobile devices carried by passengers or riders. Also note that the type and function of mobile or vehicle-based devices may be tailored for specific purposes, e.g., transit vehicles, trucks, and public safety vehicles.

The center column in the diagram shows the fundamental set of **Communications Systems** through which the System Users and System Managers directly or indirectly interact. One such system used by System Managers to communicate with System Users are broadcast media, delivered through television, radio, or internet. System Managers also rely on traffic detection systems that passively measure attributes of traffic flow (speed, density, throughput), and traffic control systems which signal or otherwise locally instruct drivers and other system users. Two other communications systems shown in the diagram transmit data or voice information directly from devices and vehicles equipped to interact with these networks. In the center of the diagram is a network of deployed roadside devices capable of sending or receiving messages via Dedicated Short Range Communication (DSRC). DSRC roadside technologies have been developed and tested by USDOT as a part of a broader research program but are not yet widely deployed. At the bottom of this column are wide area communications technologies that can carry either voice or data, such as the commercial cellular communications system.

Data generated either by passive detection or direct messaging can be integrated and prepared to support System Managers in the **Operational Data Environment** column. Data may be collected and assembled by private sector or public-sector entities, for example, in decision support systems supporting specific system users. In some cases private sector data services are used to supplement public sector data quality control (QC) and aggregation. Predictive tools may be employed to augment or leverage observed data to enhance the decision-making capability of one or more System Managers. Note that the function of prediction is embedded here but can reflect a full range of historical data analysis used to support decision making. Also note the notion of active management is reflected in the summative latency accumulated along the data-to-information chain (from the System User to the System Manager) plus the latency associated with the provision of adapted controls and information flowing in the control-to-information chain (from the System Manager to the System User). One critical characterization of active versus reactive system management is reflected by this total summative latency. Therefore, “active” is a relative term when comparing any two alternative systems, the one with the lower total *data-to-information-to-control-to-information* latency being more active than a system with a larger total latency.

The system description itself sits on a series of **Operational Conditions**, which describe different realizations of underlying variation in travel demand and transportation capacity (both recurrent and non-recurrent) resulting from multiple factors including incident patterns and variation in road/weather conditions. In our system description, we indicate that there are up to *N* operational conditions to be considered, each a combination of demand, incident, road/weather and other conditions. Each operational condition has a probability of occurrence. In each operational condition, we seek to characterize the mobility, safety and environmental impacts of a particular system alternative that connect the various elements of the system together in a particular way. These impacts can be quantified and monetized in a consistent and systematic way for comparison with total cost of system to determine cost-effectiveness. The ICM program has established some preliminary methods of both estimating the operational conditions space through cluster analyses, and an associated impact calculation method [9]. The SHRP-2 L08 report identifies an approach to identify operational scenarios and associated probabilities for data rich and data poor environments [10]. The ATDM Analysis plan also recognizes the need for scenario generation [11].

The System Description presented in Figure 2-1 is not representative of any particular alternative system we might want to test and evaluate within an AMS Testbed. Instead, it shows the fundamental building blocks with which we can describe any relevant alternative system.

In the next section, a high-level framework for the AMS Testbed is discussed.

3 AMS Framework

This section describes a framework for the AMS Testbed that is based on the combined set of AMS Testbed requirements, documented in the AMS Testbed Requirements report [4]. The proposed AMS Framework includes six components:

1. **Travel Demand Simulator**, that simulates travel demand and system user's strategic decisions regarding their travel.
2. **Transportation Network Simulator**, that simulates traffic and weather detection systems, traffic management and control systems, broadcast media, connected vehicles and devices, tactical behaviors in response to traffic conditions and control and advisory information, and resulting traveler and vehicle movements through the network.
3. **Wireless Communications Network Simulator**, that simulates message transmission and propagation.
4. **Operational Data Environment Simulator**, that simulates data quality control and aggregation.
5. **Predictive Environment Simulator**, that simulates the prediction of transportation network performance.
6. **System Manager Simulator**, that simulates system managers' decisions based on the information available from the Operational Data Environment and/or the Predictive Data Environment that is then disseminated to Traffic Management and Control Systems, Broadcast Media, Connected Vehicles and Devices, and System Users either pre-trip or en route.

Figure 3-1 is a graphical illustration of the framework. The connections between the simulators represent the flow of data and information, and include realistic errors and latencies observed in the field due to limitations of the technology, algorithm, or processing of data. The connections may be more or less close to real-time, more or less dynamic, and may include data that are more or less aggregated (or disaggregated). The framework presented is modeling scale (or resolution) and tool agnostic. Multiple approaches of varying fidelity and complexity are suggested for each box. Each testbed will have to tailor the framework according to the needs of the specific DMA bundles/ATDM strategies being modeled and evaluated, and the complexities of the selected testbed. It is critical to design a framework that is tractable and complies with the analysis plan. To feasibly implement approaches consistent with the framework and the analysis plan, each analyst has to make decisions on what to model in detail, and what to model in less detail.

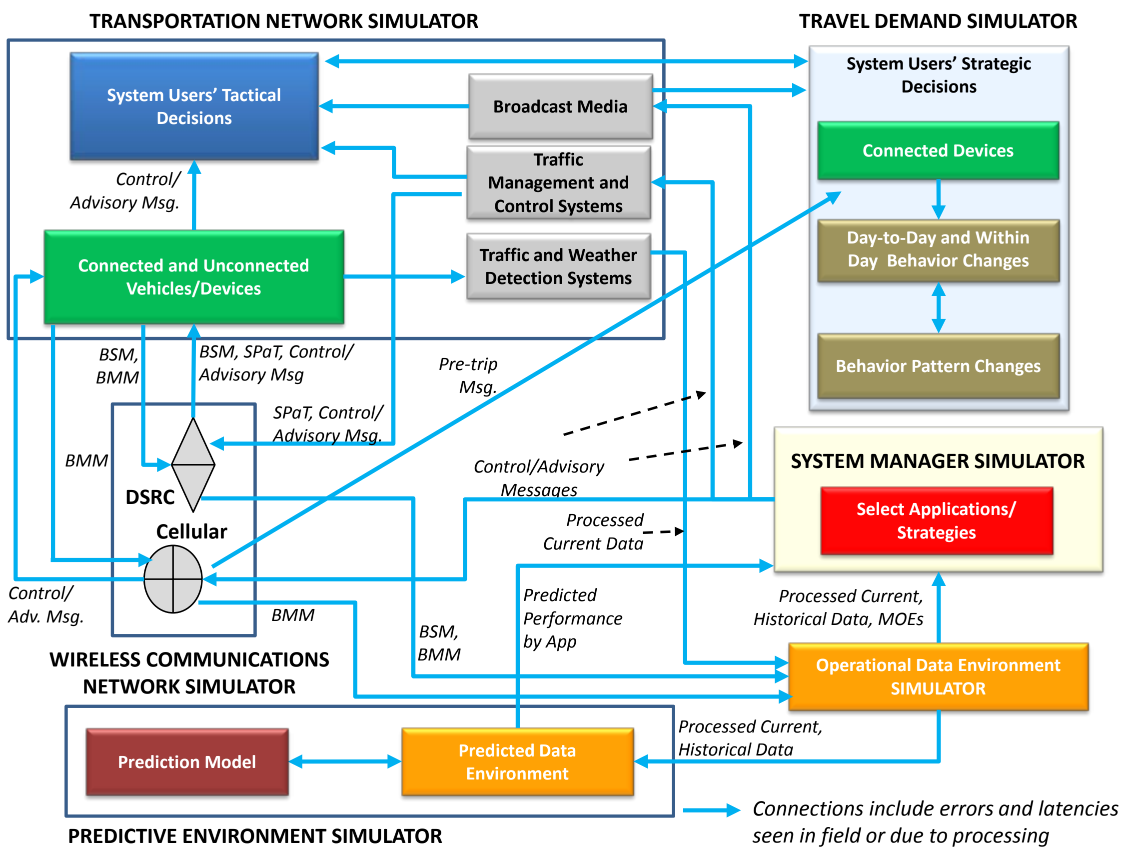

Figure 3-1. DMA-ATDM AMS Framework

3.1 Travel Demand Simulator

The AMS Testbed must represent System Users, who make a range of strategic and tactical decisions regarding their travel. Systems Users may be Travelers (Pedestrian, Non-Motorized Traveler, Light Vehicle Passenger, or Transit Rider), Light Vehicle Drivers, Transit Vehicle Drivers, Truck Drivers, Public Safety Vehicle Drivers, and other Public Safety Workers (passengers in public safety vehicles). This component models System User's strategic decisions. Strategic decisions are decisions regarding the timing and nature of trip-making made by system users (i.e., travelers and drivers) in response to traffic conditions and travel experiences. These may be long-term, habitual behaviors (e.g., check traffic and weather around 7 AM and leave for work between 7:30 and 8:00 AM) or short-term decisions made pre-trip (e.g., it's raining, I'm taking the train today). Strategic decisions may be whether to travel or not, who to travel with, what mode of travel to use, when to take a trip, what route to travel on within a mode, where to park, and what sequence of trips to make within a day (i.e., a tour) to meet a variety of obligations and desired outcomes. These decisions may be in response to: past travel experiences on a similar trip executed at the same time of day and day of week; control and advisory information communicated by System Managers via broadcast media, 511, or as opt-in services. The decisions taken will be dependent on past experience (perceived reliability) with the information service; when and where the system user receives the information; the perceived accuracy of the information; and the nature of the information.

Strategic and tactical decisions must be represented within the context of long-term (habitual) and short-term (exception) behavior. An individual may have habitual strategic behaviors (e.g., default or most typical mode choice and time of departure choices) and habitual tactical behaviors (e.g., lane choice in an approach to recurrent bottleneck). These long-term behaviors are themselves a learning-based process and may change over time with changes in travel time reliability, travel costs and other factors. Similarly, a traveler may adopt short-term strategic behaviors (e.g., mode choice) and tactical behaviors (e.g., lane choice) in response to unexpected operational conditions (e.g., a full closure resulting from a major incident). The Travel Demand Simulator must reflect the natural interplay of relatively slower-moving long-term behavioral adaptations created over many days of repeated trip-making as well as more dynamic, short-term adaptations made in response to current travel conditions.

The nature of the information is defined by the scope, precision, format, and latency. Strategic decisions may be modeled by a range of models and analytical techniques with varied accuracy and precision. Strategic decisions are specifically differentiated from tactical decisions in order to focus on the specific needs of the AMS Testbed in these two aspects of System User behavior. Tactical decisions made by drivers are those decisions and maneuvers made to pre-position or control their vehicles. Tactical decisions made by drivers may be to accelerate, decelerate, start, stop, brake, change lanes, merge, yield, choose the lane to travel in or merge into, or when to override an automated system and take physical control of the vehicle. Tactical decisions made by pedestrians include decisions such as whether to cross a street or not upon receipt of a pedestrian phase. Tactical decisions made by bicyclists may be to cross a street, yield to vehicles , slow down or stop when a vehicle is making a turn. We recognize that modeling strategic decision making and tactical decisions are related since they are both aspects of comprehensive System User behavior. However, an analyst has the option to choose more or less complex representations of strategic or tactical behaviors in a modeling approach independently, therefore they are treated independently for considerations within our framework.

Common analytical methods of representing strategic traveler behavior include:

Disaggregate (Activity-Based) Models: This is a disaggregate approach that derives demand based on the activities that users wish to perform. This approach is suitable when the intent is to capture more accurately a system user's travel behavior by predicting the sequence of activities people pursue, where, when, with whom, and for how long given fixed land use, transportation supply, and individual characteristics. Each system user and household are modeled separately. A trip is generated to connect two spatially separated sequential activities. Mode and route decisions are also modeled. This approach overcomes some of the limitations of the 4-step model and tour-based model, and can predict traveler behavior in response to policy changes. Disadvantages of a disaggregate approach include higher technical risk, less mature marketplace of commercial tools and developed networks, a lack of detailed locally-tailored data for model validation, and a relatively small body of collective research describing experience using these tools compared to aggregate approaches.

Aggregate Models: This approach is more suited when the objective is to represent users' strategic decisions at an aggregate level. Traditional 4-step and tour based models are examples of aggregate models. The limitation with 4-step models is that it ignores sequencing of trips and spatial connection between trips made by an individual. This approach also ignores the connections between trips among members of a household. Emphasis is placed on the trips rather than the activities that motivate the trips. Static 24-hour O-D trip tables are generated by trip purpose. Variants of this approach may further decompose static 24-hour trip tables into time-dependent trip tables. Tour-based models use a simplified structure for tour generation and scheduling that does not explicitly account for intra-household interactions, joint travel, and individual schedule consistency. Mode choice are modeled using logit models (such as nested logit). These approaches are not capable of predicting traveler choices in response to policy changes, such as in Dynamic Pricing or Dynamically Priced Parking. Advantages of these models include lower technical risk, broad availability of commercial tools and developed networks, and an extensive body of research work describing the collective experience of applying these approaches (strengths and weaknesses are well known and documented).

3.2 Transportation Network Simulator

This component models tactical decisions of system users (travelers and drivers), tactical movements of travelers and vehicles (connected and unconnected), traffic and weather detection systems, traffic management and control systems, and broadcast media.

3.2.1 Modeling Systems Users' Tactical Decisions and Vehicle Movements

The AMS Testbed must be capable of modeling System Users tactical decision-making as they execute their trip. Tactical decisions or maneuvers may be made in response to: control or advisory messages communicated by System Managers via road side infrastructure (e.g., variable message signs, signals, ramp meters), broadcast media (e.g., HAR, TV, commercial radio), 511,etc.; wireless communications including, vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), infrastructure-to-mobile, vehicle-to-mobile, and mobile-to-mobile communications; congestion or incidents observed; driving behaviors of other drivers in the immediate vicinity (e.g., erratic drivers, tailgaters, slow drivers); presence of vehicles in the immediate vicinity that increase perception of unsafe driving conditions; and unsafe driving conditions (e.g., wet pavement, debris on lane).

The AMS Testbed should also model Connected Vehicles and Devices as well as Unconnected Vehicles. A Connected Vehicle is a vehicle equipped with one or more Carry-In or Integrated Devices. Note that a Connected Vehicle may contain Passengers utilizing Mobile Devices; however, this is not sufficient to characterize a vehicle as a Connected Vehicle. An Unconnected Vehicle is a vehicle which is not equipped with one or more Carry-In or Integrated Devices. An Unconnected Vehicle may carry one or more Passengers utilizing a Mobile Device.

Travelers' tactical decisions and maneuvers, and vehicles may be modeled by a range of models and analytical techniques with varied accuracy, precision, and latency. This section specifically discusses the movement of Connected and Unconnected vehicles. Representation of message generation by Connected Vehicle and Devices is discussed in the next section. Common analytical methods of representing the position, movement, and tactical decision-making of System Users executing trips within the transportation system include:

Microscopic Simulation Models: Microscopic models capture vehicle interactions accurately at the link and lane level. Traffic Control Devices and Traffic Detections Systems are also accurately represented. Some models also represent pedestrian movement in detail. Time-dependent routing can also be modeled in some tools. Tactical driver behavior is fairly accurately represented but only in the presence of unconnected vehicles. Behaviors of drivers, pedestrians and bicyclists in the presence of connected vehicles and devices are relatively unknown. Multiple commercial tools are widely available and there is a broad base of application experience. However, constructing and calibrating large (corridor to sub-regional size) networks is expensive and as the modeled travel shed expands, so does technical risk and run-time constraints.

Mesoscopic Simulation Models: Mesoscopic simulation models move individual vehicles based on macroscopic speed-flow relationships. These models are capable of producing time-dependent O-D trip tables. Geometric details and tactical behaviors in system bottlenecks (freeway merge/weave sections and arterial junctions) may not be precisely represented, depending on whether lane-level mesoscopic models are employed. As such they are less superior to microscopic simulation models in representing tactical driving behaviors in complex roadway geometrics, however, because of lower underlying complexity, they are capable of representing larger networks than microscopic models due to the extensive amount of data needed for calibrating microscopic models. Pedestrian movement is not modeled. Behaviors of drivers, pedestrians, and bicyclists in the presence of connected vehicles and devices are unknown. Commercial tools and networks are available, however the body of research and experience in applying these tools is less extensive relative to microscopic tools.

3.2.2 Modeling Message Generation by Connected Vehicles and Devices

The AMS Testbed must represent the generation of messages by Connected Vehicles and Devices. Analytical techniques and traffic simulation APIs have been developed to emulate message generation that is compliant with the SAE J2735 standard for Basic Safety Message and Probe Data Message [12]. Two broad approaches for modeling message generation are detailed below.

Higher-Fidelity Models: This approach explicitly models generation of messages by individual connected vehicles and devices, including the message content, message triggers, frequency of message generation, and device storage mechanisms. There are several variants of this approach that specifically emulate SAE J2735 Basic Safety Messages and Probe Data Messages using traffic simulation tools that are less or more realistic. For example, some variants specifically emulate message triggers for probe data messages, including periodic triggers which are related to vehicle speed, and stop/start trigger related to a stop or a start of vehicle motion. Event triggers which are related to the vehicle status (e.g., engagement of Antilock Brake Systems) may be modeled as approximations since such events are not represented in traffic simulation tools (e.g., when a vehicle's deceleration rate is equal to the maximum allowable deceleration rate an event trigger may be recorded in lieu of the ABS being engaged). Messages might be stored using different mechanisms. One variant of this approach might assume that all messages generated are stored indefinitely, while a more realistic approach might use the pre-set priorities defined in the SAE J2735 standard. Vehicle identifiers might be assumed to be either persistent (a less realistic approach), or temporary, following the protocols defined in the J2735 standard. Such approaches afford the capability to accurately represent the impact of connected vehicles and devices on system performance. However, these approaches increase runtime and complexity of data processing.

Lower-Fidelity Models: This is a high-level approach to modeling message generation when the desire is to estimate communications load at an aggregate-level. This approach does not explicitly model message generation, including triggers that cause message generation and message frequency. Message content by device type is also overlooked. For example, the type of messages that might be available from an integrated device is very different what is available from a carry-in device or a mobile device. That is every connected vehicle and device generates the same message (e.g., BSM Part1 or a subset of BSM Part 1), regardless of the capability of the device. Buffer size is assumed to be infinite, implying that no messages are deleted. Identifiers are assumed to be persistent, i.e., anonymity is not an issue. Message triggers and message frequency may be modeled as a factor of the facility type, but are not explicitly modeled. Thus, these models assume that if there is a connected vehicle or device in the traffic mix, pre-set message content is available from them at a pre-set frequency with no loss. Such an approach is an approximation of how communications might impact the data that are available from vehicles and travelers. The advantage of such an approach is that sophisticated message generation emulators or detailed wireless communications simulations need not be created and integrated with transportation simulations. However, such an approach only provides a broad approximation of system performance as a result of enhanced data from connected vehicles and devices.

3.2.3 Modeling Traffic and Weather Detection Systems

Traffic and Weather Detection Systems include loop detectors, Road-Weather Information Systems, Bluetooth readers and other roadside devices that have their own power source and are capable of passively detecting and classifying attributes of vehicle or pedestrian movement within a specific range of the location of the device. The detection system includes supporting roadside/wayside communications systems that aggregate, prepare, or otherwise process local data prior to transmission to Operational Data Environments supporting System Managers.

Independent tools that specifically model traffic detection systems are not routine elements of the analyst toolkit. Generally, the operation of traffic detection systems are simulated using higher and lower-fidelity approaches within traffic simulations (either microscopic or mesoscopic). In some cases APIs have been constructed to represent or emulate a specific detection technology or product. Even more rarely, “hardware in the loop” approaches have been used to more directly represent specific products and technologies. There are two suggested approaches to modeling traffic detection systems, which may be interfaced with existing traffic simulation approaches to realistically represent the capture the exact nature of the data that are available, the inherent errors, and latencies.

Higher-Fidelity Models: In this approach, precise locations of the Traffic Detections System devices are modeled. The type, scope, quality, and latency of information available from each device are represented accurately. For example, if travel times are available with certain accuracy from Bluetooth readers deployed on a facility, then only travel times on the facility between the two readers are modeled as available. Secondly, errors in the processed information (in our example, estimation of travel times) are represented. Errors may be due to the limitations of the detection technology, limitations of the algorithms used to process the data, or due to the data itself (not enough sample points). In our example, errors in travel times might be represented as a factor of the facility type (interrupted flow on arterials are likely to have higher errors), facility volume (higher the volume higher the percentage of Bluetooth devices in the traffic mix) the distance between the two readers, and the detection zone of the readers. Thirdly, latency between detection and transmitting the processed information (or measure) to the Operational Data Environments are also represented.

Lower-Fidelity Models: In this approach, location and scope are approximated. Looking at the Bluetooth reader example, exact locations of the Bluetooth readers are not represented. Travel times are assumed to be available for the entire facility where the Bluetooth readers are placed. However, quality and latency are modeled explicitly, using a similar approach as used in the Higher-Fidelity Models approach. Variants of this approach might assume perfect quality (no errors) and/or no latency (i.e., processed information is available as soon as a vehicle, traveler, or device is detected).

3.2.4 Modeling Traffic Management and Control Systems

Traffic Management and Control Systems are signage and signaling systems such as arterial traffic signal systems, ramp metering systems, dynamic message boards, and static signage used to influence and control driver decision making in a localized area. These control systems may act in a fixed or autonomous manner locally supported by dedicated local detection systems. These control settings may be directly or indirectly updated according to control decisions made by System Managers. The capability of system managers to rapidly and precisely manage control settings are inherently limited by the capability of the control systems to receive, process, and implement these changes.

Traffic Management and Control Systems, like Traffic and Weather Detection Systems, are not specifically modeled using independent tools. The operation of Traffic Management and Control Systems are simulated using higher and lower-fidelity approaches within traffic simulations (either microscopic or mesoscopic). There are APIs to emulate traffic signal control applications, and “hardware in the loop” approaches to directly represent specific signal controllers. There are two broad approaches to modeling Traffic Management and Control Systems and the control information that are available from these systems.

Higher-Fidelity Models: In this approach, precise locations of the Traffic Management and Control Systems are modeled. The type of information (signal controls, advisory messages, lane use information, etc.), visibility of the information (e.g., visible only 500 ft upstream of the system), quality, and latency of information available from each equipment are represented accurately. The type of information should be dependent on the capability of the Traffic Management and Control System equipment. For example, if a dynamic message board is only capable of informing drivers of congestion and advising them to take alternate routes, then this approach will not model travel times on alternate routes as being available when determining the best alternate route; instead historical travel times (if experienced traveler) or travel times at posted speed limits will be used.

Lower-Fidelity Models: In this approach, the type of information available from Traffic Management and Control Systems is modeled. Quality and latency of information may be modeled; alternately, perfect information with zero latency might be modeled. Visibility of the information and location of the systems are approximated. Continuing with our earlier example, in this approach all drivers are assumed to be aware of congestion, and are not constrained by the visibility of the information on the Traffic Management and Control System equipment. Variants of this approach might even assume perfect knowledge of travel times on alternate routes when estimating the best alternate route.

3.2.5 Modeling Broadcast Media

Broadcast information include pre-trip and en route forms of communication reaching system users over a wide area or geographic region, as opposed to localized forms of information provision associated with Traffic Management and Control Systems. Examples include traffic reports delivered through commercial radio, Highway Advisory Radio (HAR) and television media as well as broadcast forms of information provided over the Internet, including color-coded congestion maps and other advisories accessed with or without utilization of a wide-area wireless network.

Existing tools do not explicitly model broadcast media. Provision of traveler information through broadcast media is usually approximated using higher and lower-fidelity approaches within traffic simulations (either microscopic or mesoscopic), assuming availability of unconstrained communications bandwidth. Modeling information content, accuracy, nature, location, precision, and scope are all dimensions of high and low-fidelity approaches.

Higher-Fidelity Models: Each form of broadcast media may be modeled explicitly to represent the content, precision, accuracy, geographic coverage, and latency of information available. This approach will explicitly model when a system user receives the information - i.e., pre-trip or en route.

For example, commercial radio may provide precise and accurate travel times on a few routes and advisories (e.g., long queues on the ramp to the Eastbound Beltway) on other routes but with high latency (i.e., time lag between estimating and reporting is long). Television media may also provide similar content with similar precision, accuracy, coverage, and latency as the commercial radio, however the information is unavailable while en route. For a realistic representation of traveler information available through commercial radio, HAR, and television, it is essential to provide advisories and travel times to only a subset of System Users, and on a few major routes or facilities (even if the System User's route does not comprise these facilities) at specific times of the day. Color-coded congestion maps on the internet may provide more detailed information on the speeds and possible reasons (e.g., work zones, vehicle fire, disabled vehicle) on more facilities than what is covered on the radio or television. Latency should be accurately represented by introducing a time lag between the time the simulation model shows for example, queuing and the time the information is available to System Users, via any form of broadcast media. The internet may provide traveler information with lower latency than the television or the radio – accordingly the time lag chosen should be different. Accuracy of information may be realistically represented for specific broadcast media, if the information is available, or approximated. These approaches differentiate between the capability of the media, and affords a more realistic representation of what messages might be available, when, where and to whom, which will influence the pre-trip (strategic) and en route (tactical) decisions made by system users, and is appropriate when the focus is on capturing system users' choices and behaviors**.**

Lower-Fidelity Models: In this approach, the broadcast media is not modeled; instead only the content is approximated. For example, instead of explicitly modeling congestion maps along with its inherent lack of precision and accuracy, it is assumed that travel times are known for a few major routes and at certain times of the day. Accuracy is approximated rather than modeled as a factor of the media type. Variants of this approach might differentiate between the type of traveler information available via the broadcast media (e.g., advisory messages versus precise travel times) and the error rates applied.

Ideal Broadcast Media Emulation: In this approach, assumptions are made about the media capability that are not realistic; this approach is at best an emulation of an ideal system that is non-existent today, cost-prohibitive, and unnecessary. No distinction is made between the types of broadcast media and the content, to whom information is available, where, and when. For example, a commercial radio might be modeled by providing current, highly precise travel time estimates for every link in the modeled network to all system users.

3.3 Wireless Communications Network Simulator

The AMS Testbed should be capable of modeling a range of communications media, DSRC roadside device network and wide-area wireless network. The DSRC network may receive or transmit messages broadcast over the designated DSRC communications frequency (5.9 GHz). Mobile Devices and Connected Vehicles may broadcast messages via DSRC that can be received by the DSRC Roadside Network when the devices and vehicles are within communication range. The DSRC Roadside Network may receive and transmit messages from System Managers or the Traffic Management and Control System to broadcast to devices and vehicles within range.

Wide-Area Wireless Networks include forms of wide-area communication that cover a complete geographic region, as opposed to localized forms of communications like those using the DSRC Roadside Network. Wide area messaging are not broadcast messages, but point-to-point data or voice transmissions between two entities within the system. A user utilizing a cell phone to access a 511 service to obtain a personalized traffic report is an example of utilization of a wide-area wireless voice network, as is the utilization of an application on the cell phone to obtain a data message from the 511 service provider with similar personalized content.

A broad range of commercial and open source communications simulation software are available to model communications systems in detail. Recent efforts have linked traffic simulation tools with wireless communications network simulator tools to emulate vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications. Some efforts have also developed analytical tools that focus on unconstrained message generation (i.e., propagation is unhindered by bandwidth capacity). There are three broad approaches for modeling DSRC-roadside device network and wide area wireless network.

Unconstrained and Partially-Constrained Aggregate Communications Models: This is a high-level approach to modeling communications when the desire is to estimate communications load at an aggregate-level without explicitly modeling message transmission protocols, latency, communication interference, or communication network congestion. This approach also overlooks the number of messages received, the latency between message transmission and receipt, and the transmission range of communication devices. Total messages transmitted are estimated through rough approximation by multiplying the total vehicle miles traveled by a pre-determined average number of messages transmitted per mile. Average number of messages transmitted per mile may be computed as a factor of the facility type and facility volume. For example, average probe data messages generated per mile might be lower on a freeway facility compared to an arterial due to fewer stops and starts. If the facility volume is high, the number of messages being transmitted will be high as well, which might result in dropped messages or messages not being received. However, in this approach loss or error in messages are either not modeled (i.e., all messages are assumed to be received without any error or loss) or approximated. For example, the desired bandwidth usage may be computed as a factor of the facility volume and facility type, either near a specific location for short-range (DSRC) communications or within a specified geographic cordon for wide-area communications technologies. If the estimated usage exceeds communications system capacity then messages are dropped (randomly or according to pre-set priorities). Such an approach is an approximation of how communications might impact the data that are available from vehicles and travelers. The advantage of such an approach is that detailed communications simulations need not be created and integrated with transportation simulations, however, such an approach only provides an estimate of communications system load and a broad approximation of communication system performance.

Partially-Constrained Disaggregate Communications Models: This approach explicitly models message transmission protocols, and transmission range of communication devices without explicitly modeling interference or communication network congestion. Transmission protocols may be modeled to comply with the SAE J2735 standard. Alternately, simplistic transmission protocols might be modeled. For example, devices might transmit messages continuously when in range of an RSE or messages might be transmitted with persistent vehicle identifiers. Transmission range of communication devices might vary depending on the type, power, and state of motion of the device. These may be modeled explicitly. Communications latency is not explicitly modeled; instead it is approximated. For example, latency might be represented as a factor of the facility volume, facility type, and/or number and location of roadside equipment capable of receiving messages. Loss or error in messages are approximated by applying average failure rates, which may vary by the type of communication media, number of messages generated on a facility, etc. The limitation with this approach is that while message transmission by device type is represented accurately, the fidelity of communications is reduced due to the approximation of latency and interference. The advantage with this approach is that detailed interfaces with simulation tools do not have to be built, while still being capable of distinguishing messages by device type (which is lacking in the aggregate communications modeling approach).

Communications Network Simulators and Analytical Models: These approaches are the most comprehensive, with the capability to explicitly representing network communications in detail, including propagation and interference. There are two distinct approaches - network simulators that make use of discrete event simulation and analytical models that make use of queuing theory. These may be interfaced with traffic simulation tools to represent message transmission and propagation, interference, and network congestion, along with the corresponding latency and loss accurately.

3.4 Operational Data Environment Simulator

3.4.1 Modeling Operational Data Environments

Operational data environments aggregate and enhance data passed from Traffic and Weather Detection Systems and Wireless Communications Network Simulator to support the System Manager's decision-making. Data quality control is performed on the received data. Note that the process of conducting this aggregation and quality check introduces some latency into the data-to-information chain, and the level of quality checking may be more or less rigorous. The rigor with which data quality control is performed is a key question that should be examined by the analyst. What levels of error are acceptable to achieve the desired targets of performance? How rapidly is data cleaning performed to achieve the desired performance targets?

Operational data environments include current and archived data needed as input to the DMA and ATDM applications as well as current and historical estimates of performance measures (e.g., passenger throughput, travel times). Note that these estimates of system state and performance are not ground truth reflections of system performance, they reflect data accumulated system-wide with concomitant imperfections. These data imperfections may be the result of poor accuracy, long latency, or simply the lack of any reliable reporting mechanism for specific geographic elements of the transportation system. These processed data are sent to the System Manager Simulator and the Predictive Environment Simulator. For example, the simulator might combine basic safety messages received from the Wireless Communications Network Simulator, and detector speeds from the Traffic and Weather Detection System to estimate queue location and length, which are then sent to the System Manager Simulator and the Predictive Environment Simulator. Operational data environments also include estimates of performance measures to aid the System Manager in the decision making process.

Operational Data Environments comprise a mix of data with different sources, reliability and latency. There are two approaches to representing operational data environments. These may vary by System Manager (e.g., to emulate differences in policies adopted by different jurisdictions or even by System Manager type).

Although complex methods have been developed to integrate and error check data in current data management systems, there are no stand-alone models that abstract and model these methods. Transportation system analysts have typically relied upon the default assumptions embedded within software packages regarding the calculation of system performance measures. These are related to the way vehicle and traveler movement are internally represented and calculated. For example, a mesoscopic simulation may track the release of vehicles from one link to another at the downstream (end) node of each link. Little work has been done on the explicit representation of data integration from multiple sources (e.g., combining different types of data to compute a link travel time), as well as other factors such as modeling time-to-compute related to accuracy. That said, if such approaches were to be differentiated, it is possible that these could be represented either as off-line or API linkages to the transportation network simulator. The key difficulty in modeling these systems in detail is the introduction of error and other realistic factors into the simulated data stream. The simulation generates internal ground truth representations of system performance, and the skillful analyst must alter these representations to reflect realistically imperfect information flow through more or less capable operational data environments.

Realistic Operational Data Environment Emulation: This approach aggregates the data from the Transportation Network Simulator, Travel Demand Simulator, and Wireless Communications Network Simulator, into data needed by System Managers and Predicted Environment Simulator. Errors observed in real systems (from literature) are applied to the data elements. The time needed to clean and process the data are introduced as latency to the data elements. For example if queuing is detected at 8 AM in the Transportation Network Simulator, but if queue detection typically takes 20 minutes using data from the field, then the Operational Data Environment will log the occurrence of a queue only at 8:20 AM.

Ideal Operational Data Environment Emulation: This approach assumes that the data available are of perfect quality. No errors are applied. However, the time needed to process and aggregate the data are applied as latency.

3.4.2 Modeling Private Sector Data Services

Approaches for modeling private sector data services are similar to those for modeling operational data environments. The level of aggregation and quality control may be different.

3.5 Predictive Environment Simulator

Predictive Environment Simulator simulates the prediction of transportation network performance to assist the System Manager in the decision-making process. Current and historical data from the operational data environment flow into the predicted data environment. These data are used as input to simulate various applications and predict estimates of performance measures for a set of alternative responses (combination of applications and the control settings). The information is sent to the System Manager Simulator for decision-making. The process of predicting performance for a varied set of responses introduces latency, and possibly errors due to limitations in the prediction tool or approach.

There are multiple forms of prediction that may be modeled. The level and frequency of prediction required is a key question that needs to be examined by the analyst. Do we need advanced prediction capabilities to augment the deployment of every DMA and ATDM application? Where and when is it more beneficial? How often should prediction occur and over what time horizon? When no prediction is utilized, data describing current conditions, which reside in the Operational Data Environment, are assumed to persist indefinitely, and decision-making under such an assumption is considered *reactive*. Note that even if data are only collected once a year, if new control plans are put in place based on these data, this is still reactive management. The intent of the AMS Testbed effort is not to build a reliable and accurate prediction system; rather it is to represent predictive capabilities (in the absence of a real prediction tool) and determine the value of different forms of prediction (less accurate to highly accurate) to the overall system performance. A particular predictive method may be assessed, however, using the Testbed.

The representation of predictive systems in a modeling construct has traditionally taken the form of an off-line or real-time module working in conjunction with a traffic simulation tool. The simulation tool itself is often utilized for system prediction. For the purposes of this framework, a similar approach can be considered. A key observation is that within a simulated construct like the AMS Testbed, the simulated system itself represents a definitive ground truth for system performance. To represent one or more predictive systems, the analyst may choose to alter this ground truth data parametrically to reflect deficiencies in abstract predictive methods. Alternatively, predictive methods may be emulated within the construct. The former (abstract parametric representation) is less complex than the latter (predictive method emulation). Both approaches are valid and useful technical approaches serving to answer different questions. The abstract representation helps to answer questions like: what is the value of more or less accurate, comprehensive, and precise predictive methods that we might seek but have not yet developed? Detailed emulation illustrates how accurate, comprehensive, and precise a specific predictive method might be.

Abstract Parametric Representation: This approach is a representation of how prediction will impact the overall system performance. The AMS Testbed is run over a specific time horizon (the prediction time horizon) under specific control strategy (or combination of strategies). Performance measures are estimated for the entire time horizon. These measures represent the “ground truth.” Errors are introduced arbitrarily to the performance measures so that they are less accurate, precise, or comprehensive. For example, if travel times are assumed to be predicted for one freeway and two arterial corridors in a regional network, then errors are introduced to the “ground truth” travel times for these three corridors. The predicted travel times are sent to the System Manager Simulator along with historical travel times for the rest of the network. The process is repeated for the collection of strategies enabling the System Manager Simulator to select the optimal strategy or strategies. Note that the AMS Testbed is instantiated within the Predictive Environment Simulator and uses data from the Transportation Network Simulator and/or the Travel Demand Simulator (i.e., data without errors introduced by the analyst) and not the data from the Operational Data Environment Simulator. The goal with this approach is to examine the value of prediction on system performance - what ranges of prediction errors are acceptable, and how comprehensive the prediction should be for specific system performance. The approach does not determine what predictive techniques are reliable.

Historical or Retrospective Predictive Environment Emulation: This is an example of a detailed prediction emulation approach. This approach makes use of current and archived data from the operational data environment to predict traffic evolution over a rolling time horizon. Statistical methods from the literature are used to predict performance measures based on current and archived data. Note this approach does not make use of the AMS Testbed as a predictor. The predicted performance measures are sent to the System Manager Simulator, where the optimal strategy or strategies are selected. The time taken for the prediction is introduced as latency in the predictive data that are available to the System Manager.

AMS-Augmented Predictive Environment Emulation: This is another example of detailed prediction emulation method. This approach makes use of current and archived data from the operational data environment, and an instantiation of the AMS Testbed to predict traffic flow over a rolling time horizon for a specific strategy or combinations of strategies. The AMS Testbed is instantiated within the Predictive Environment Simulator, as was done in the Abstract Parametric Representation approach, but uses data from the Operational Data Environment Simulator, with its inherent inaccuracies rather than the data from Transportation Network Simulator or the Travel Demand Simulator. The goal with this approach is to emulate a realistic predictive environment where the analyst has to make predictions using a simulation testbed given the data that he or she has. The time taken for running the instantiation of the AMS Testbed and making predictions are introduced as latency in the predictive data that are sent to the System Manager Simulator.

3.6 System Manager Simulator

3.6.1 Modeling System Managers

System Managers control a particular aspect of the system and are responsible for ensuring the safe and efficient operation of their element of the transportation system. Note that while System Managers are humans, some aspects of system management may be automated and do not require human intervention or decision-making on a regular basis. A System Manager, without any technological assistance, has a limited view of system performance or the actions of the System Users. System Managers are dependent on the nature, accuracy and reliability of Operational Data Environments and Predictive Environments created to provide insight into the state of the system and the effectiveness of potential changes to controls at their direction. Likewise, the nature of controls possible in a surface transportation system are also limited to a set of authorized alterations in traffic control systems, information provided through broadcast media, and the adjustment of policies related to the price and nature of access to elements of the transportation system. Note that some elements of this control are intended to influence short-term behavior of System Users currently on the transportation system, depending on the nature of current conditions, such as the modification of target speeds on selected roadway sections. Other elements of control are intended to influence longer-term behavior of System Users, including High-Occupancy Vehicle (HOV) facility access or the cost of utilizing the facility (in the case of tolled facility).

There are three approaches for modeling system managers.

Decision-Makers as Automaton Models: This approach models automated Decision Support Systems (DSS) without human intervention (state of the practice). Data used for the DSS may come from the Predictive Environment Simulator or the Operational Data Environment Simulator (depending on the sophistication of the DSS being emulated). The DSS assesses the impacts of various strategy implementations, and recommends an optimal strategy. A variant of the approach is to introduce error and latency in the decisions generated by the DSS. This is the most typical default model used in nearly all transportation system analyses – a specific rule set of control policies are utilized under specific conditions, much like the implementation of an expert system or rule-book. For example, if an incident occurs at a specific location, a specific control policy is initiated to alter ramp metering rates. Such an approach is useful in assessing systems where there is little manager flexibility in control decisions, but over-simplifies system manager decision making where there is greater flexibility in response.

Discrete Choice Models in the Absence of DSS: System managers' decisions in the absence of decision support systems have never been represented in AMS studies. One approach might be to make use of discrete choice models to represent the decisions made by each system manager. The system manager may make use of data from the Predictive Environment Simulator or the Operational Data Environment Simulator. Decisions may be dependent on the type and precision of the data (e.g., passenger throughput or travel time reliability estimates versus color coded congestion maps), information dissemination mechanism (e.g., graphical displays vs. audio vs. tables and statistics), and prior experience on the accuracy of the information. A variant of this approach might examine decisions made by multiple system managers jointly, who may or may not be co-located. There is high technical risk with this approach since there is little data and research to date.

Discrete Choice Models in the Presence of DSS: In this approach, discrete choice models are used to represent the decisions made by the system manager in response to the recommendations of the DSS. Decisions may be dependent on the type and precision of the data, information dissemination mechanism, and prior experience on the accuracy and reliability of recommendations of the DSS. A variant of this approach might examine decisions made by multiple system managers jointly, who may follow a rule-book developed jointly in advance. The technical risk with this approach is relatively lower than the one where no DSS is present, and decisions are made entirely by the system manager, but higher than the one that makes use of automated systems.

3.6.2 Modeling ATDM Strategies and DMA Applications

DMA and ATDM strategies and application may provide new forms of system control for System Managers. Twenty two ATDM Strategies are defined in the ATDM Concept of Operations in three categories: Active Demand Management Strategies, Active Traffic Demand Management Strategies, and Active Parking Management Strategies. DMA applications are defined in seven bundles: Enabling Advanced Traveler Information (EnableATIS),Freight Traveler Information Systems (FRATIS), Next Generation Integrated Corridor Management (ICM), Intelligent Dynamic Transit Operations (IDTO), Intelligent Network Flow Optimization (INFLO), Multi-Modal Intelligent Signal Systems (MMITSS), and Response, Emergency Staging and Communications, Uniform Management, and Evacuation (R.E.S.C.U.M.E). Concepts of Operation and System Requirements have been developed for five of the seven DMA bundles with the exception of EnableATIS and Next-Generation ICM. The five bundles are either in the process or will soon be developing prototype applications. Once developed they will be made available for the AMS Testbed development effort. ATDM Strategies and DMA Applications have been developed separately in the two programs, and there are some overlaps and differences between the defined set of applications.

The Predictive Environment Simulator represents the predicted impacts of the applications. The System Manager Simulator selects the applications or strategies and the control settings. Control and advisory information resulting from these applications and strategies are sent by the System Manager to travelers (pre-trip and/or en route) either directly to connected vehicles and devices through the Wireless Communications Network Simulator and/or via Broadcast media and Traffic Management and Control Systems. Error and latency are built into the information sent.

The applications do not reside in any one module or box; instead they are represented throughout the system.

An Example Implementation of Queue Warning Application

Let's examine a queue warning application, which is an ATDM strategy in the absence of connected vehicles and devices as well as a DMA application in the presence of connected vehicles and devices. To understand the differences in alternatives where there is no queue warning application versus one there is queue warning, we should be able to model at an aggregate level system users' strategic decisions, including mode. These decisions are sent to the Transportation Network Simulator which might include a mesoscopic model of a sub-regional network and microscopic model of a freeway corridor with parallel, adjacent arterials, which frequently experience bottlenecks and queuing. The microscopic model is able to represent congestion and queuing accurately, and the mesoscopic model is able to represent the overall impacts of congestion. The Traffic and Weather Detection Systems detect slow speeds which are then sent to Operational Data Environment Simulator, which cleans and processes the data and detects presence and location of a queue. The current and archived data and queue estimates are sent to the Predictive Environment Simulator, which predicts that in the absence of a queue warning application, more queues will be formed, and the system will reach capacity. In the presence of a queue warning application, queue warning messages can be sent to drivers pre-trip as well en route allowing them the capability to re-route causing queue dissipation. The System Manager Simulator makes use of a DSS that determines that queue warning application needs to be implemented and corresponding messages are sent via Broadcast Media and Traffic Management and Control Systems to drivers en route. Messages are also sent pre-trip to travelers. For the scenario where there are connected vehicles and devices, messages are also communicated from the System Manager through the Wireless Communications Network Simulator to the vehicles (en route only) and devices (en route as well pre-trip). Drivers are able to select appropriate lane or route to avoid the queue. Travelers are able to make decisions on delaying their trip or taking an alternate route or mode. Thus, the queue warning application is represented in all modules, as raw data, processed queue measures, predicted queue information, queue warning messages, or traveler's and driver's trip-making decisions. To accurately capture the impacts of queue warning application, it is thus essential to represent tactical decisions with high fidelity. Strategic decisions may or may not be represented in detail. A Wireless Communications Network Simulator may make use of aggregate modeling if there are no connected vehicles and devices, or may make use of partially constrained disaggregate modeling. Prediction plays a key role to not only detect existing queues but also predict impending queues. The flow of information from the System Manager Simulator to travelers is essential for yielding the benefits of a queue warning application.

To examine the impacts of applications, it is essential to examine the modules and the flow of information that are necessary for the functioning of the application. This exercise may be repeated for each application.

3.7 Connections and Flow of Information

3.7.1 Interfaces To Travel Demand Simulator

To examine the system-wide impacts of DMA and ATDM applications and strategies, it is necessary to examine how a systems user's pre-trip travel choices (destination, mode, departure time or desired arrival time, route) vary within a day, day to day, and in the long term. These strategic decisions are dependent on the system user's and the household's characteristics, vehicle and network characteristics, safety and security, variations in network flow, deployed applications (e.g., Dynamic Congestion Pricing), adverse weather, and pre-trip traveler information. The Travel Demand Simulator receives data and information from the Transportation Network Simulator (including Broadcast Media) and the Wireless Communications Network Simulator (if connected devices are being represented). The System Manager Simulator does not directly interact with the Travel Demand Simulator – information flows from the System Manager Simulator to users through Broadcast Media or Wireless Communications Network.

Transportation Network Simulator: When developing the AMS Testbed, individual trip plans or time-dependent trip tables by mode and purpose, and travel times are iteratively exchanged between the Travel Demand Simulator and the Transportation Network Simulator until convergence is achieved. Convergence criteria is established based on the complexity of the testbed. An example process by which the two are interfaced are discussed at length in the ICM AMS Methodology [5].

The frequency with which subsequent feedback loops are executed is dependent on the state of the system (e.g., new application introduced by System Manager, adverse weather), pre-trip traveler information received from the System Manager through Broadcast Media or through connected devices (via Wireless Communications Network Simulator), and the type of model chosen to represent users' strategic decisions. Pre-trip information that influences individual choices within day are much better represented in a disaggregate model than in an aggregate model, which primarily captures longer-term behavioral patterns.

Broadcast Media: Control/advisory information (e.g., travelers advised to take alternate routes due to major accident on a freeway) sent to the broadcast media from the System Manager Simulator, are disseminated upon receipt. The information is accessible to travelers pre-trip (via television, radio, internet) as well as en route (via radio, HAR). Pre-trip information may impact travelers' within day travel choices, which might impact day to day choices, and subsequently overall behavioral patterns. Pre-trip information may be used to revise individual trip plans (for a disaggregate approach) or trip tables (for an aggregate approach). The frequency with which the trip plans or trip tables are revised should depend on whether the information is likely to cause system-wide re-distribution of flow, changes in mode, and trip departure times.

Wireless Communications Network Simulator: Control/advisory information (e.g., dynamic parking information) are sent from the System Manager Simulator to travelers who have opted in to receive information via connected devices. The information is first sent to the Wireless Communications Network to represent message transmission, propagation, and interference, and then to the connected devices. The information is accessible by travelers pre-trip as well as en route. Messages received pre-trip impact travelers' strategic choices in the near-term as well as in the long term. As mentioned previously, trip tables or individual trip plans may be revised if the information is likely to cause changes in mode, trip departure time, route, or destination.

3.7.2 Interfaces To Transportation Network Simulator

The Transportation Network Simulator receives data and information from the Travel Demand Simulator (discussed above), Wireless Communications Network Simulator (if connected vehicles and devices are in the mix), and System Manager Simulator. Within the Transportation Network Simulator, there is flow of information from Traffic Management and Control Systems, Broadcast Media, and Connected Vehicles and Devices that affect System User's Tactical Decisions.

Broadcast Media: Control/advisory information sent from the System Manager Simulator are available to drivers and travelers en route (via radio, HAR). En route information may impact drivers' tactical decisions (e.g., take an alternate route), which are represented within the model chosen for the Transportation Network Simulator (i.e., microscopic or mesoscopic).

Traffic Management and Control Systems: Control/advisory information are available to drivers via variable message signs, static signs, traffic signal controllers or ramp meters. Tactical decisions made by drivers in response to these messages (e.g., lane closed, work zone ahead, lane-specific target speed, queue ahead, congestion pricing), are represented within the modeling approach chosen for the simulator.

Connected Vehicles and Devices: Control/advisory information are available via connected vehicles and devices which the driver or traveler can access with no distraction. These are the recommendations or control settings from the DMA applications, which are sent by the System Manager Simulator. Examples of such messages include warning drivers to look out for emergency personnel or pedestrians on a crosswalk, advising drivers of target speeds, informing drivers of potential ride match, etc. These messages impact tactical decisions, which need to represented within the model.

Wireless Communications Network Simulator: Exchange of information with the Wireless Communications Network Simulator occurs only if there are connected vehicles and devices in the mix. There is flow of information from the DSRC and cellular networks to connected vehicles and devices. Control and advisory information sent from the System Manager Simulator are sent via cellular network to connected devices that have opted in to receive the information. Note, all connected devices and vehicles do not automatically get the information. Control and advisory information are also broadcast by DSRC-based RSE to connected vehicles when in range. DSRC-based transmission allows all DSRC-enabled connected vehicles and devices to receive the information; however, the limitation is that they have to be within range (which in some cases might be too late for a traveler to modify the trip, mode, route, or lane). Cellular-based transmission has a longer transmission range and is not geographically constrained, allowing travelers to alter their strategic or tactical behaviors; however, not all travelers are capable of receiving the information which may result in limited system-wide impacts.

In addition to control and advisory information, SPaT Messages are also sent via the DSRC network to connected vehicles and devices from DSRC-based Signal Controllers. This allows drivers to make tactical choices, such as accelerate, decelerate, or come to a stop. BSM Part 1 that are broadcast using V2V communications are also sent via the DSRC network.

System Manager Simulator: After the System Manager Simulator selects the application or applications, and the corresponding control settings, relevant recommendations are sent to Broadcast Media, in a format that is acceptable by the media type (e.g., incident ahead advisory message), to Traffic Controls Systems (as messages for display on variable message signs, as control setting for the ramp meter or the signal controller, etc.), and to Connected Vehicles and Devices via the cellular network. Note, message are also sent via the DSRC network; however, these are re-routed through the Traffic Management and Control Systems. The frequency with which the recommendations are sent is dependent on the capability of the system and service being modeled, and the information that is being disseminated. For example, travel time information via broadcast radio might only be made available to vehicles every 10 minutes.

3.7.3 Interfaces To Wireless Communications Network Simulator

The Wireless Communications Network Simulator receives data and information from the Transportation Network Simulator and System Manager Simulator.

Connected Vehicles and Devices: Connected vehicles and devices send BSM and/or BMM messages to the DSRC or the cellular network, depending on the device capability and the transmission protocol (e.g., when in range of an RSE). BSM are sent only to the DSRC network, while BMM may be sent to a DSRC or a cellular network depending on the capability of the device (i.e., whether it is a DSRC-enabled device, cellular device, or a dual-mode device capable of transmitting via both DSRC and cellular). The Wireless Communications Network Simulator emulates the message propagation process (using any of the three suggested approaches documented in the Wireless Communications Network Simulator section). The messages, and the corresponding latencies and errors are sent to the Operational Data Environment Simulator. The frequency with which the information sent is different for different vehicles and devices, and is a factor of the device type. For example, an integrated vehicle that is capable of generating BSM Part 1 every 10^{th} of second will need to send the temporary identifier, position, speed, acceleration, yaw rate, heading, vehicle length/width, vehicle subsystem status, and time stamp every 10^{th} of a second. On the other hand a vehicle with a carry-in device might be capable of sending BMM only every 1 minute – in that case, the flow of information from the vehicle will only be every minute.

Traffic Management and Control Systems: DSRC-based signal controllers send SPaT messages to connected vehicles via the DSRC network. Control and advisory information sent by the System Manager are sent via DSRC network using V2I communications to connected vehicles and devices when in range. The frequency with which messages are sent is dependent on what information is being disseminated, and the transmission protocol.

System Manager Simulator: Once a strategy is selected, the System Manager Simulator sends relevant recommendations to the cellular network for dissemination via connected devices to travelers who have signed up to receive the information. The frequency with which the recommendations are sent is dependent on the service being modeled, and the information that is being disseminated. For example, travelers who have signed up for transit information might get en route information only if they are carrying a device and if there is a change in the transit trip itinerary.

3.7.4 Interfaces To Operational Data Environment Simulator

The Operational Data Environment Simulator receives data and information from the Transportation Network Simulator and the Wireless Communications Network Simulator.

Traffic and Weather Detection Systems: Whenever a vehicle, pedestrian, or bicyclist is detected by the Traffic and Weather Detection Systems modeled in the AMS Testbed, the data are sent to the Operational Data Environment Simulator. The data may be processed and aggregated to some extent. The Operational Data Environment Simulator further combines data from multiple sources (i.e., Traffic Detections Systems and Wireless Communications Network Simulator) and cleans, processes, and aggregates them.

Wireless Communications Network Simulator: BSM and BMM are sent by the DSRC network or the cellular network to the Operational Data Environment Simulator, where it is processed and aggregated to estimate performance measures.

3.7.5 Interfaces To Predictive Environment Simulator

The Predictive Environment Simulator receives data and information from the Operational Data Environment Simulator. Note that the Predictive Environment Simulator does not obtain data directly from either the Transportation Network Simulator or the Travel Demand Simulator. The nature of the data passed to it must reflect the capture, transmission, and aggregation of the data collected by the broad alternatives being assessed within the AMS Testbed. Only the Simulated Ground Truth Performance Module (see next section) is allowed to directly access the Network and Travel Demand Simulator to generate performance measures, representing the comprehensive, omniscient view used in the comparison of the alternative systems evaluated using the AMS Testbed.

Operational Data Environment Simulator: Current and historical data are sent from the Operational Data Environment Simulator to the Predictive Environment at a frequency dictated by the prediction method. Data are cleaned and processed into a format that is required by the prediction method. This interface need not be invoked if trying to emulate an agency that doesn’t make use of prediction.

3.7.6 Interfaces To System Manager Simulator

The System Manager Simulator receives data and information from the Operational Data Environment Simulator and the Predictive Environment Simulator. The System Manager Simulator transforms the information into a format that helps the system manager’s decision-making process.

Operational Data Environment Simulator: Cleaned and processed current and historical data, and performance measures are sent to the System Manager Simulator. The frequency with which the flow of information occurs is dependent on the processing time for cleaning, aggregating, and measure estimation, as well as the System Manager's capability (which is dictated by the requirements of the DSS, rule-book, or policy).

Predictive Environment Simulator: Predicted performance by application is sent to the System Manager Simulator. The System Manager Simulator transforms the information into a format that helps the system manager's decision-making process. The frequency with which the flow of information occurs is dependent on the prediction method's capability (how quickly can prediction occur), and the System Manager's capability.
In the next section, essential AMS activities that need to be performed irrespective of the framework or the technical approach are presented. In the following section, four sample AMS approaches that follow the AMS framework are discussed.

4 Supporting AMS Activities

When developing an AMS Testbed, there are essential activities that need to be performed irrespective of the framework or the technical approach chosen for the AMS Testbed. This section discusses these key activities (presented graphically in(Figure 4-1): operational conditions identification; calibration; and ground truth performance calculation.

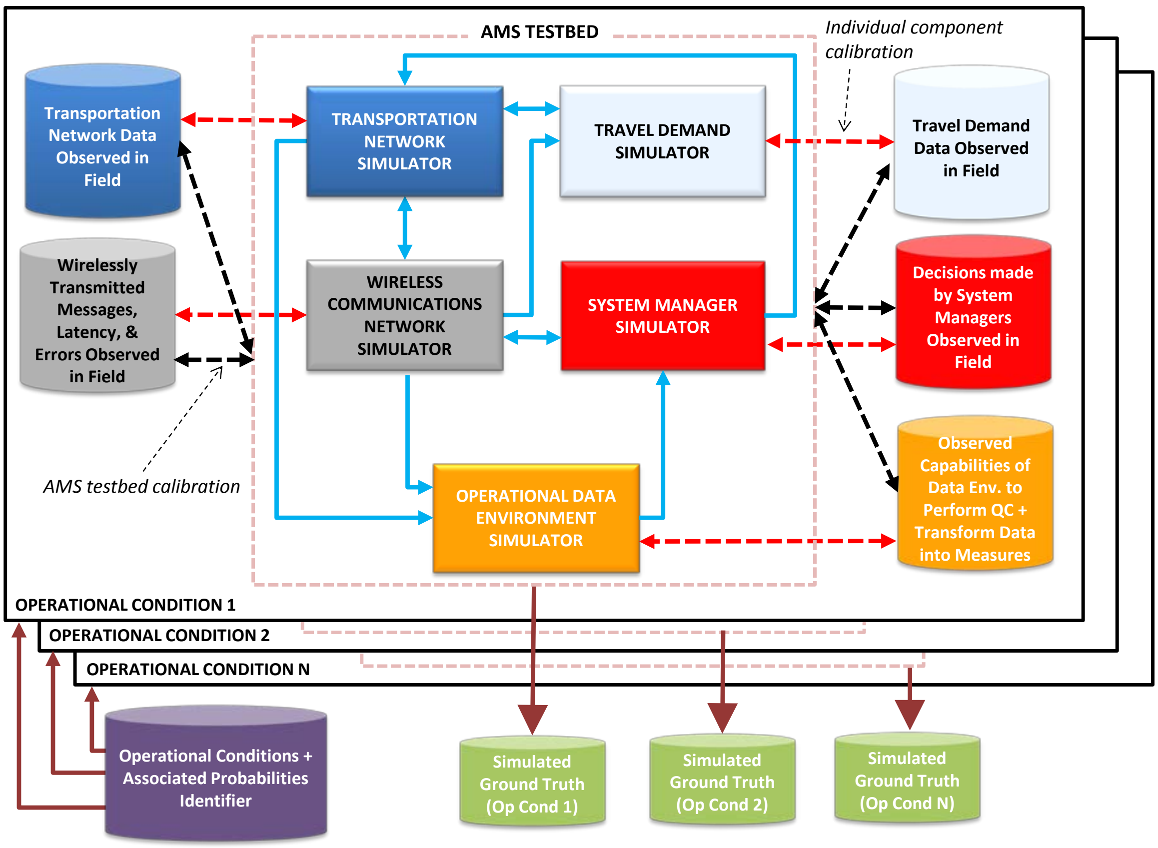

Figure 4-1: Essential AMS Activities: Operational Conditions Identification, Calibration, and Ground Truth Calculation

4.1 Operational Conditions Identification

Operational conditions describe the travel conditions, and the corresponding frequency and intensity, experienced by a traveler in the region over the course of a year. Operational conditions may be identified by a combination of specific traffic demand levels (e.g., low, medium or high demand), incident (e.g., no impact, medium impact, high impact), and weather (e.g., clear, rain, snow, ice, fog) conditions. Operational conditions should be identified based on the data or the observed travel conditions, rather than exogenously (i.e., without looking at the field data) as conditions of interest to the analyst. Each operational condition has a probability of occurrence. Once operational conditions and their probabilities are identified, an analyst may need to prioritize the ones that may be examined in detail due to schedule or resource constraints. Prioritization might be based on probability of occurrence (e.g., higher the probability of occurrence, higher the priority for detailed examination), the operational conditions that potentially might have significant benefits if a DMA application or an ATDM strategy is implemented (For example, a medium demand day with clear weather with a probability of occurrence of 30% might be ranked lower than a medium demand day with an incident with a probability of occurrence of 10% if the second set of days will have significant benefits with combined ATDM strategies of queue warning and predictive traveler information.), or the operational conditions that are of significant concern to stakeholders in the region (For example, implementation of weather-based speed harmonization on a rural road would necessitate detailed examination of operational conditions that include adverse weather.). Thus operational conditions may be prioritized and lower priority ones may be weeded out from further analyses.

As mentioned previously, the ICM Program and the SHRP 2 L08 effort have developed approaches for identifying operational conditions and their associated probabilities of occurrence. Similar approaches may be used when developing the AMS Testbed.

Specific operational conditions that will be modeled and examined in detail should be discussed in a testbed-specific analysis plan prior to developing the testbed. Days (and corresponding travel demand, traffic demand, weather, and incident conditions) that represent the operational conditions are also identified during this step for use in calibration (please see below). Note these days are not the median or average for each cluster representing the operational condition but are the actual days that are closest to the medians or averages.

4.2 Calibration

Calibration is defined as a process whereby the analyst adjusts the model parameters that cause the model to best reproduce field-observed local traveler behavior and traffic operations conditions. The analyst performs visual and statistical verification of the model outputs vis à vis the field-observed conditions to determine if the model has been calibrated.

Calibration is typically done using data for a single "average" day. There are inherent inaccuracies with this abstraction of a single day, since it does not represent an actual day. Even if the day that is closest to the "average" day were to be used, behaviors observed during an "average" day are not representative of behaviors on an adverse weather day (e.g., rainy day or day with dense fog or wet pavement) or a day with a major accident. If resources and schedule permit, the analyst should calibrate to a set of days that represent each operational condition that is being examined in detail. At a minimum, the calibration process should include calibrating to a day that is closest to the average day and to a known incident day [5] and a known weather day (i.e., if weather is an operational condition of interest in the region).

Secondly, to calibrate the AMS Testbed, it is essential to calibrate individual components (represented as red dashed lines in (Figure 4-1) as well as the system as a whole (represented as black dashed lines). The extent of calibration required for each component is a factor of the type of modeling approach used in representing the component. For example, if the Wireless Communications Network Simulator makes use of a communications network simulator, then as part of the calibration process it is essential to examine if the messages transmitted by vehicles and devices by the Wireless Communications Network Simulator are nearly the same as the messages transmitted by vehicles and devices in the field. It is also critical to examine if the messages received and the communications latency and errors simulated are the same as what are observed in the field. If the Wireless Communications Network Simulator makes use of a partially-disaggregate communications modeling approach then during calibration, it is important to examine if the time and content of messages transmitted in the simulator match those observed in the field. However, messages received, and the corresponding latency and errors may not need to be calibrated since the simulator does not explicitly represent them. Thus the analyst will need to tailor the calibration according to the modeling approach.

4.2.1 Calibrating Individual Components

Travel Demand Simulator: There is significant literature on calibrating aggregate and disaggregate models, and are not discussed in this report. As noted previously, the extent of calibration will differ by the model choice, and the amount and type of data required for calibrating the models will also differ.

Transportation Network Simulator: There are FHWA and state DOT guidelines on calibration of simulation models, and hence a detailed calibration approach is not restated in this report. The key thing to note is that for an AMS Testbed that is in line with the DMA and ATDM Program visions it is necessary for the testbed to represent an actual system – i.e., the model should be able to replicate data flowing from existing, real-world detection systems. This is slightly different from what is typically done, where a subset of the real-world data on one or two days are used to calibrate the model using an offline approach – and validated against a related but independent data set. However, once the model is calibrated no additional verification is performed to determine if the calibrated model continues to represent operational conditions indicated by the data flowing from the detection systems (Note, the data may be received, and stored in a data management system which can be used for verification purposes.). For the AMS Testbed, it will be necessary to not only calibrate the model using an offline approach but also verify (statistically and/or visually) if simulated outputs match the field data in near real time.

Wireless Communications Network Simulator: Calibration will vary depending on the type of approach used in the simulator. For an approach that makes use of a communications network simulator, BSM, BMM, SPaT, and control/advisory messages transmitted from simulated vehicles, devices, and the infrastructure, and the time when transmitted should be compared with messages transmitted in the field. Other calibration measures include messages received (by vehicles, devices, and infrastructure), latency, and errors. This will need to be examined for specific communication technologies (e.g., DSRC, cellular, Wi-Fi). For example, if field data are available from a connected vehicle testbed that makes use of V2V communication via DSRC, then the simulator should emulate a DSRC network, and the corresponding latencies and errors associated with a DSRC network. It is also critical to examine if overloading the bandwidth causes the similar loss or dropped messages in the simulator as observed in the field. Data from the DMA bundle prototyping efforts, and the connected vehicle testbeds may be used to calibrate the simulator.

For an approach that makes use of unconstrained or partially constrained aggregate communications modeling, the level of calibration might be minimal. Number of messages transmitted and received in the field are compared with those calculated through approximation.

For an approach that makes use of partially constrained disaggregate communications modeling, as mentioned earlier in this section, the time and content of messages transmitted by simulated vehicles, devices, and infrastructure are compared with those observed in the field. Latency, errors, and received messages are not calibrated since these are not generated as outputs from the simulator.

Operational Data Environment Simulator: Operational data environments as described in sections 2 and 3 are typically not modeled. Errors and latencies with respect to data cleaning, processing, aggregation, and measures estimation are usually not factored into a simulation study. An approach to calibrating Operational Data Environment Simulator is to compare the capabilities of an existing data management or data environment system (in the region that the testbed is emulating) to clean, process, and transform data into measures of interest with what is being represented in the simulator. Observed data for calibration might include: processing time, quality of data, aggregation level, and performance measures estimated. The verification process might be a qualitative assessment. If the region does not have a sophisticated data management system that transforms data into performance measures, then “performance measures estimated” may be omitted from the calibration process. If measures such as processing time are not available (as is highly likely), then data might need to be collected locally for a short period of time on how rapidly data are processed.

System Manager Simulator: System manager decisions are typically not modeled, and consequently calibration is non-existent. An approach to calibrating the system manager simulator is to identify decisions made by system managers (either individual or a DSS) on days that represent key operational conditions, and compare them to those made by the simulator. Observed data for calibration might include: decisions made and time when decisions made after receipt of data or information (from a data management system).

4.2.2 Calibrating Entire System

Once each component is calibrated, it is critical to calibrate the entire system to determine if the AMS Testbed is able to replicate the observed conditions. The extent of calibration is dependent on the AMS Testbed’s capabilities (i.e., the technical approaches used to represent the various components), and the applications and strategies being evaluated.

4.3 Ground Truth Performance Calculation

System Performance Measures characterize the mobility, safety and environmental impacts of a particular system alternative that connect the various elements of the system together in a particular way [8]. The AMS Testbed should be capable of representing the “ground truth” in terms of system performance measures for calibrating the entire system as well as to compare various alternatives. The ground truth should be computed using the simulated outputs prior to introducing “errors” and “latencies,” and not the data that are available from the Operational Data Environment Simulator.

5 Sample AMS Testbed Technical Approaches and Constructs

There are multiple technical approaches to modeling the system presented in section 2 that is consistent with the AMS Testbed Framework, each with specific strengths and weaknesses in evaluating the portfolio of DMA and ATDM applications and strategies. The following are four such technical approaches that follow the AMS Testbed Framework detailed in section 3.

1. **Strategic Traveler Behavior Focus**: This technical approach aims to accurately represent traveler's trip making choices prior to trip start in response to travel experiences and traffic conditions at a metropolitan regional level. Vehicle-to-vehicle or vehicle-to-pedestrian interactions are modeled in less detail in order to make the approach computationally tractable. This technical approach is mostly suited for evaluating travel demand management applications that impact pre-trip choices of travelers with respect to tour, time of departure, mode, and route, and have an immediate impact on travel demand through re-distribution or elimination of trips.
2. **Tactical Traveler Behavior Focus**: This technical approach aims to accurately represent individual vehicle and pedestrian movements and interactions between them. Strategic traveler behaviors are approximated. Given that, this approach is applicable for assessing traffic management applications that impact tactical driving behaviors and tactical movement decisions of pedestrians and bicyclists, and have significant impact on the flow of vehicles on a facility.
3. **Multi-Resolution Modeling Approach**: This technical approach aims to accurately represent traveler's trip making choices prior to trip start as well as individual vehicle and pedestrian movements and interactions between them. This approach is relevant for assessing applications that not only have an immediate impact on travel demand but also in managing recurring and non-recurring congestion on a facility. This approach appears to be suitable for assessing almost any application, but has the most technical risk among all technical approaches due to the need to manage online interfaces between travel demand modeling, transportation network modeling, system manager decision modeling, and communications modeling.
4. **Communications/Management Latency Focus**: This technical approach aims to accurately represent communications between vehicles, devices, and the infrastructure, as well as system managers' decision making. Thus, this approach is suited for applications that are impacted by communications bandwidth overload, dropped messages, communication latencies or system management latencies.

Table 5-1 presents an assessment of the capabilities of the four technical approaches in representing 18 DMA applications and 23 ATDM strategies. The Strategic Traveler Behavior Focused testbed approach can represent 17 applications and strategies very well, three partially, and 21 not at all. The Communications/Management Latency Focused testbed approach has similar strengths as the Tactical Traveler Behavior Focused testbed approach as both emphasize tactical decisions, and detailed communications modeling. Thus, both can represent the same set of 22 applications and strategies very well, two partially, and 17 not at all. The Multi-Resolution Modeling Approach can represent 31 applications and strategies very well, 6 partially, and 4 not at all. The Multi-Resolution Modeling Approach appears to be the most superior for representing ATDM strategies because it combines the capabilities of the Strategic and Tactical testbeds. However, it is also the approach with the most technical risk, and shouldn't be viewed as the only solution to representing the strategies. The other approaches are equally superior in modeling 21 out of 23 ATDM strategies. The ATDM strategies where multi-resolution approach appears to be the only, best approach are Dynamic HOV/Managed Lanes and Dynamic Lane Reversal or Contraflow Lane Reversal. The Multi-Resolution Modeling Approach is, however, not the only best solution for DMA applications. For three of the bundles (EnableATIS, FRATIS, and IDTO), both Strategic and Multi-Resolution Modeling approaches may be used effectively. For INFLO, MMITSS, and R.E.S.C.U.M.E., Multi-Resolution Modeling Approach is not capable of accurately representing the bundles due to their need for detailed communications modeling. Tactical and Communications Latency Focused approaches are more relevant.

Table 5-1: Assessment of AMS Testbed Capability in Representing DMA and ATDM Applications and Strategies

Application	Strategic Traveler Behavior Focus	Tactical Traveler Behavior Focus	Multi-Resolution Modeling Approach	Communications/ Management Latency Focus
Active Transportation and Demand Management				
Active Demand Management Strategies				
Dynamic Fare Reduction	●	○	●	○
Dynamic HOV/Managed Lanes	◉	◉	●	◉
Dynamic Pricing	●	○	●	○
Dynamic Ridesharing	●	○	●	○
Dynamic Routing	◉	●	●	●
Dynamic Transit Capacity Assignment	●	○	●	○
On-Demand Transit	●	○	●	○
Predictive Traveler Information	●	○	●	○
Transfer Connection Protection	●	○	●	○
Active Traffic Management Strategies				
Adaptive Ramp Metering	○	●	●	●
Adaptive Traffic Signal Control	○	●	●	●
Dynamic Junction Control	○	●	●	●
Dynamic Lane Reversal or Contraflow Lane Reversal	◉	◉	●	◉
Dynamic Lane Use Control	○	●	●	●
Dynamic Merge Control	○	●	●	●
Dynamic Shoulder Lanes	○	●	●	●
Dynamic Speed Limits	○	●	●	●
Queue Warning	○	●	●	●
Transit Signal Priority	○	●	●	●
Active Parking Management Strategies				
Dynamic Overflow Transit Parking	●	○	●	○
Dynamic Parking Reservation	●	○	●	○
Dynamic Wayfinding	●	○	●	○

Application	Strategic Traveler Behavior Focus	Tactical Traveler Behavior Focus	Multi-Resolution Modeling Approach	Communications/ Management Latency Focus
Dynamically Priced Parking	●	○	●	○
Dynamic Mobility Applications				
EnableATIS	●	●	●	●
FRATIS				
Freight-Specific Dynamic Travel Planning and Performance	●	○	●	○
Intermodal Drayage Operations Optimization	●	○	●	○
IDTO				
Connection Protection	●	○	●	○
Dynamic Transit Operations	●	○	●	○
Dynamic Ridesharing	●	○	●	○
INFLO				
Queue Warning	○	●	⦿	●
Dynamic Speed Harmonization	○	●	⦿	●
Cooperative Adaptive Cruise Control	○	●	○	●
MMITSS				
Intelligent Traffic Signal System	○	●	⦿	●
Transit Signal Priority	○	●	⦿	●
Pedestrian Mobility	○	●	○	●
Freight Signal Priority	○	●	⦿	●
Emergency Vehicle Priority	○	●	○	●
R.E.S.C.U.M.E.				
Incident Scene Pre-Arrival Staging Guidance for Emergency Responders	○	●	⦿	●
Incident Scene Work Zone Alerts for Drivers and Workers	○	●	○	●
Emergency Communications for Evacuation	○	●	●	●
Next Gen ICM	○	○	●	○

● - Fully represented ⦿ - Partially represented ○ - Not represented

The discussion below provides one specific realization (i.e., AMS Testbed Construct) within each of the four broad categories of technical approaches. Note that just as there are many other potential technical approaches to the AMS Testbed than the four we have listed above, there are many potentially different AMS Testbed Constructs within each technical approach. We present one such AMS Testbed Construct for each technical approach only to be illustrative. It is also expected that more robust, capable and innovative approaches are now within reach. We provide these illustrations to begin the conversation with the simulation and modeling community with the expectation that the most valuable technical approaches and AMS Testbed Constructs are yet to be determined.

5.1 Strategic Traveler Behavior Focus

In this technical approach, individual traveler activity models are integrated with a dynamic regional representation of surface transportation systems. Tour-making, mode choice, time of departure choice, and route choice are individually modeled. Vehicle-to-vehicle interactions are modeled in less detail in order to make the approach computationally tractable. Communication loads by communication media are similarly estimated at a high-level. The testbed is defined at a metropolitan regional level to capture a significant majority of tours and trips from origin to destination within the modeled area.

Figure 5-1 illustrates an example AMS framework for the testbed. In such a testbed, the focus is on representing System Users' strategic long-term behaviors as well as pre-trip decisions in the near-term in response to traffic conditions and travel experiences. As disaggregate models are more suited for accurately representing individual choices, this testbed makes use of a disaggregate model as the Travel Demand Simulator. Individual trip plans are iteratively exchanged with the Transportation Network Simulator, until there is convergence.

The Transportation Network Simulator makes use of a mesoscopic simulation model since it is more suited for modeling regional level networks. Tactical driving decisions may or may not be modeled in detail. Accordingly, the mesoscopic model may or may not be interfaced with a microscopic model.

If connected vehicles and devices are modeled, lower-fidelity models are used to approximate message generation, which do not explicitly model BSM and BMM. Since the testbed makes use of a mesoscopic model for regional level representation, BSM and BMM are not explicitly modeled as these messages require representation of detailed vehicle or device movement. Approximate or imprecise messages from connected vehicles and devices are sent to the Wireless Communications Network Simulator.

Lower-fidelity models are used for Traffic Detections Systems and Traffic Management and Control Systems, but quality and latency of information are explicitly modeled. Broadcast Media are represented by higher-fidelity, realistic models, as the accuracy, precision, and content of messages delivered en route or pre-trip significantly impact traveler behaviors. Processed data from Traffic and Weather Detection Systems are sent to the Operational Data Environment Simulator.

Communications are modeled only at a high-level, and hence the Wireless Communications Simulator makes use of an aggregate communications model that is unconstrained by bandwidth (i.e., there are no dropped messages). The approximate messages from connected vehicles and devices are sent to the Operational Data Environment Simulator.

The Operational Data Environment Simulator makes use of a realistic operational data environment – i.e., errors are applied to the data elements. The time needed to process and aggregate the data are applied as latency. Processed current and historical data are sent to the Predictive Environment Simulator.

The testbed makes use of a Historical or Retrospective Predictive Environment in the Predictive Environment Simulator, which uses statistical methods to predict performance by application based on the given current and historical data from the Operational Data Environment Simulator.

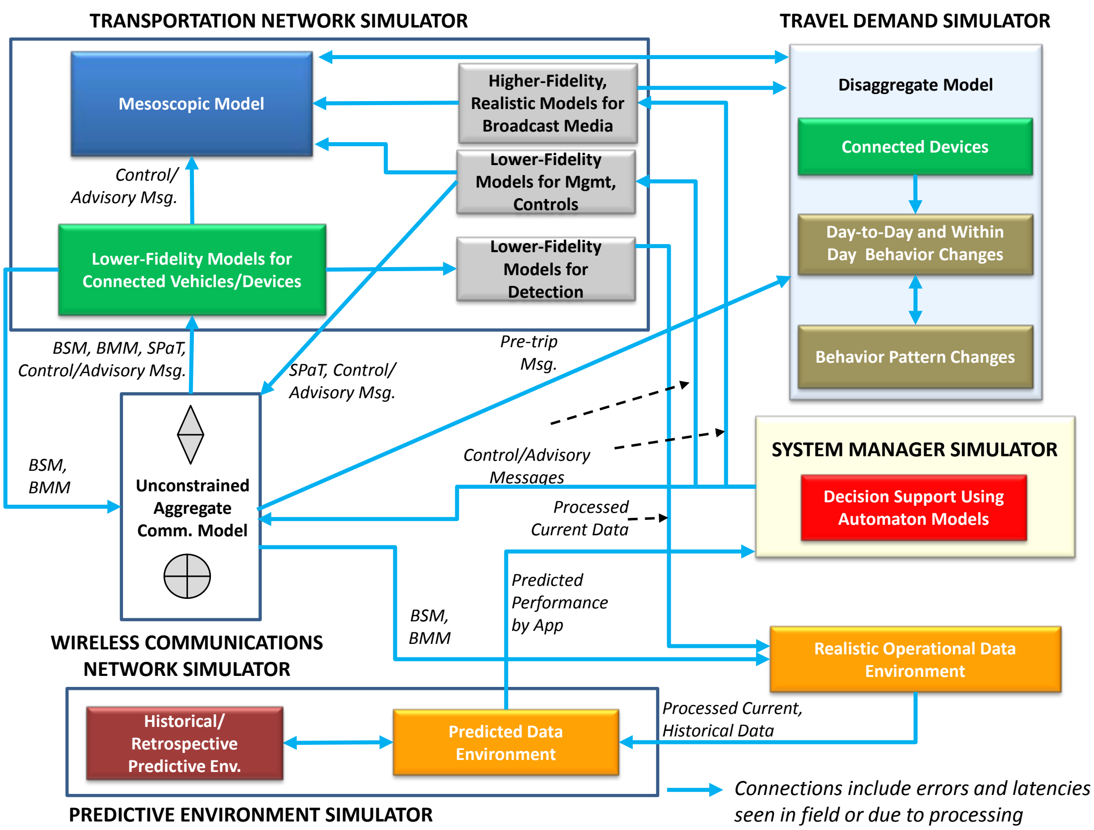

Figure 5-1. Example AMS Framework for a Strategic Traveler Behavior Focused Testbed

The predicted information is sent to the System Manager Simulator, which makes use of an automaton model for decision support (i.e., no human intervention). The information is sent to the Traffic Management and Control Systems in the Transportation Network Simulator, where the new application and corresponding control settings are implemented, and to the Broadcast Media. The information from the Broadcast Media is used as pre-trip messages in the Travel Demand Simulator and as en route messages for tactical behaviors. The information from Traffic Management and Control Systems impacts drivers and travelers' tactical decisions. There is also flow of information from Traffic Management and Control Systems to connected vehicles and devices via the Wireless Communications Network. The flow of information includes control and advisory information, and approximations of BSM, BMM, and SPaT messages. For example, vehicles traveling on an arterial facility that has a DSRC-based signal controller will have SPaT information irrespective of their position on the facility. The System Manager Simulator also sends control and advisory information which is sent as pre-trip messages to connected devices in the Travel Demand Simulator and en route messages to devices in the Transportation Network Simulator via the Wireless Communications Network Simulator.

The exchange of information between the Transportation Network Simulator, Wireless Communications Network Simulator, Operational Data Environment Simulator occurs concurrently and periodically throughout the duration of the assessment period. The flow of information from the Operational Data Environment Simulator and the Predictive Environment Simulator occurs only at specific time intervals (e.g., every 15 minutes of simulation time). The flow of predicted performance from the Predictive Environment Simulator to the System Manager also occurs at the same time interval (i.e., 15 minutes from the example). If there is a change in the control settings based on the predicted performance, the System Manager Simulator sends the relevant control and advisory information to the Transportation Network Simulator and the Wireless Communications Network for dissemination as pre-trip messages to travelers with connected devices who have signed in to receive the information. This flow of information is repeated for the duration of the assessment period, and the overall system-wide impacts of the application(s) is estimated (in the Operational Data Environment Simulator).

5.2 Tactical Traveler Behavior Focus

In this modeling construct, individual vehicle and pedestrian movement and interaction are modeled in detail, including the explicit representation of individual messages passing between mobile devices, vehicles, and infrastructure that are capable of transmitting and receiving connected vehicle messages. Emphasis is given to the accurate representation of vehicle position at the lane level, and non-uniform tactical driver behavior (e.g., lane changing, following distance, target speed) is modeled in a detailed way. The influence of advisory messages on driver behavior is also modeled in detail, including driver response to messages warning of pedestrians, stopped vehicles, unsafe weather conditions, target speeds, and impending or existing queues. Sources of interference to short-range communications (e.g., buildings, terrain and foliage) are directly modeled. To manage analytical complexity, only a portion of a network is modeled with high fidelity rather than a full region. Strategic traveler decisions are approximated or indirectly modeled.

Figure 5-2 illustrates an example AMS framework for the testbed. In this testbed as tactical behaviors and decisions are the focus, strategic behaviors are represented using aggregate models in the Travel Demand Simulator. Time-dependent trip tables by mode and purpose are iteratively exchanged with the Transportation Network Simulator, until there is convergence. There is no exchange of information with the Travel Demand Simulator from any of the component modules after convergence is reached.

The Transportation Network Simulator makes use of a mesoscopic simulation model for modeling a regional level network, and a microscopic model for modeling a portion of the network (e.g., a corridor) in great detail.

If connected vehicles and devices are modeled, higher-fidelity models are used to represent message generation in the portion of the network that is represented using microscopic model. Lower-fidelity models are used in the rest of the network to approximate the message generation process. Messages are sent to the Wireless Communications Network Simulator.

Higher-fidelity models are used for Traffic Detections Systems and Traffic Management and Control Systems. Broadcast Media are represented by lower-fidelity, realistic models, as the objective in this testbed is to emulate the impact of the information on drivers and travelers' tactical behaviors, rather than on the media itself (which has more impact on strategic decisions pre-trip). Processed data from Traffic and Weather Detection Systems are sent to the Operational Data Environment Simulator.

The Wireless Communications Network makes use of two types of models - an open source or commercially available communications network simulator which is interfaced with the microscopic model and an unconstrained aggregate communications model which is interfaced with the mesoscopic model. Highly accurate representations of the messages, latency, and errors from the microscopic network, and the approximate messages from the mesoscopic network are sent to the Operational Data Environment Simulator.

The Operational Data Environment Simulator makes use of a realistic operational data environment – i.e., errors are applied to the data elements. The time needed to process and aggregate the data are applied as latency. Processed current and historical data are sent to the Predictive Environment Simulator. Processed current and historical data and measures are sent to the System Manager Simulator, to allow the System Manager to make decisions while waiting for the Predictive Environment Simulator to send predicted performance.

The testbed makes use of an AMS-Augmented Predictive Environment in the Predictive Environment Simulator, which uses a combination of data, predictive tools, and the AMS Testbed, to predict performance by application. The predicted information is sent to the System Manager Simulator.

The System Manager Simulator makes use of a discrete choice model in the absence of a Decision Support System. The control and advisory decisions are sent to the Traffic Management and Control Systems in the Transportation Network Simulator, where the new application and corresponding control settings are implemented, and to the Broadcast Media. The information from Traffic Management and Control Systems and Broadcast Media impact drivers and travelers' tactical decisions. There is also flow of information from Traffic Management and Control Systems to connected vehicles and devices via the Wireless Communications Network. The flow of information includes control and advisory information to all connected vehicles and devices in the network. BSM, BMM, and SPaT messages are sent to vehicles and devices on the network that is simulated using a microscopic model, and approximations of BSM, BMM, and SPaT messages to the rest of the network. The System Manager Simulator also sends control and advisory information which is sent as en route messages to connected devices in the Transportation Network Simulator via the Wireless Communications Network Simulator.

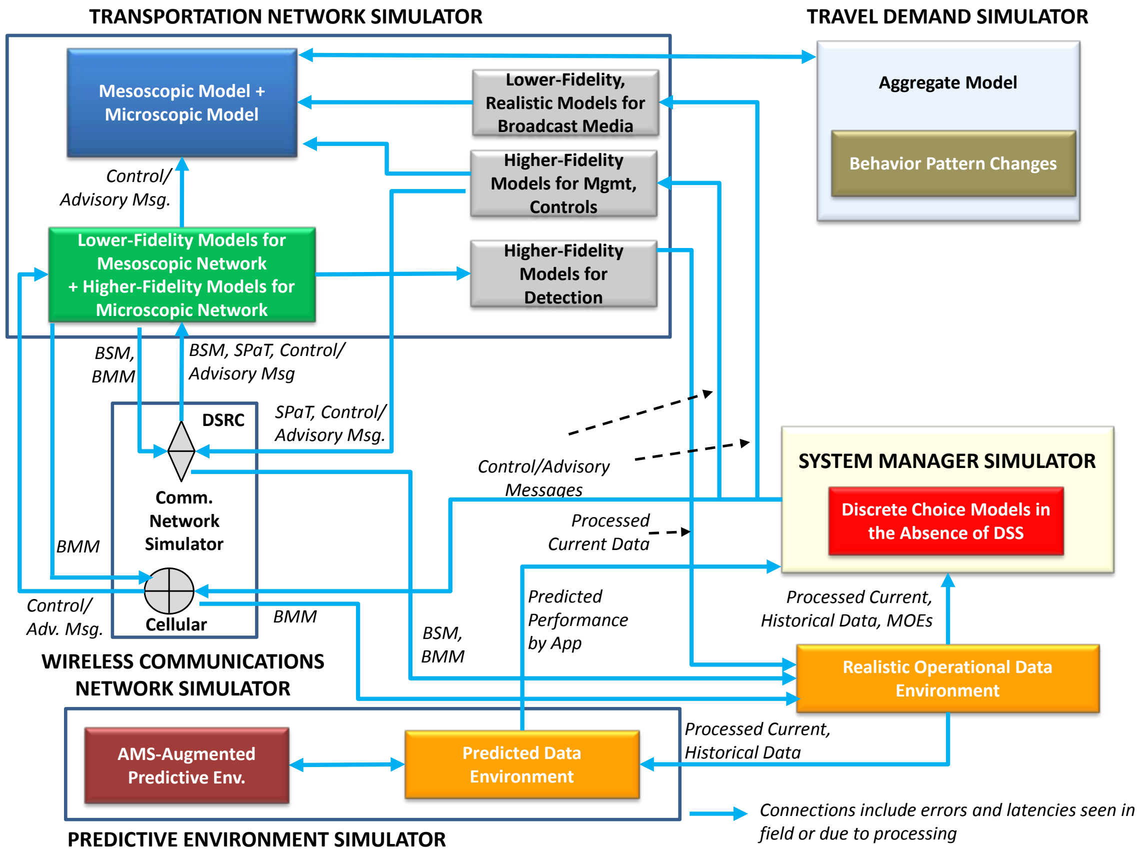

Figure 5-2. Example AMS Framework for a Tactical Traveler Behavior Focused Testbed

The exchange of information between the Transportation Network Simulator, Wireless Communications Network Simulator, Operational Data Environment Simulator, and System Manager Simulator occurs concurrently and frequently, so that they are synched in real-time, throughout the duration of the assessment period. If the System Manager has not received any information from the Predictive Environment Simulator, the System Manager makes use of the data and measures from the Operational Data Environment. If there is a change in the control settings based on this data, the System Manager Simulator sends the relevant control and advisory information to the Transportation Network Simulator. Information is not sent to the Travel Demand Simulator as this testbed's emphasis is on tactical behaviors. The flow of information from the Operational Data Environment Simulator and the Predictive Environment Simulator occurs only at specific time intervals. The flow of predicted performance from the Predictive Environment Simulator to the System Manager also occurs at the same time interval. If there is a change in the control settings based on the predicted performance, the System Manager Simulator sends the relevant control and advisory information to the Transportation Network Simulator and the Wireless Communications Network for dissemination as en route messages to travelers and drivers with connected devices.

This flow of information is repeated for the duration of the assessment period, and the overall system-wide impacts of the application(s) is estimated (in the Operational Data Environment Simulator).

5.3 Multi-Resolution Modeling Approach

A tactical driver testbed is embedded within a strategic traveler behavior testbed, and interaction between the two analytical constructs managed by way of a real-time or offline interface. The approach has the advantage of potentially capturing detail where needed as well as strategic traveler behavior. However, additional technical risk must be managed in the interface between the two modeling constructs, as well as issues of potential differences in results when boundaries between the two models are arbitrarily determined. Note that the management of these interfaces applies not only to interfaces between transportation simulation modeling but also interfaces between traveler behavior modeling, system manager decision modeling, and communications modeling.

Figure 5-3 illustrates an example AMS framework for the testbed. To represent strategic behaviors, this testbed adopts a similar approach as the Strategic Traveler Behavior focused testbed. Disaggregate models are used in the Travel Demand Simulator for accurately representing individual choices. Individual trip plans are iteratively exchanged with the Transportation Network Simulator, until there is convergence.

The Transportation Network Simulator makes use of a mesoscopic simulation model for modeling a regional level network, and a microscopic model for modeling a portion of the network (e.g., a corridor) in great detail. Depending on the type of connection modeled between the two scales, traffic management interventions or incidents within the microscopic sub-network must be reflected in the regional mesoscopic tool and vice versa. Connections may be concurrent multi-scale, where both tools operate on the same simulation master clock, or off-line where interactions are asynchronous.

If connected vehicles and devices are modeled, higher-fidelity models are used to represent message generation in the portion of the network that is represented using microscopic model. Lower-fidelity models are used in the rest of the network to approximate the message generation process. Messages are sent to the Wireless Communications Network Simulator.

Higher-fidelity models are used for Traffic Detections Systems and Traffic Management and Control Systems. Broadcast Media are represented by higher-fidelity, realistic models. Processed data from Traffic and Weather Detection Systems are sent to the Operational Data Environment Simulator.

A partially-constrained aggregate communications model is used in the Wireless Communications Network Simulator. This approach allows representing communications at a high-level without the need for detailed communications network simulation, while capturing loss in messages due to bandwidth overload. The messages from connected vehicles and devices are sent to the Operational Data Environment Simulator.

The Operational Data Environment Simulator makes use of a realistic operational data environment – i.e., errors are applied to the data elements. The time needed to process and aggregate the data are applied as latency. Processed current and historical data are sent to the Predictive Environment Simulator. Processed current and historical data and measures are sent to the System Manager Simulator, to allow the System Manager to make decisions while waiting for the Predictive Environment Simulator to send predicted performance.

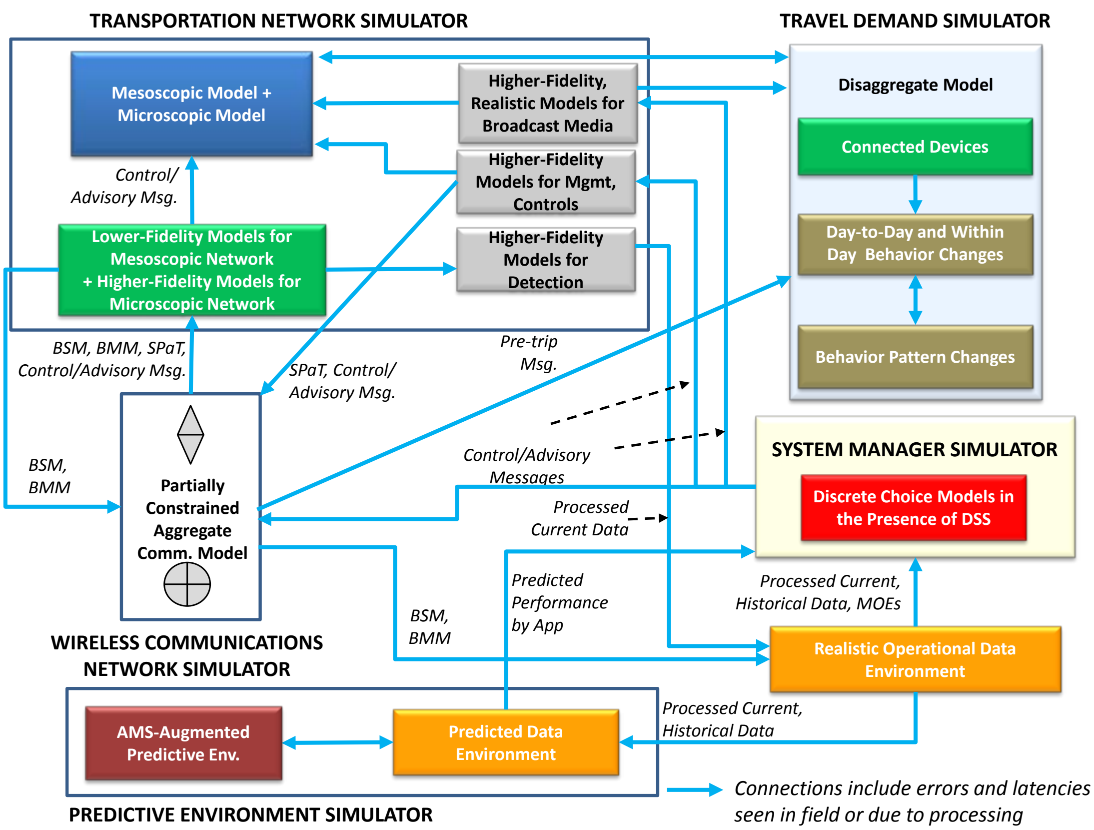

Figure 5-3. Example AMS Framework for a Multi-Resolution Modeling Approach

The testbed makes use of an AMS-Augmented Predictive Environment in the Predictive Environment Simulator, which uses a combination of data, predictive tools, and the AMS Testbed, to predict performance by application. The predicted information is sent to the System Manager Simulator.

The System Manager Simulator makes use of a discrete choice model in the presence of a Decision Support System (i.e., DSS with human intervention). The control and advisory decisions are sent to the Traffic Management and Control Systems in the Transportation Network Simulator, where the new application and corresponding control settings are implemented, and to the Broadcast Media. The information from the Broadcast Media is used as pre-trip messages in the Travel Demand Simulator and as en route messages for tactical behaviors. The information from Traffic Management and Control Systems impacts drivers and travelers' tactical decisions. There is also flow of information from Traffic Management and Control Systems to connected vehicles and devices via the Wireless Communications Network. The flow of information includes control and advisory information to all connected vehicles and devices in the network. BSM, BMM, and SPaT messages are sent to vehicles and devices on the network that is simulated using a microscopic model, and approximations of BSM, BMM, and SPaT messages to the rest of the network. The System Manager Simulator also sends control and advisory information which is sent as en route messages to connected devices in the Transportation Network Simulator via the Wireless Communications Network Simulator.

The exchange of information between the Transportation Network Simulator, Wireless Communications Network Simulator, Operational Data Environment Simulator, and System Manager Simulator occurs concurrently and periodically throughout the duration of the assessment period. If the System Manager has not received any information from the Predictive Environment Simulator, the System Manager makes use of the data and measures from the Operational Data Environment. If there is a change in the control settings based on this data, the System Manager Simulator sends the relevant control and advisory information to the Transportation Network Simulator and the Wireless Communications Network for dissemination as pre-trip messages to travelers with connected devices who have signed in to receive the information (in the Travel Demand Simulator). The flow of information from the Operational Data Environment Simulator and the Predictive Environment Simulator occurs only at specific time intervals (e.g., every 15 minutes of simulation time). The flow of predicted performance from the Predictive Environment Simulator to the System Manager also occurs at the same time interval (i.e., 15 minutes from the example). If there is a change in the control settings based on the predicted performance, the System Manager Simulator sends the relevant control and advisory information to the Transportation Network Simulator and the Wireless Communications Network for dissemination as pre-trip messages to travelers with connected devices. This flow of information is repeated for the duration of the assessment period, and the overall system-wide impacts of the application(s) is estimated (in the Operational Data Environment Simulator).

5.4 Communications/Management Latency Focus

Rather than focusing on creating communication model inputs from transportation simulation outputs, this technical approach begins from a detailed dynamic model of message/data movement from detection to assembly to incorporation within a system managers decision support system. Unlike other approaches, which focus primarily on behaviors of travelers and drivers, this construct focuses on a detailed representation of system manager tactical decision making. Vehicle and traveler movements are modeled indirectly or at a high-level. Integration of this concept with the above three can also be considered but will have similar issues as noted for the multi-resolution modeling approach.

Figure 5-4 illustrates an example AMS framework for the testbed. In this testbed the focus is on detailed communications modeling as well as system manager's decision making process. Hence, strategic behaviors are represented using aggregate models in the Travel Demand Simulator. Time-dependent trip tables by mode and purpose are iteratively exchanged with the Transportation Network Simulator, until there is convergence. There is no exchange of information with the Travel Demand Simulator from any of the component modules after convergence is reached.

The Transportation Network Simulator makes use of a mesoscopic simulation model for modeling a regional level network, and a microscopic model for modeling a portion of the network (e.g., a corridor) in great detail.

If connected vehicles and devices are modeled, higher-fidelity models are used to represent message generation in the portion of the network that is represented using microscopic model. Lower-fidelity models are used in the rest of the network to approximate the message generation process. Messages are sent to the Wireless Communications Network Simulator.

Higher-fidelity models are used for Traffic Detections Systems and Traffic Management and Control Systems. Broadcast Media are not represented in this testbed. Processed data from Traffic and Weather Detection Systems are sent to the Operational Data Environment Simulator.

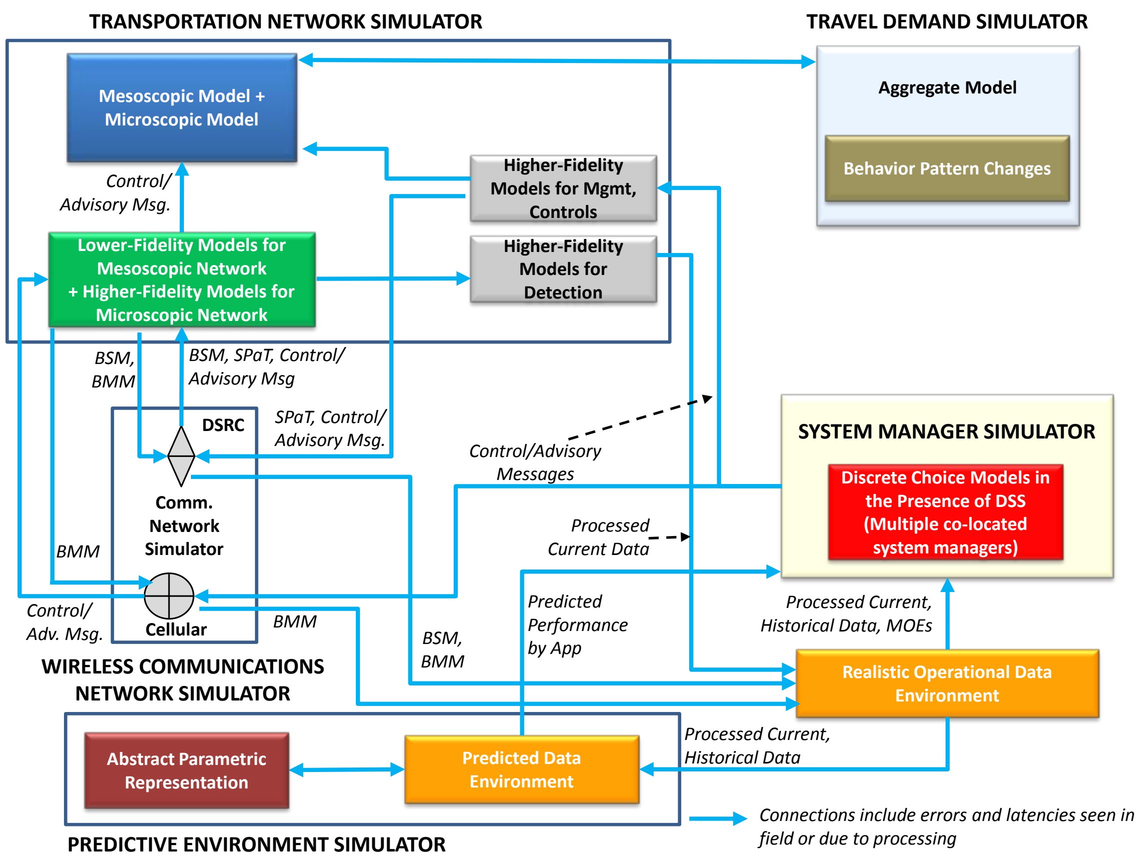

Figure 5-4. Example AMS Framework for a Communications/Management Latency Focused Testbed

The Wireless Communications Network makes use of two types of models - an open source or commercially available communications network simulator which is interfaced with the microscopic model and an unconstrained aggregate communications model which is interfaced with the mesoscopic model. Highly accurate representations of the messages, latency, and errors from the microscopic network, and the approximate messages from the mesoscopic network are sent to the Operational Data Environment Simulator.

The Operational Data Environment Simulator makes use of a realistic operational data environment – i.e., errors are applied to the data elements. The time needed to process and aggregate the data are applied as latency. Processed current and historical data are sent to the Predictive Environment Simulator. Processed current and historical data and measures are sent to the System Manager Simulator, to allow the System Manager to make decisions while waiting for the Predictive Environment Simulator to send predicted performance.

The testbed makes use of an Abstract Parametric Representation in the Predictive Environment Simulator, which helps examine the value of prediction on system performance without specifically modeling any prediction technique. The predicted information is sent to the System Manager Simulator.

The System Manager Simulator makes use of a discrete choice model in the presence of a Decision Support System. Decisions are made by multiple system managers who are co-located. The control and advisory decisions are sent to the Traffic Management and Control Systems in the Transportation Network Simulator. The information from Traffic Management and Control Systems impact drivers and travelers' tactical decisions. There is also flow of information from Traffic Management and Control Systems to connected vehicles and devices via the Wireless Communications Network. The flow of information includes control and advisory information to all connected vehicles and devices in the network. BSM, BMM, and SPaT messages are sent to vehicles and devices on the network that is simulated using a microscopic model, and approximations of BSM, BMM, and SPaT messages to the rest of the network. The System Manager Simulator also sends control and advisory information which is sent as en route messages to connected devices in the Transportation Network Simulator via the Wireless Communications Network Simulator.

The exchange of information between the Transportation Network Simulator, Wireless Communications Network Simulator, Operational Data Environment Simulator, and System Manager Simulator occurs concurrently and frequently, so that they are synched in real-time, throughout the duration of the assessment period. If the System Manager has not received any information from the Predictive Environment Simulator, the System Manager makes use of the data and measures from the Operational Data Environment. If there is a change in the control settings based on this data, the System Manager Simulator sends the relevant control and advisory information to the Transportation Network Simulator. Information is not sent to the Travel Demand Simulator as this testbed's emphasis is on tactical behaviors. The flow of information from the Operational Data Environment Simulator and the Predictive Environment Simulator occurs only at specific time intervals. The flow of predicted performance from the Predictive Environment Simulator to the System Manager also occurs at the same time interval. If there is a change in the control settings based on the predicted performance, the System Manager Simulator sends the relevant control and advisory information to the Transportation Network Simulator and the Wireless Communications Network for dissemination as en route messages to travelers and drivers with connected devices. This flow of information is repeated for the duration of the assessment period, and the overall system-wide impacts of the application(s) is estimated (in the Operational Data Environment Simulator).

Table 5-2 presents a mapping of the AMS Testbed Requirements to the four technical approaches. A high-level assessment is done based on the sample AMS Testbed Constructs presented for each technical approach above, and will vary if alternate AMS Testbed Constructs are used for the four technical approaches. The assessment also does not take into account the capabilities of existing tools in representing the requirements; rather it is an assessment to determine if the technical approaches can broadly satisfy all requirements. Note that in the case of the Strategic Traveler Behavior Focus approach, we assume that mesoscopic model is utilized, but do not assume that the mesoscopic tool represents lane-level vehicle movements. Our assessment shows that there is no requirement that is not met by at least one of the four approaches, with the caveat that current tools may or may not have to be enhanced significantly to accurately represent the requirements.

Table 5-2 Mapping AMS Testbed Requirements to AMS Testbed Technical Approaches

ID	Requirement	Strategic Traveler Behavior Focus	Tactical Traveler Behavior Focus	Multi-Resolution Modeling Approach	Communications/ Management Latency Focus
SU-1	The AMS Testbed shall emulate and track each **Traveler**'s time-referenced geographic location (position) as he/she plans, executes, and completes a trip within the transportation system.	○	●	●	●
SU-2	The AMS Testbed shall emulate and track each **Travelers'** time-referenced state and transition among various potential states (pre-trip, pedestrian, non-motorized traveler, light vehicle driver, light vehicle passenger, and transit rider) as they plan, execute, and complete trips within the transportation system.	⦿	⦿	●	⦿
SU-3	The AMS Testbed shall emulate each **Traveler**'s time-delimited tour planning, both in the pre-trip as well as en route states, subject to the nature and accuracy of available data on travel cost (parking fee, toll, fuel consumption, transit fare), expected trip duration, trip travel time reliability, safety and environmental impact.	●	○	●	○
SU-4	The AMS Testbed shall emulate decision making by **Pedestrians**, and **Travelers in Non-motorized Modes** of travel in the absence and presence of mobile devices, subject to the nature and accuracy of data available to support decision making.	⦿	●	●	●
SU-5	The AMS Testbed shall emulate decision making by **Light Vehicle Drivers** in the absence and presence of mobile devices, carry-in devices, integrated devices, and message signs subject to the nature and accuracy of data available to support decision making.	○	●	●	●
SU-6	The AMS Testbed shall emulate decision making by **Light Vehicle Passengers** in the absence and presence of mobile devices subject to the nature and accuracy of data available to support decision making.	○	●	●	●
SU-7	The AMS Testbed shall emulate decision making by **Transit Riders** in the absence and presence of mobile devices subject to the nature and accuracy of data available to support decision making.	○	●	●	●

ID	Requirement	Strategic Traveler Behavior Focus	Tactical Traveler Behavior Focus	Multi-Resolution Modeling Approach	Communications/ Management Latency Focus
SU-8	The AMS Testbed shall emulate tactical driving decisions made by **Light Vehicle Drivers** with respect to lane selection, lane changing, gap acceptance, following headway, speed, acceleration, deceleration, stopping, braking, hard braking, yielding, and merging subject to the nature and accuracy of data available to support decision making.	○	●	●	●
SU-9	The AMS Testbed shall emulate and track each **Transit Driver** and associated transit vehicle's time-referenced geographic location (position) within the transportation system.	○	●	●	●
SU-10	The AMS Testbed shall emulate tactical driving decisions made by **Transit Drivers** with respect to lane selection, lane changing, gap acceptance, following headway, speed, acceleration, deceleration, stopping, braking, hard braking, yielding, and merging subject to the nature and accuracy of data available to support decision making.	○	●	●	●
SU-11	The AMS Testbed shall emulate fixed route/fixed schedule transit, flexible route bus, rail transit and paratransit.	●	⦿	●	⦿
SU-12	The AMS Testbed shall emulate a **Transit Driver**'s adherence to dynamic transit dispatch plans (e.g., to counteract bus bunching) when received subject to the nature and accuracy of data available to support decision making.	●	⦿	●	⦿
SU-13	The AMS Testbed shall emulate decision making by **Transit Drivers** in the absence and presence of mobile devices, carry-in devices, integrated devices, and message signs subject to the nature and accuracy of data available to support decision making.	⦿	●	●	●
SU-14	The AMS Testbed shall emulate and track each **Truck Driver** and associated freight vehicle's time-referenced geographic location (position) within the transportation system.	○	●	●	●
SU-15	The AMS Testbed shall emulate tactical driving decisions made by **Truck Drivers** with respect to lane selection, lane changing, gap acceptance, following headway, speed, acceleration, deceleration, stopping, braking, hard braking, yielding, and merging subject to the nature and accuracy of data available to support decision making.	○	●	●	●
SU-16	The AMS Testbed shall emulate a **Truck Driver**'s adherence to plans when received on dynamic routing, tours, and actions at waypoints subject to the nature and accuracy of data available to support decision making.	●	⦿	●	⦿
SU-17	The AMS Testbed shall emulate decision making by **Truck Drivers** in the absence and presence of mobile devices, carry-in devices, integrated devices, and message signs subject to the nature and accuracy of data available to support decision making.	○	●	●	●

ID	Requirement	Strategic Traveler Behavior Focus	Tactical Traveler Behavior Focus	Multi-Resolution Modeling Approach	Communications/ Management Latency Focus
SU-18	The AMS Testbed shall emulate and track each **Public Safety Worker** and public safety vehicle's time-referenced geographic location (position) within the transportation system, including in an active incident zone.	○	●	●	●
SU-19	The AMS Testbed shall emulate tactical driving decisions made by **Public Safety Vehicle Drivers** with respect to lane selection, lane changing, gap acceptance, following headway, speed, acceleration, deceleration, stopping, braking, hard braking, yielding, and merging subject to the nature and accuracy of data available to support decision making.	○	●	●	●
SU-20	The AMS Testbed shall emulate a **Public Safety Vehicle Driver**'s adherence to plans when received on dynamic routing, and response staging subject to the nature and accuracy of data available to support decision making.	○	●	●	●
SU-21	The AMS Testbed shall emulate the time-referenced geographic location of **Public Safety Workers** acting as emergency response personnel within an active incident zone in the absence and presence of mobile devices subject to the nature and accuracy of data available to support decision making.	○	●	●	●
SU-22	The AMS Testbed shall emulate decision making by **Public Safety Vehicle Drivers** in the absence and presence of mobile devices, carry-in devices, integrated devices, and message signs subject to the nature and accuracy of data available to support decision making.	○	●	●	●
SU-23	The AMS Testbed shall emulate adherence by **Drivers** of light, transit, and freight vehicles with directions when received on presence of emergency response personnel subject to the nature and accuracy of data available to support decision making.	○	●	●	●
SU-24	The AMS Testbed shall emulate various compliance rates of **System Users** (drivers, pedestrians, bicyclists, light vehicle passengers, transit riders, transit drivers, truck drivers, and public safety vehicle driver) when presented with advisory and regulatory information.	◉	●	●	●
CV-1	The AMS Testbed shall emulate **Mobile Devices** that are capable of transmitting messages via cellular or DSRC or both.	○	●	◉	●
CV-2	The AMS Testbed shall emulate the time-referenced geographic location, operational status (ON, OFF, NOT FUNCTIONING), and power status of a **Mobile Device**, and the state of the device (in use and connected to the vehicle, not in use but within a vehicle, outside a vehicle, etc.).	○	●	◉	●
CV-3	The AMS Testbed shall emulate **Carry-In Devices** that are capable of transmitting messages via cellular or DSRC or both.	○	●	◉	●

ID	Requirement	Strategic Traveler Behavior Focus	Tactical Traveler Behavior Focus	Multi-Resolution Modeling Approach	Communications/ Management Latency Focus
CV-4	The AMS Testbed shall emulate the time-referenced geographic location, and operational status (ON, OFF, NOT FUNCTIONING) of **Carry-In Devices**.	○	●	⦿	●
CV-5	The AMS Testbed shall emulate **Integrated Devices** that are capable of transmitting messages via cellular or DSRC or both.	○	●	⦿	●
CV-6	The AMS Testbed shall emulate the time-referenced geographic location, and operational status (ON, OFF, NOT FUNCTIONING) of **Integrated Devices**.	○	●	⦿	●
CV-7	The AMS Testbed shall emulate coordinated or independent transmission of messages from **Mobile Devices, Carry-in Devices and Integrated Devices** when co-located in a vehicle (light, transit, freight, public safety) via cellular or DSRC or both.	○	●	⦿	●
CV-8	The AMS Testbed shall emulate the reception of messages by DSRC-capable **Mobile Devices, Carry-in Devices and Integrated Devices** from other local DSRC-capable mobile, carry-in, and integrated devices.	○	●	⦿	●
CV-9	The AMS Testbed shall emulate the reliability of **Mobile Devices, Carry-in Devices and Integrated Devices**, specifically the reliability of a device to receive or send messages subject to local interference, device malfunction, or user error.	○	●	⦿	●
CV-10	The AMS Testbed shall track the time-referenced geographic- location and emulate the movement of **Connected** and **Unconnected Vehicles** within the transportation system, including time parked between trips made as a part of a multi-trip tour.	○	●	⦿	●
CV-11	The AMS Testbed shall reflect differences in vehicle size and weight among **Light Vehicles**, **Transit Vehicles**, **Trucks** and **Public Safety Vehicles** and associated differences in vehicle performance.	○	●	●	●
CS-1	The AMS Testbed shall emulate the geographic location (position), operational status (FUNCTIONING, NOT FUNCTIONING), and range of individual DSRC-capable Roadside Equipment (RSE) deployed as an element of a **DSRC Roadside Device Network**.	○	●	⦿	●
CS-2	The AMS Testbed shall emulate latency and reliability of messages passing through a **DSRC Roadside Device Network**, subject to the location and density of nearby roadside devices, relative position and capability of DSRC-capable devices (*Mobile Devices*, *Carry-In Devices*, and *Integrated Devices*) sending DSRC messages, and communications load local to individual roadside devices.	○	●	⦿	●
CS-3	The AMS Testbed shall emulate latency and reliability of communications using a **Wide-Area Wireless Network**, subject to the location of capable devices, sources of interference, and overall communications load.	○	●	⦿	●

ID	Requirement	Strategic Traveler Behavior Focus	Tactical Traveler Behavior Focus	Multi-Resolution Modeling Approach	Communications/ Management Latency Focus
CS-4	The AMS Testbed shall emulate provision of roadside/local control by **Traffic Control Systems** through dynamic message signs, lane control signs, ramp meters, and traffic signals.	○	●	●	●
CS-5	The AMS Testbed shall emulate provision of advisory information by **Traffic Control Systems** through dynamic message signs and other forms of advisory information provision.	○	●	●	●
CS-6	The AMS Testbed shall emulate the capability of **Traffic Control Systems** to receive, process, and implement control setting changes from *System Managers*, including the latency and reliability of response to *System Manager* direction.	○	●	●	●
CS-7	The AMS Testbed shall emulate the provision of traveler information via **Broadcast Media**, including television, radio and through the internet, including a differentiation of information delivered to *System Users* in pre-trip and en route states.	○	◉	●	◉
CS-8	The AMS Testbed shall emulate data capture from **Traffic Detection Systems** utilizing passive detection to estimate individual vehicle speed, location, and size or to estimate roadway segment occupancy, travel time, and aggregate vehicle flow where deployed in the transportation system, including the reliability of these sensors.	○	●	●	●
CS-9	The AMS Testbed shall emulate the accuracy, precision, latency and reliability of data aggregation and pre-processing actions within the **Traffic Detection System** prior to those data being made available to *System Managers* within an *Operational Data Environment*.	○	●	●	●
OD-1	The AMS Testbed shall emulate **Data Quality Control (QC) and Aggregation** processes, including the nature and effectiveness of quality checks and data performed for different data types.	●	●	●	●
OD-2	The AMS Testbed shall emulate the processing time associated with performing **Data Quality Control and Aggregation** processes.	●	●	●	●
OD-3	The AMS Testbed shall emulate and differentiate between integrated and independent **Data Quality Control and Aggregation** processes in support of System Managers.	●	●	●	●
OD-4	The AMS Testbed shall emulate the capture and aggregation of data from Connected Vehicles, Mobile Devices, and Detection Systems into **Private Sector Data Services**.	●	●	●	●
OD-5	The AMS Testbed shall account for the processing time associated with performing *Data Quality Control and Aggregation* processes within **Private Sector Data Services**.	●	●	●	●
OD-6	The AMS Testbed shall emulate the provision of aggregated and quality controlled data products from **Private Sector Data Services** into *Data QC and Aggregation* processes supporting *System Managers*.	●	●	●	●

ID	Requirement	Strategic Traveler Behavior Focus	Tactical Traveler Behavior Focus	Multi-Resolution Modeling Approach	Communications/ Management Latency Focus
OD-7	The AMS Testbed shall emulate the use of **Predictive Tools** within an Operational Data Environment, dependent on the flow of data from Data QC and Aggregation processes.	●	●	●	●
OD-8	The AMS Testbed shall emulate and differentiate among alternative forms of **Predictive Tools**, including their prediction horizon, accuracy, scope and processing time.	●	●	●	●
SM-1	The AMS Testbed shall emulate the duration and outcomes of decision-making by **Freeway System and Tollway Managers**, subject to the latency, accuracy, reliability and nature of Operational Data Environments available to support this decision-making.	●	●	●	●
SM-2	The AMS Testbed shall emulate the duration and outcomes of decision-making by **Arterial System Managers**, subject to the latency, accuracy, reliability and nature of Operational Data Environments available to support this decision-making.	◉	●	●	●
SM-3	The AMS Testbed shall emulate the duration and outcomes of decision-making by **Road-Weather System Managers**, subject to the latency, accuracy, reliability and nature of Operational Data Environments available to support this decision-making.	●	●	●	●
SM-4	The AMS Testbed shall emulate the duration and outcomes of decision-making by **Transit System Managers**, subject to the latency, accuracy, reliability and nature of Operational Data Environments available to support this decision-making.	●	●	●	●
SM-5	The AMS Testbed shall emulate the duration and outcomes of decision-making by **Parking System Managers**, subject to the latency, accuracy, reliability and nature of Operational Data Environments available to support this decision-making.	●	●	●	●
SM-6	The AMS Testbed shall emulate the duration and outcomes of decision-making by **Freight System Managers**, subject to the latency, accuracy, reliability and nature of Operational Data Environments available to support this decision-making.	●	●	●	●
SM-7	The AMS Testbed shall emulate the duration and outcomes of decision-making by **Public Safety Managers**, subject to the latency, accuracy, reliability and nature of Operational Data Environments available to support this decision-making.	◉	●	●	●
SM-8	The AMS Testbed shall emulate the duration and outcomes of decision-making by **Information Service Providers**, subject to the latency, accuracy, reliability and nature of Operational Data Environments available to support this decision-making.	●	●	●	●

ID	Requirement	Strategic Traveler Behavior Focus	Tactical Traveler Behavior Focus	Multi-Resolution Modeling Approach	Communications/ Management Latency Focus
SM-9	The AMS Testbed shall emulate and differentiate the duration and outcomes of integrated versus independent decision-making among **System Managers**, including *Freeway and Tollway System Managers*, *Signal System Mangers, Road-Weather System Managers, Parking System Managers, Freight System Managers, Public Safety Managers*, and *Information Service Providers*.	○	○	○	●
SM-10	The AMS Testbed shall emulate the forms, scope and limitations of system control exerted by **Freeway System and Tollway Managers**, including messages passed through *Broadcast Media, Traffic Control Systems, the DSRC Roadside Network or Wide-Area Wireless Networks* to control or influence *System User* decision-making.	●	●	●	●
SM-11	The AMS Testbed shall emulate the forms, scope and limitations of system control exerted by **Arterial System Managers**, including messages passed through *Traffic Control Systems, the DSRC Roadside Network or Wide-Area Wireless Networks* to control or influence *System User* decision-making.	●	●	●	●
SM-12	The AMS Testbed shall emulate the forms, scope and limitations of system control exerted by **Road-Weather System Managers**, including messages passed through *Broadcast Media, Traffic Control Systems, the DSRC Roadside Network or Wide-Area Wireless Networks* to control or influence *System User* decision-making.	●	●	●	●
SM-13	The AMS Testbed shall emulate the forms, scope and limitations of system control exerted by **Transit System Managers**, including messages passed through *Broadcast Media, Traffic Control Systems, the DSRC Roadside Network or Wide-Area Wireless Networks* to control or influence *System User* decision-making.	●	●	●	●
SM-14	The AMS Testbed shall emulate the forms, scope and limitations of system control exerted by **Parking System Managers**, including messages passed through *Broadcast Media, Traffic Control Systems, the DSRC Roadside Network or Wide-Area Wireless Networks* to control or influence *System User* decision-making.	●	●	●	●
SM-15	The AMS Testbed shall emulate the forms, scope and limitations of system control exerted by **Freight System Managers**, including messages passed through *Broadcast Media, Traffic Control Systems, the DSRC Roadside Network or Wide-Area Wireless Networks* to control or influence *System User* decision-making.	●	●	●	●

ID	Requirement	Strategic Traveler Behavior Focus	Tactical Traveler Behavior Focus	Multi-Resolution Modeling Approach	Communications/ Management Latency Focus
SM-16	The AMS Testbed shall emulate the forms, scope and limitations of system control exerted by **Public Safety Managers**, including messages passed through *Broadcast Media, Traffic Control Systems, the DSRC Roadside Network or Wide-Area Wireless Networks* to control or influence S*ystem User* decision-making.	●	●	●	●
SM-17	The AMS Testbed shall emulate the forms, scope and limitations of system control exerted by **Information Service Providers**, including messages passed through *Broadcast Media, the DSRC Roadside Network or Wide-Area Wireless Networks* to influence S*ystem User* decision-making.	●	●	●	●
SM-18	The AMS Testbed shall emulate the utilization of **Automated Control** by one or more *System Managers* who delegate specific forms of routine decision-making and control message generation.	●	○	●	●
DI-1	The AMS Testbed shall emulate the transmission and reception of **Information and Data Flows** between System Entities over a specific communications system, whether broadcast or point-to-point in nature, the interval at which the data flow occurs, and the content of the message contained in the data flow.	○	●	⊙	●
DI-2	The AMS Testbed shall emulate the transmission and reception of **Basic Safety Messages (BSM)** among *Connected Vehicles, Mobile Devices,* and the *DSRC Roadside Network*.	○	●	⊙	●
DI-3	The AMS Testbed shall emulate the transmission of **Basic Mobility Messages (BMM)** from *Connected Vehicles* and *Mobile Devices* to the *System Entity* tasked with managing BMM messaging (either a *Private Sector Data Services* or a *Data QC and Aggregation* process)	○	●	⊙	●
DI-4	The AMS Testbed shall emulate the transmission of **Signal, Phase and Timing (SPaT) Messages** from the *DSRC Roadside Device Network* to DSRC-capable *Connected Vehicles*.	○	●	⊙	●
AP-1	The AMS Testbed shall emulate **Dynamic Shoulder Lanes**.	○	●	●	●
AP-2	The AMS Testbed shall emulate driver behaviors in **Dynamic Shoulder Lanes** that are distinct from behaviors on regular lanes.	○	●	●	●
AP-3	The AMS Testbed shall emulate restriction of access to **Dynamic Shoulder Lanes** by vehicle type (e.g., transit) and vehicle occupancy (e.g., HOV 2+, HOV 3+).	○	●	●	●
AP-4	The AMS Testbed shall emulate **Dynamic Lane Use Control**, including shoulder lanes.	○	●	●	●
AP-5	The AMS Testbed shall emulate **Dynamic HOV/Managed Lanes**.	⊙	⊙	●	⊙
AP-6	The AMS Testbed shall emulate detection of position, start time, duration, and length of queues on freeways and arterials in support of a **Queue Warning** DMA or **Queue Warning** strategy supporting *System Manager* decision-making.	○	●	⊙	●

ID	Requirement	Strategic Traveler Behavior Focus	Tactical Traveler Behavior Focus	Multi-Resolution Modeling Approach	Communications/ Management Latency Focus
AP-7	The AMS Testbed shall emulate altered driving behavior in response to **Queue Warning** messages generated by the Q-WARN DMA and delivered to *Carry In* or *Integrated Devices* within *Connected Vehicles* or through local signage within the Traffic Control System.	○	●	⦿	●
AP-8	The AMS Testbed shall emulate the estimation of dynamic target speed recommendations by roadway section and lane made by the **SPD-HARM** application or the **Dynamic Speed Limits** strategy deployed in support of *System Managers*.	○	●	⦿	●
AP-9	The AMS Testbed shall emulate transmission of **SPD-HARM** enhanced target speed recommendations via message signs; or directly to *Carry-In* or *Integrated Devices* running the SPD-HARM application within a *Connected Vehicle*.	○	●	⦿	●
AP-10	The AMS Testbed shall emulate driver decision-making in response to target speed recommendations made by the **SPD-HARM** application running on a *Carry-In* or *Integrated Device* within a *Connected Vehicle*.	○	●	⦿	●
AP-11	The AMS Testbed shall emulate altered driving behavior in response to combined queue warning and target speed recommendations made by a combined **Q-WARN/SPD-HARM** application.	○	●	⦿	●
AP-12	The AMS Testbed shall emulate the creation, movement, and dispersion of a platoon of *Connected Vehicles* utilizing **Coordinated Adaptive Cruise Control** (CACC) application, traveling at the same speed and maintaining the same gap with their respective leaders in the platoon.	○	●	○	●
AP-13	The AMS Testbed shall emulate the identification and implementation of altered signal control settings enhanced by the **M-ISIG** DMA bundle or the ATDM **Adaptive Traffic Signal Control and Adaptive Ramp Metering** strategies.	○	●	⦿	●
AP-14	The AMS Testbed shall emulate the identification and implementation of signal control settings optimized to allow for the rapid and safe movement of Public Safety Vehicles (**PREEMPT**), Trucks (**FSP**), Transit Vehicles (**TSP**), and Pedestrians (**PED-SIG**).	○	●	⦿	●
AP-15	The AMS Testbed shall emulate the dynamic creation of high-occupancy vehicles through the **DRIDE** application running on Mobile Devices or through other **Dynamic Ridesharing** services supporting informal ridesharing.	●	○	●	○
AP-16	The AMS Testbed shall emulate multi-modal forms of traveler information services that include cost, reliability and parking delivered pre-trip through Broadcast Media or pre-trip and en route through Mobile Devices, Carry-In Devices, and Integrated Devices.	⦿	⦿	●	⦿

ID	Requirement	Strategic Traveler Behavior Focus	Tactical Traveler Behavior Focus	Multi-Resolution Modeling Approach	Communications/ Management Latency Focus
AP-17	The AMS Testbed shall emulate **Active Parking Management Strategies** employed to support decision-making by *Parking System Managers*, including Dynamic Wayfinding, Dynamic Overflow Transit Parking, Dynamic Parking Reservation, and Dynamic Priced Parking	●	○	●	○
AP-18	The AMS Testbed shall emulate **Dynamic HOV Lane Conversion**, including dynamic alterations to access policy (e.g., HOV-2 to HOV-3) and price.	◉	◉	●	◉
AP-19	The AMS Testbed shall emulate **Intelligent Dynamic Transit Operations (IDTO)**, including transit connection protection and dynamic dispatch.	●	○	●	○
AP-20	The AMS Testbed shall emulate **Incident Management** practices, including the management of local incident zones, the staging of emergency response vehicles and personnel, and the closure of lanes and facilities required as a part of the incident response.	○	●	◉	●
AP-21	The AMS Testbed shall emulate **Dynamic Pricing and Dynamic Fare Reduction** strategies, including dynamic changes to roadway tolls or transit fares.	●	○	●	○
AP-22	The AMS Testbed shall emulate the concurrent deployment of two or more DMAs or ATDM strategies, including synergies or conflicts arising from this interaction.	◉	◉	◉	◉
AP-23	The AMS Testbed shall emulate **Dynamic Junction Control**	○	●	●	●
AP-24	The AMS Testbed shall emulate **Dynamic Merge Control**	○	●	●	●
AP-25	The AMS Testbed shall emulate **Dynamic Lane Reversal or Contraflow lanes**, including dynamically adjusting the lane directionality in response to real-time traffic conditions.	◉	◉	●	◉
AP-26	The AMS Testbed shall emulate freight operations, including drayage optimization and freight traveler information	●	○	●	○
OC-1	The AMS Testbed shall emulate a range of **Operational Conditions**, including variations in travel demand, weather, and incident patterns.	●	●	●	●
OC-2	The AMS Testbed shall be capable of calculating a consistent set of **Performance Measures** describing mobility, safety and environmental impacts, over all Operational Conditions and subject to multiple alternative systems linking System Users and System Managers.	●	●	●	●
OC-3	The AMS Testbed shall be capable of being calibrated and validated using relevant **Performance Measures** against real-world conditions, both in terms of the representation of Operational Conditions and Alternative Systems, where such data are available from actual surface transportation systems.	●	●	●	●

● - Well represented ◉ - Partially represented ○ - Not represented

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APPENDIX A. List of Acronyms

Acronym	Name
ABS	Antilock Braking System
AMS	Analysis, Modeling, and Simulation
AP	Application Program
API	Application Program Interface
ATDM	Active Transportation and Demand Management
ATIS	Multi-Modal Real-Time Traveler Information
BMM	Basic Mobility Message
BSM	Basic Safety Message
CACC	Cooperative Adaptive Cruise Control
CONOPS	Concept of Operations
CS	Communications System
CV	Connected Vehicle
DI	Data and Information
DMA	Dynamic Mobility Applications
DOT	Department of Transportation
DRG	Dynamic Routing of Vehicles
D-RIDE	Dynamic Ridesharing
DR-OPT	Drayage Optimization
DSRC	Dedicated Short Range Communications
DSS	Decision Support System
ECO	Connected Eco Driving
EFP	Multimodal Integrated Payment System
EnableATIS	Enable Advanced Traveler Information System
EVAC	Emergency Communications and Evacuation
F-ATIS	Freight Real-Time Traveler Information with Performance Monitoring
F-DRG	Freight Dynamic Route Guidance

Acronym	Name
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRATIS	Freight Advanced Traveler Information System
FSP	Freight Signal Priority
FTA	Federal Transit Administration
HAR	Highway Advisory Radio
HOV	High-Occupancy Vehicle
ICM	NxGen Integrated Corridor Management
IDTO	Integrated Dynamic Transit Operations
INC-ZONE	Incident Scene Work Zone Alerts for Drivers and Workers
INFLO	Intelligent Network Flow Optimization
I-SIG	Intelligent Traffic Signal System
ITS	Intelligent Transportation Systems
JPO	Joint Program Office
MAYDAY	Mayday Relay
MDSS	Maintenance Decision Support System
M-ISIG	Multi-Modal Intelligent Traffic Signal System
MMITSS	Multi-Modal Intelligent Traffic Signal System
NHTSA	National Highway Traffic Safety Administration
NIST	National Institute of Standards and Technology
OC	Operational Condition
OD	Operational Data
O-D	Origin and Destination
PED-SIG	Mobile Accessible Pedestrian Signal
PREEMPT	Emergency Vehicle Priority
Q-WARN	Queue Warning
R.E.S.C.U.M.E	Response, Emergency Staging and Communications, Uniform Management, and Evacuation
RESP-STG	Incident Scene Pre-Arrival Staging
RITA	Research and Innovative Technology Administration
RSE	Roadside Equipment

Acronym	Name
SAE	Society of Automotive Engineers
SHRP 2	Strategic Highway Research Program
SM	System Manager
SPaT	Signal Phasing and Timing
SPD-HARM	Dynamic Speed Harmonization
SU	System User
T-CONNECT	Connection Protection
T-DISP	Dynamic Transit Operations
T-MAP	Universal Map Application
TMC	Transportation Management Center
TSP	Transit Signal Priority
USDOT	United States Department of Transportation
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
VMT	Mileage Based User Fees
WX-INFO	Real-Time Route Specific Weather
WX-MDSS	Enhanced MDSS Communications

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