Analysis, Modeling, and Simulation (AMS) Preliminary Evaluation Plan for Dynamic Mobility Applications (DMA) Program

www.its.dot.gov/index.htm

Final Report — November 2013

Publication Number: FHWA-JPO-13-097

U.S. Department of Transportation
Research and Innovative Technology Administration

Produced by Noblis, Inc.
U.S. Department of Transportation
ITS Joint Program Office
Research and Innovative Technology Administration

Notice

Technical Report Documentation Page

1. Report No. FHWA-JPO-13-097	**2. Government Accession No.**	**3. Recipient's Catalog No.**
4. Title and Subtitle Analysis, Modeling, and Simulation (AMS) Testbed Preliminary Evaluation Plan for Dynamic Mobility Applications (DMA) Program		**5. Report Date** November 2013 **6. Performing Organization Code**
7. Author(s) Meenakshy Vasudevan and Karl Wunderlich		**8. Performing Organization Report No.**
9. Performing Organization Name And Address Noblis, Inc., 600 Maryland Ave, SW, Suite 755, Washington, DC 20024		**10. Work Unit No. (TRAIS)** **11. Contract or Grant No.** DTFH61-11-D-00018
12. Sponsoring Agency Name and Address ITS Joint Program Office (ITS JPO), 1200 New Jersey Avenue, SE, Washington, DC 20590		**13. Type of Report and Period Covered** FINAL **14. Sponsoring Agency Code** USDOT RITA JPO

15. Supplementary Notes

Work Performed for:
James Colyar, FHWA Office of Operations (Government Task Manager)
John Halkias, FHWA Office of Operations
Kate Hartman, RITA/ITS JPO

16. Abstract

Analysis Modeling and Simulation (AMS) Testbeds 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 Dynamic Mobility Applications (DMA) and Active Transportation and Demand Management (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.

The purpose of this report is to document a preliminary plan for evaluating impacts of individual DMA applications, individual DMA bundles, and logical combinations of bundles and applications, and identifying conflicts and synergies for maximum benefit. Elements that are covered include:

- Key research questions and hypotheses that should be tested in the AMS Testbed
- Performance measures that underpin the hypotheses
- Description of analysis scenarios
- Key technology and market penetration assumptions
- Sensitivity analyses
- Results reporting

A companion document provides a preliminary plan for ATDM strategies. These plans are intended to assist AMS Testbed developers in preparing an overarching evaluation methodology as well as detailed analytical plans tailored to specific testbed locations and analytical approaches.

17. Key Words DMA, ATDM, connected vehicles, modeling, AMS, evaluation plan		**18. Distribution Statement**	
19. Security Classif. (of this report)	**20. Security Classif. (of this page)**	**21. No. of Pages** 41	**22. Price**

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

Acknowledgements

The authors wish to acknowledge several contributors to this study:

DMA-ATDM AMS Testbed Key Content Review Team: James Colyar (FHWA Operations; Noblis Task Manager), John Halkias (FHWA Operations), Kate Hartman (RITA/ITS JPO; DMA Program Manager), Joe Bared (FHWA R&D), Randy Butler (FHWA Operations), Taylor Lochrane (FHWA R&D), Robert Sheehan (RITA/ITS JPO), James Sturrock (FHWA Resource Center), Chung Tran (FHWA Resource Center), Eric Pihl (FHWA Resource Center), for their review and comments.

DMA and DCM Programs: Kate Hartman (DMA Program Manager), Ben McKeever (FHWA R&D, MMITSS Lead), Bob Ferlis (FHWA R&D), Bob Rupert (FHWA Operations, EnableATIS Lead), Brian Cronin (RITA/ITS JPO), Carl Andersen (FHWA), Dale Thompson (RITA/ITS JPO, DCM Program Manager), Gabe Guevara (FHWA Operations), Gene McHale (FHWA R&D), Linda Dodge (RITA/ITS JPO, R.E.S.C.U.M.E. Lead), Mohammed Yousuf (FHWA R&D, INFLO Lead), Randy Butler (FRATIS Lead), Ron Boenau (FTA, IDTO Lead), Walter During (FHWA Operations, Policy Lead), and Suzanne Sloan (Volpe) for their feedback and support.

Noblis: Aaron Casey, Drennan Hicks, and Aretha Howard for formatting and 508-conversion of the report.

Table of Contents

List of Tables

List of Figures

Executive Summary

Analysis Modeling and Simulation (AMS) Testbeds 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 Dynamic Mobility Applications (DMA) and Active Transportation and Demand Management (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.

The purpose of this report is to document a preliminary plan for evaluating impacts of individual DMA applications, individual DMA bundles, and logical combinations of bundles and applications, and identifying conflicts and synergies for maximum benefit. Elements that are covered include:

- Key research questions and hypotheses that should be tested in the AMS Testbed
- Performance measures that underpin the hypotheses
- Description of analysis scenarios
- Key technology and market penetration assumptions
- Sensitivity analyses
- Results reporting

A companion document provides a preliminary plan for ATDM strategies. These plans are intended to assist AMS Testbed developers in preparing an overarching evaluation methodology as well as detailed analytical plans tailored to specific testbed locations and analytical approaches.

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	

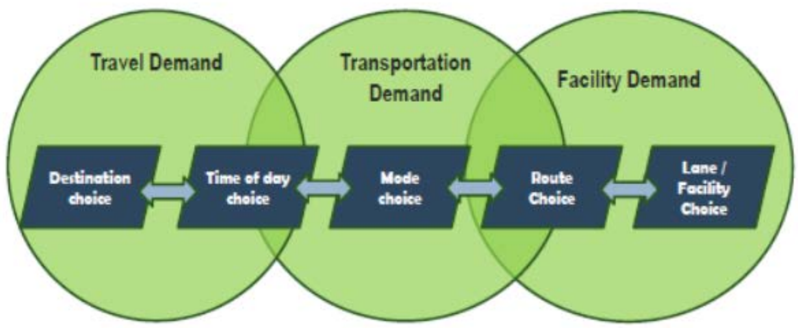

Figure 1-1: Trip Chain and Relation to Demand Activities [2]

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.

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

[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).

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 (this report)
- AMS Testbed Framework for DMA and ATDM Programs [6]
- 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 report is to document a preliminary plan for evaluating impacts of individual DMA applications, individual DMA bundles, and logical combinations of bundles and applications, and identifying conflicts and synergies for maximum benefit. Elements that are covered include:

- Key research questions and hypotheses that should be tested in the AMS Testbed
- Performance measures that underpin the hypotheses
- Description of analysis scenarios
- Key technology and market penetration assumptions
- Sensitivity analyses
- Results reporting

A companion document will provide a preliminary plan for ATDM strategies. These plans are intended to assist AMS Testbed developers in preparing an overarching evaluation methodology as well as detailed analytical plans tailored to specific testbed locations and analytical approaches.

2 Key Research Questions and Hypotheses

This section identifies key research questions that the DMA Program expects will be addressed through the AMS Testbed development and evaluation activities. A corresponding set of key hypotheses that should be tested for the DMA Program using the AMS Testbed is presented. These research questions and hypotheses will guide the development of the rest of the components of the evaluation plan.

2.1 Key Research Questions

The DMA Program seeks 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, maximize the productivity of the system, and enhance the mobility of individuals within the system, while reducing negative environmental impacts and safety risks.

Multiple efforts have been initiated by the DMA Program to assess the impacts of individual bundles. The DMA Program will seek suitably tested and promising application bundles from the six high priority bundles for possible inclusion in a larger scale pilot deployment operational test. The DMA Program has now reached a stage where the mobility impacts of a regional deployment of multiple bundles can be estimated in a simulation environment.

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. The DMA Analytical Roadmap provides ongoing and potential activities related to the development and application of analytical tools in support of the DMA Program (Appendix B).

The DMA Program expects the AMS Testbed effort to help address a number of key research questions, which are documented in Table 2-1.

Table 2-1: Table 2 1: Key DMA AMS Testbed Research Questions

ID	Research Question
I	**Connected Vehicle Technology vs. Legacy Systems**
1	Will DMA applications yield higher cost-effective gains in system efficiency and individual mobility, while reducing negative environmental impacts and safety risks, with wirelessly-connected vehicles, infrastructure, and travelers' mobile devices than with legacy systems? What is the marginal benefit if data from connected vehicle technology are augmented with data from legacy systems? What is the marginal benefit if data from legacy systems are augmented with data from connected vehicle technology?
II	**Synergies and Conflicts**
2	Are the DMA applications and bundles more beneficial when implemented in isolation or in combination?
3	What DMA applications, bundles, or combinations of bundles complement or conflict with each other?
4	Where can shared costs or cost-effective combinations be identified?
5	What are the tradeoffs between deployment costs and benefits for specific DMA bundles and combinations of bundles?
III	**Operational Conditions, Modes, Facility Types with Most Benefit**
6	What DMA bundles or combinations of bundles yield the most benefits for specific operational conditions?
7	Under what operational conditions are specific bundles the most beneficial?
8	Under what operational conditions do particular combinations of DMA bundles conflict with each other?
9	Which DMA bundle or combinations of bundles will be most beneficial for certain modes and under what operational conditions?
10	Which DMA bundle or combinations of bundles will be most beneficial for certain facility types (freeway, transit, arterial) and under what operational conditions?
11	Which DMA bundle or combinations of bundles will have the most benefits for individual facilities versus system-wide deployment versus region-wide deployment and under what operational conditions?
12	Are the benefits or negative impacts from these bundles or combinations of bundles disproportionately distributed by facility, mode or other sub-element of the network under specific operational conditions?
IV	**Messaging Protocols**
13	Is SAE J2735 BSM Part 1[4] transmitted via Dedicated Short Range Communications (DSRC) every 10^{th} of a second critical for the effectiveness of the DMA bundles? Will alternate messaging protocols, such as Probe Data Message (PDM), Basic Mobility Messages (BMM), etc., suffice? Given a set of specific messages, what combinations of bundles have the most benefit? Conversely, given a specific combination of bundles, what messages best support this combination?

ID	Research Question
14	To what extent are messaging by pedestrians, pre-trip and en route(e.g., transit riders) travelers critical to the impact of individual bundles or combinations of bundles? Does this criticality vary by operational condition?
V	**Communications Technology**
15	Will a nomadic device[2] that is capable of communicating via both DSRC as well as cellular meet the needs of the DMA bundles? When is DSRC needed and when will cellular suffice?
VI	**Communications Latency and Errors**
16	What are the impacts of communication latency on benefits?
17	How effective are the DMA bundles when there are errors or loss in communication?
VII	**RSE/DSRC Footprint**
18	What are the benefits of widespread deployment of DSRC-based RSEs compared with ubiquitous cellular coverage?
19	Which technology or combination of technologies best supports the DMA bundles in terms of benefit-cost analysis?
VIII	**Prediction and Active Management Investment**
20	Can new applications that yield transformative benefits be deployed without a commensurate investment in prediction and active management (reduced control latency)? How cost-effective are DMA bundles when coupled with prediction and active management?
IX	**Deployment Readiness**
21	To what extent are connected vehicle data beyond BSM Part 1 instrumental to realizing a near-term implementation of DMA applications? What specific vehicle data are the most critical, and under what operational conditions?
22	At what levels of market penetration of connected vehicle technology do the DMA bundles (collectively or independently) become effective?
23	What are the impacts of future deployments of the DMA bundles in the near, mid, and long term (varying market penetration, RSE deployment density, and other connected vehicle assumptions)?
X	**Policy**
24	In simulating different policy conditions (such as availability of PII versus no PII), what are the operational implications? For example, what are the incremental values to certain applications of knowing travel itineraries in real-time versus with some delay (i.e., 1-5 minutes)?
25	To what level are applications dependent upon agency/entity participation to deliver optimal results? What happens to the effectiveness of an application if, for example, local agency participation varies within a regional deployment?

[2] A nomadic device is a device that can be carried by a single person throughout a complete door-to-door trip, including pedestrian, transit and private vehicle modes. The device function can vary throughout the trip.

ID	Research Question
26	What are the variations if an application is set up to deliver system-optimal results versus user-optimal results? At what level of user "opt-in" does an application succeed/fail to deliver anticipated benefits, particularly to off-set costs, if costs are associated with it?
27	How sensitive are individual applications to the availability (or lack thereof) of data from multiple sources/agencies?
28	What type of data are necessary from non-transportation entities (for instance, hospitals or weather)? What data, and/or levels of participation by these entities would be required/optimal?
29	What are the benefits to benefits to participants versus non-participants?

2.2 Key Hypotheses

Each research question has a corresponding hypothesis that will be tested in an AMS Testbed. Table 2-2 presents the hypotheses and a mapping of each hypothesis to a research question. The table also shows the AMS Testbed technical approaches that might be suitable for testing the hypothesis.

The four AMS Testbed technical approaches that follow the AMS Testbed Framework [6] are the following:

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 2-2: Key DMA AMS Testbed Hypotheses

ID	Research Question Category	Hypothesis	Research Question ID	Strategic Traveler Behavior Focus	Tactical Traveler Behavior Focus	Multi-Resolution Modeling Approach	Communications/ Management Latency Focus
1	Connected Vehicle Technology vs. Legacy Systems	Compared to legacy systems, DMA applications that make use of new forms of wirelessly-connected vehicle, infrastructure, and mobile device data will yield cost-effective gains in system efficiency and individual mobility, while reducing negative environmental impacts and safety risks.	1	⦿	⦿	⦿	⦿
2	Synergies and Conflicts	DMA bundles that are synergistic will be more beneficial when implemented in combination than in isolation.	2	⦿	⦿	⦿	⦿
3	Synergies and Conflicts	Certain DMA applications, bundles, or combinations of bundles will complement each other resulting in increased benefits, while others will conflict with each other resulting in no benefits or reduced benefits.	3	⦿	⦿	⦿	⦿
4	Synergies and Conflicts	Bundles that are highly synergistic will have shared connected vehicle technology deployment costs .	4	⦿	⦿	⦿	⦿
5	Synergies and Conflicts	Incremental increase in deployment will result in higher benefit-cost ratio up to a certain deployment cost threshold, after which benefit-cost ratio will reduce.	5	⦿	⦿	⦿	⦿

6	Operational Conditions, Modes, Facility Types with Most Benefit	Certain DMA bundles or combinations of bundles will yield the highest benefits under specific operational conditions. For example, a combination of R.E.S.C.U.M.E and EnableATIS will have greater impact on days with high-demand and incidents than a combination of FRATIS and EnableATIS.	6	◉	◉	◉	◉
7	Operational Conditions, Modes, Facility Types with Most Benefit	A DMA bundle will yield the highest benefits only under certain operational conditions. For example, on non-incident days, R.E.S.C.U.M.E. will have limited impact.	7	◉	◉	◉	◉
8	Operational Conditions, Modes, Facility Types with Most Benefit	Certain combinations of bundles will conflict with each other under specific operational conditions, resulting in no benefits or reduced benefits.	8	◉	◉	◉	◉
9	Operational Conditions, Modes, Facility Types with Most Benefit	Certain DMA bundles or combinations of bundles will yield the highest benefits for specific modes and under certain operational conditions.	9, 25	◉	◉	◉	◉
10	Operational Conditions, Modes, Facility Types with Most Benefit	Certain DMA bundles or combinations of bundles will yield the highest benefits for specific facility types and under certain operational conditions.	10, 25	◉	◉	◉	◉
11	Operational Conditions, Modes, Facility Types with Most Benefit	Certain synergistic DMA bundles will yield the most benefits when deployed together on individual facilities rather than as system-wide or region-wide deployments and under certain operational conditions.	11	◉	◉	◉	◉

12	Operational Conditions, Modes, Facility Types with Most Benefit	Certain synergistic DMA bundles will yield the most benefits when deployed together on a system rather than as facility-specific or region-wide deployments and under certain operational conditions.	11	◉	◉	◉	◉
13	Operational Conditions, Modes, Facility Types with Most Benefit	Certain synergistic DMA bundles will yield the most benefits when deployed together in a region rather than as facility-specific or system-wide deployments and under certain operational conditions.	11	◉	◉	◉	◉
14	Operational Conditions, Modes, Facility Types with Most Benefit	Benefits or negative impacts from bundles will be unevenly distributed by facility, mode or other sub-element of the network.	12	◉	◉	◉	◉
15	Messaging Protocols	BSM Part 1 data transmitted every 10th of a second via DSRC is not critical for the effectiveness of DMA applications, with the exception of CACC.	13	○	○	○	●
16	Messaging Protocols	DMA bundles will be more effective with alternate messaging protocols in addition to BSM Part 1.	13	○	○	○	●
17	Messaging Protocols	Bundles that most significantly influence or are impacted by travelers' trip making decisions (EnableATIS, IDTO) or pedestrian movements (MMITSS, R.E.S.C.U.M.E.) will have the most critical need for messaging by pedestrians, and pre-trip and en route travelers. This criticality will vary by operational condition.	14	○	○	○	●

18	Communications Technology	Nomadic devices that are capable of communicating via both DSRC as well as cellular will meet most of the needs of the DMA applications; however, additional data from the infrastructure will be required for DMA applications to be effective.	15	○	○	○	●
19	Communications Technology	DMA applications, with the exception of component applications of the INFLO and MMITSS bundles, will not need data to be transmitted via DSRC as higher-latency communications media (e.g., cellular) will suffice.	15	○	○	○	●
20	Communications Latency and Errors	As communication latency increases, benefits will decrease. Most significant decrease will be observed for MMITSS and INFLO than for the other bundles.	16	○	○	○	●
21	Communications Latency and Errors	Effectiveness of some DMA bundles will be more impacted than others due to errors or loss in communication. MMITSS and INLFO will be most impacted by errors or loss in communication.	17	○	○	○	●
22	RSE/DSRC Footprint	In comparison to widespread cellular coverage, widespread deployment of DSRC-based RSEs will be excessive for DMA bundles.	18	○	○	○	●
23	RSE/DSRC Footprint	Concentrated deployment of DSRC-based RSEs will be more cost-beneficial in highly congested urban areas than in non-urban or low to moderate congested urban areas.	18	○	○	○	●

24	RSE/DSRC Footprint	More cost-effective benefits will be observed when connected vehicles transmit and receive messages using dual mode communications (e.g., both DSRC and cellular).	19	○	○	○	●
25	Prediction and Active Management Investment	DMA bundles (individually and in combination) will be more cost-effective only when coupled with prediction and active management.	20	⦿	⦿	⦿	●
26	Deployment Readiness	BSM Part 1 sent via DSRC is critical only to CACC; however other DMA applications will also need some elements of BSM Part 1 (i.e., position, speed, and acceleration) to be effective even in the near term. This is valid for all operational conditions.	21	○	○	○	●
27	Deployment Readiness	Benefits will increase with increase in market penetration of connected vehicle technology; some bundles will yield significant benefits even at lower market penetration levels.	22, 25	⦿	⦿	⦿	⦿
28	Deployment Readiness	Bundles that influence traveler decision-making and leverage widely deployed mobile device technology, such as EnableATIS, FRATIS, and IDTO, will yield measureable but geographically diffused system-level impacts under near-term deployment assumptions.	23, 25	⦿	⦿	⦿	⦿

29	Deployment Readiness	Bundles that influence tactical driver decision-making and depend on emerging localized low-latency messaging concepts, e.g., MMITSS, Q-WARN and SPD-HARM, will yield measureable localized benefits in urban areas under near-term deployment assumptions, but limited system-level impacts until market penetration of connected vehicle technology reaches bundle-specific thresholds.	23, 25	⦿	⦿	⦿	●
30	Policy	Effectiveness of some DMA bundles will be more impacted than others due to availability of PII. Bundles that influence traveler decision-making, such as EnableATIS, FRATIS, and IDTO, will be most impacted with availability of PII versus no PII.	24	⦿	⦿	⦿	⦿
31	Policy	Effectiveness of DMA bundles will be impacted by the lack of participation by local agencies/entities.	25	⦿	⦿	⦿	⦿
32	Policy	Incremental increases in number of “opt-in” users will result in higher benefit-cost ratio for certain DMA bundles up to a certain opt-in user threshold, after which benefit-cost ratio will be reduced.	26	⦿	⦿	⦿	⦿
33	Policy	Effectiveness of DMA bundles will be impacted by the lack of multi-source data from different agencies.	27	⦿	⦿	⦿	⦿
34	Policy	Effectiveness of DMA bundles cannot be examined to the full extent without some data from non-transportation entities (e.g., weather data).	28	⦿	⦿	⦿	⦿

35	Policy	Participants and non-participants will both experience benefits.	29	◉	◉	◉	◉

● - Applicable ◉ - Partially applicable ○ - Not applicable

3 Key Performance Measures

This section identifies key performance measures that are common to all six DMA bundles and component applications. Each DMA bundle, as part of the Concept Development and Needs Identification effort, has identified bundle-specific performance measures, which were first vetted by bundle-specific stakeholders and later at the Mobility Workshop held May 2012 (see Appendix A).

The AMS Testbed development effort will assess the impacts of individual bundles and applications as well as combinations of synergistic bundles and applications on multiple testbeds. The bundle-specific performance measures reveal the primary impacts of the bundle. In addition, it is essential to define system-level measures that are application or bundle-independent. Defining such measures provides a level playing field when examining what combinations of applications are most effective in concert with one another to improve overall system performance. Also, such measures provide a level playing field for an analysis of market adoption rates of connected vehicle technology. For example, an analysis may be done to determine the market adoption rate before a measurable system-level impact can be expected.

All analytical experimentation conducted in support of DMA objectives should at a minimum examine the following three key system-level, application-independent performance mobility measures [5]:

- **Travel Time Reliability**: Travel time reliability is a measure of the consistency or dependability in travel times experienced by a traveler making the same trip over many days and operational conditions [6]. The FHWA Office of Operations has recommended four measures to characterize travel time reliability (i) 90th or 95th percentile travel time, (ii) buffer index, (iii) planning time index, and (iv) frequency that congestion exceeds some expected threshold.
- **Delay:** Delay is defined as the travel time in excess of some subjective minimum travel time threshold [7]. Typically, discussions of delay focus solely on roadway-only travel and delays are estimated with respect to travel times at posted speeds or 85th percentile speeds. Delays should be computed across all modes and by both vehicles and persons.
- **Reliable Throughput:** Reliable throughput is defined as traveler trips or traveler miles delivered reliably by the system [5]. Typically, throughput is defined as a point measure. Traveler trips and miles traveled (without considering reliability) are often ineffective measures when differentiating a well-managed system and a poorly managed system . For example, a twenty-mile trip completed in 25 minutes counts equally with the same twenty-mile trip completed in one hour. Reliable traveler trips should be computed as the total number of trips with travel times less than or equal to the 95th percentile travel time for that trip. Reliable traveler miles delivered should be computed as the total miles traveled on the reliable trips.

In 2010, the DMA Program sponsored the development of an open source performance measurement application, (the DMA Performance Measurement Application, DMA-PMA) that estimates the above mode-independent performance measures [8]. The application was developed by making use of trip-based system performance measure algorithms developed as part of the USDOT's Integrated Corridor Management (ICM) Program and adapting them for use with observed data to measure impact in mobility and productivity. The algorithms developed under ICM, estimate key measures of corridor performance (delay, travel time reliability, and throughput) from time-variant traffic simulation outputs. The software code for the performance measurement application will be released through the DMA Program's Open Source Application Development Portal (OSADP), and is available for use and or modification by analysts and developers.

Performance measures in addition to those mentioned in the bundle-specific Concept of Operations and the three application-independent system-level measures may be identified when detailed testbed-specific analysis plans are developed.

4 Analysis Scenarios

This section discusses analysis scenarios. Each analysis scenario is a combination of a specific operational condition and an alternative being examined.

4.1 Operational Conditions

It is essential to identify under what travel or operational conditions an application might be most beneficial to facilitate a System Manager's decision-making process as to what application or collection of applications to deploy. As hypothesized earlier in section 2, a DMA bundle may not yield similar benefits under all operational conditions. Some DMA bundles may be more valuable than others depending on the operational condition. For example, for an incident scenario R.E.S.C.U.M.E. may be more valuable than the other bundles in improving incident response time; and EnableATIS may be more valuable than the other bundles in improving traveler reliability. Secondly, operational conditions do not have the same probability of occurrence. Some may occur more frequently than others, and these may vary by site. Knowledge of operational conditions that will occur most frequently will be helpful to the System Manager in deciding to what application or collection of applications to focus on.

Prior to selection of testbed sites it might be necessary to identify a few key operational conditions that should be examined for a DMA bundle. However, the specific operational conditions that should be modeled for a testbed site should be driven by the data. For example, the evaluation of the R.E.S.C.U.M.E bundle requires the modeling and simulation of incident conditions. The validity of models used to evaluate incident conditions are much stronger if field data associated with real incident conditions are used in operational condition development. A purely hypothetical incident case could be used as a last resort, but since this condition was not seen in observed data, it has limited value in characterizing annualized benefit.

Appendix C presents two data-driven approaches suggested for grouping the days based on similar travel or operational conditions - one that makes use of a pre-determined bins (Option 1: Pre-Determined Binning) and another that makes use of cluster analysis to identify the bins or clusters (Option 2: Cluster Analysis). The preferred option is Option 2, which uses cluster analysis.

4.2 Baseline/Do-Nothing Alternative

The baseline or the Do-Nothing alternative describes the current state of the testbed site being modeled. The baseline should be modeled to reveal potential improvements that can be realized by deploying DMA bundles or applications at the site. The delta from the baseline helps identify the most effective bundles/applications for the site, and provides quantitative and or qualitative evidence of the value of investing in DMA bundles and applications to decision-makers and stakeholders that have a vested interest in the site.

Modeling the baseline also helps other areas and agencies recognize the range of benefits that is possible through DMA for possible future implementation in their areas. If the AMS Testbed is calibrated to an area that is either a progressive site and a front-runner among its peers or lagging behind its peers in ITS deployments, then it might become necessary to model a second Baseline or Do-State-of-the-Practice Alternative that describes a national state of the practice to capture the full extent of benefits that can be achieved. If resources and schedule permit, it is advisable to model a baseline for each operational condition that is observed at the site.

4.3 Alternatives

Alternatives should be defined based on the research questions being addressed at the testbed site and the operational conditions identified for the site. The parameters that should be examined include communication technology, predictive capability, active management, and applications. The parameters and the corresponding ranges should be tailored for each site and type of modeling approach used, and site-specific alternatives should be developed.

4.3.1 Communication Technology

As connected vehicle environment is agnostic to communications media, the DMA Program is interested in examining both short-range (e.g., DSRC) as well as long-range (e.g., 4G LTE) communications. The AMS Testbed should be capable of modeling a range of communications media, DSRC roadside equipment (RSE) network and wide-area wireless network, and examining the effectiveness of DMA applications and bundles for various types of communications media, RSE deployments, wide-area wireless coverage, and messages generated. The DMA Program Evaluation effort is tasked to develop deployment assumptions for connected vehicle technology over the next 30 years. If these assumptions are available at the time of conducting AMS activities, then those values or ranges need to be modeled as well.

Communications Media

The following communications media should be examined:

- DSRC: the device is capable of transmitting and receiving messages only via a DSRC network
- Cellular: the device is capable of transmitting and receiving messages only via a cellular network
- Dual Mode (DSRC + Cellular): the device is capable of transmitting and receiving messages via DSRC network or cellular, depending on what is available

RSE Footprint

The following RSE footprint should be examined (Note that if RSE deployment assumptions are available from the DMA Program Evaluation effort, those need to be modeled in lieu of what is presented below.):

- RSEs deployed at major signalized intersections and interchanges
- RSEs deployed at regular intervals on all major roadways
- RSEs deployed at regular intervals on all roadways

Wide-Area Wireless Coverage

The following wide-area wireless coverage should be examined:

- Ubiquitous coverage
- Coverage available only in non-urban canyon part of the network

Vehicle-Centric Messages Generated/Received

The messages generated by vehicle-centric communication devices (i.e., integrated or aftermarket devices) will depend on the device capability. Even if all vehicles with integrated or aftermarket devices are capable of generating SAE J2735 BSM, the content of the messages will vary by vehicle depending on the vehicle manufacturer since some of the data elements are optional. To accurately represent the mix of devices that will be available, the types of messages and frequency with which the messages are generated and received should be varied.

Capability of devices to generate messages should be varied as follows:

- All devices generate BSM Part 1
- All devices generate BSM Part 1 and Basic Mobility Message (BMM) (NOTE: the content of a BMM is still under investigation.)
- All devices generate BSM Part 1, and weather data (Possible weather data elements include: external ambient air temperature, road coefficient of friction, precipitation rate, snow or water depth on the roadway, barometric pressure, visibility.)
- All devices receive BSM Part 1 and weather data from other devices, and control messages from the System Manager

Capability of devices to receive messages should be varied as follows:

- All devices receive BSM Part 1 from other devices and control messages from the System Manager
- All devices receive BSM Part 1 and BMM from other devices, and control messages from the System Manager
- All devices receive BSM Part 1 and weather data from other devices, and control messages from the System Manager

Messages Generated /Received by Travelers' Mobile Devices

Capability of devices to generate messages should be varied as follows:

- All devices generate position and speed
- All devices generate position, speed, and itinerary data (Possible itinerary data include: origin, destination, departure time, desired arrival time, purpose, transit special request (e.g., need for bike rack, wheelchair).
- All devices are capable of receiving position and speed from other devices, and traveler and transit information from the System Manager.

Frequency of Message Generation by Vehicle-Centric Devices

The frequency with which messages are generated should be varied as follows:

- BSM Part 1 is generated every 10^{th} of second via DSRC or every 1 to 5 minutes via cellular
- BMM is generated every 1 to 5 minutes, via DSRC or cellular
- Weather data is generated every 1 to 5 minutes, via DSRC or cellular

Frequency of Message Generation by Travelers' Mobile Devices

The frequency with which messages are generated should be varied as follows:

- Position and speed are generated every 10^{th} of second via DSRC or every 1 to 5 minutes via cellular
- Itinerary data are generated every 1 to 5 minutes, via DSRC or cellular

In addition to the above, it may also be interesting to examine the effectiveness of the applications when devices that are modeled don't have uniform communications capability, i.e., the type of media used, the messages generated, and the frequency of message generation differ by device. In addition, depending on the communications model used, transmission range, latency of transmission, and loss or failure in communication may also be varied.

4.3.2 Predictive Capability

The AMS Testbed should be capable of modeling and examining the effectiveness of DMA applications and bundles for various types of prediction capabilities, including the time horizon over which prediction is performed, the speed and accuracy of prediction, and capability to predict System User behaviors. Depending on the type of modeling approach used for the System Manager Simulator (See AMS Testbed Framework), capability to predict System Managers' behaviors may also need to be modeled and varied.

Prediction Time Horizon

Time horizon may be varied as follows:

- Short-term (10 min)
- Mid-term (10-30 min)
- Long-term (>30 min)

Prediction Speed

Prediction speed may be varied as follows:

- Short lead time (< 5 min)
- Medium lead time (5 – 20 min)
- Long lead time (> 20 min)

Prediction Accuracy

Prediction accuracy may be varied as follows:

- Low (>50% error)
- Medium (10-50% error)
- High (<10% error)

System Users' Behavioral Prediction

Behavioral prediction capability may be varied as follows:

- None modeled
- Randomly assigned
- Behavioral models

4.3.3 Active Management Capability

The AMS Testbed should be capable of modeling and examining the effectiveness of DMA applications and bundles when combined with active management. Active management capability is a measure of latency between detection/prediction of traffic phenomena (including bottlenecks, queues, shockwaves, incidents, etc.) and dissemination of control or advisory information by System Managers to System Users (travelers and drivers).

Control latency may be varied as follows:

- Low (< 5 min)
- Medium (5-30 min)
- High (> 30 min)

4.3.4 DMA Applications

The AMS Testbed should be capable of modeling individual DMA applications and bundles. In addition, the AMS Testbed should be capable of modeling logical combinations of applications and bundles. Logical combinations may be identified as applications with common objectives. Identifying synergies between applications helps to not only assess the added benefit of combining applications but also prevents overestimating or underestimating benefits and costs, which is a common problem when examining applications only in isolation. For example, if a queue warning application is found to increase throughput by 20% and speed harmonization is also found to increase throughput by 20%, an agency cannot expect a 40% increase in throughput by implementing both queue warning and speed harmonization. A joint deployment of the two applications might for example yield only a 30% increase in throughput due to both applications being deployed on nearby facilities rather than on the same facility or a 50% increase due to simultaneous smoothing of traffic while enabling re-routing and lane re-positioning. Table 4-1shows a set of pre-analysis synergy hypotheses. A check mark implies expected or predicted synergy between the bundles in analysis. If synergy is observed between a bundle and a component application of another bundle, rather than the entire bundle, the application is listed in parenthesis.

Table 4-1: Hypothesized Synergistic Bundles/Applications

Bundle	EnableATIS	FRATIS	IDTO	INFLO	MMITSS	R.E.S.C.U.M.E.
EnableATIS		✓	✓	✓	✓	✓
FRATIS	✓			✓ (INFLO - Q-WARN)	✓ (MMITSS - FSP)	✓ (R.E.S.C.U.M.E. - EVAC)
IDTO	✓				✓ (MMITSS - TSP)	
INFLO	✓	✓ (INFLO – Q-WARN)			✓	✓ (INFLO – Q-WARN)
MMITSS	✓	✓ (MMITSS - FSP)	✓ (MMITSS - TSP)	✓		✓ (MMITSS - PED-SIG)
R.E.S.C.U.M.E.	✓	✓ (R.E.S.C.U.M.E. - EVAC)		✓ (INFLO - Q-WARN)	✓ (MMITSS - PED-SIG)	

5 Assumptions, Sensitivity Analyses, and Reporting

This section discusses assumptions, sensitivity analyses, and results reporting. From a portfolio of (expected) multiple analytical test beds and multiple experiments within each test bed, the DMA analyst must construct a defensible collective argument either supporting or rejecting the overarching DMA hypotheses. This will not be straightforward nor trivial. However, a systematic method must be developed that integrates results at differing scales from a variety of analytical tools to provide nuanced responses to the key DMA research questions.

Detailed micro-simulation tools may be required to identify primary impacts of applications influencing tactical driving behaviors. Different disaggregate tools may be required to capture the impact of applications influencing strategic traveler decision-making. The overarching evaluation methodology must address both the statistical significance comparing the same tool in multiple runs and operational conditions for two alternatives, as well as a logical approach for integrating results from different locations and tools to address key DMA hypotheses.

More detailed analysis plans leveraging the tools and data associated with the analytical effort must be prepared for each tool and testbed location in the overall plan. This section provides some guidance on the preparation of both the overarching evaluation method as well as the detailed testbed location-specific analysis plans.

5.1 Key Assumptions

It is critical to develop valid and realistic assumptions, as the analyses may result in benefits that are unachievable or unrealistic in the field.

Assumptions need to be developed for:

- **Market adoption rates of technologies**, including DSRC and non-DSRC based devices (i.e., vehicle-centric devices, RSEs). Assumptions on the level of vehicle automation may be necessary. A key overarching set of assumptions on technology adoption rates will made available from the DMA Program Evaluation effort.
- **Vehicle-centric devices**, including number of devices. These may be deduced from the market adoption rates.
- **Mobile devices**, including number of devices. These may be assumed to be higher for urban areas (close to 50%) than for non-urban areas.
- **Compliance rate of drivers (light, freight, transit)**. For example, a motorist may not comply with target speed recommendations, or a freight truck driver may take an alternate route due to an un-reported overturned vehicle on the freeway. These may be assumed to vary randomly by time of day and or by driver aggressiveness.

- **Infrastructure**, including number of sign gantries, DSRC-based Roadside Equipment, SPAT Controllers. Connected vehicle enabled infrastructure assumptions may be available from the DMA Program Evaluation effort. Sign gantries may be assumed to be deployed every half mile along freeway corridors in urban areas and every mile in non-urban areas.
- **Policy**, including assumptions for each application and bundle. These may be obtained from the individual bundle impacts assessment activities. For example can transit drivers alter route if there are road closures due to major incidents? How often will target speeds be changed? How often can a dispatcher alter freight plans?

5.1.1 Sensitivity Analyses

Sensitivity analyses helps to measure the impact of uncertainty in assumptions since these will affect the benefits/costs analyses, and ultimately the decisions made. In more detailed, testbed location-specific analysis plans to be developed, this section should identify the parameters corresponding to assumptions that will be varied.

5.1.2 Results Reporting

In more detailed, testbed location-specific analysis plans to be developed, this section should document the benefits/costs analyses of DMA bundles and applications. Benefit/cost ratio is useful in comparing the relative value of the applications.

Estimate Monetized Benefits

Benefits should be monetized for calculating the benefits/costs ratio. Monetization may be done using the federal government's standard guidance on monetizing benefits. Net Present Value (NPV) may be determined by applying discount rates as suggested in the Office of Management and Budget (OMB) Circular A-94.

Estimate Costs

Cost for each application should include, capital costs, operations and maintenance (O&M) costs, and replacement costs. The one-time capital cost for each application should include development, testing, and integration costs. Capital costs and O&M costs may be further disaggregated to include incremental costs (e.g., costs of incrementally adding an RSE). O&M costs should include items such as staffing, in addition to hardware and software costs. Appropriate service costs associated with use of commercial services, such as cellular, should also be included. Costs should not only be calculated for individual applications, but also for applications that are synergistic with common technology needs. For example, deployment of connected vehicle technology (such as RSE or vehicle-centric devices) may be treated as a joint cost across all connected vehicle applications rather than as a sunk cost. Thus, costs should calculated for individual applications, interdependent applications with common objectives, and interdependent applications with common technology needs.

Reporting

Parametric analysis, sensitivity analyses and probability models can play a key role to show tradeoffs between various types and levels of connected vehicle deployment and benefits/costs from specific DMA bundles. Results should be documented in table format as well as in graphical charts. There should be a clear link between the reporting and hypotheses that are tested. Given below are some illustrative charts that show the results while providing a visual confirmation of the hypotheses. Figure 5-1 shows the expected impact of connected vehicle market penetration and latency in communications on system delay, while providing a visual proof for hypotheses 11 and 12. Figure 5-2 shows the expected impact of connected vehicle market penetration and latency in communications on system delay for various communication media and messages, while validating hypotheses 6 through 10. Figure 5-3 shows the bundle that has the most significant impact for a specific operational condition, providing visual proof for hypotheses 3 and 4. Similar charts should be developed, and existing ones presented below should be modified with actual results.

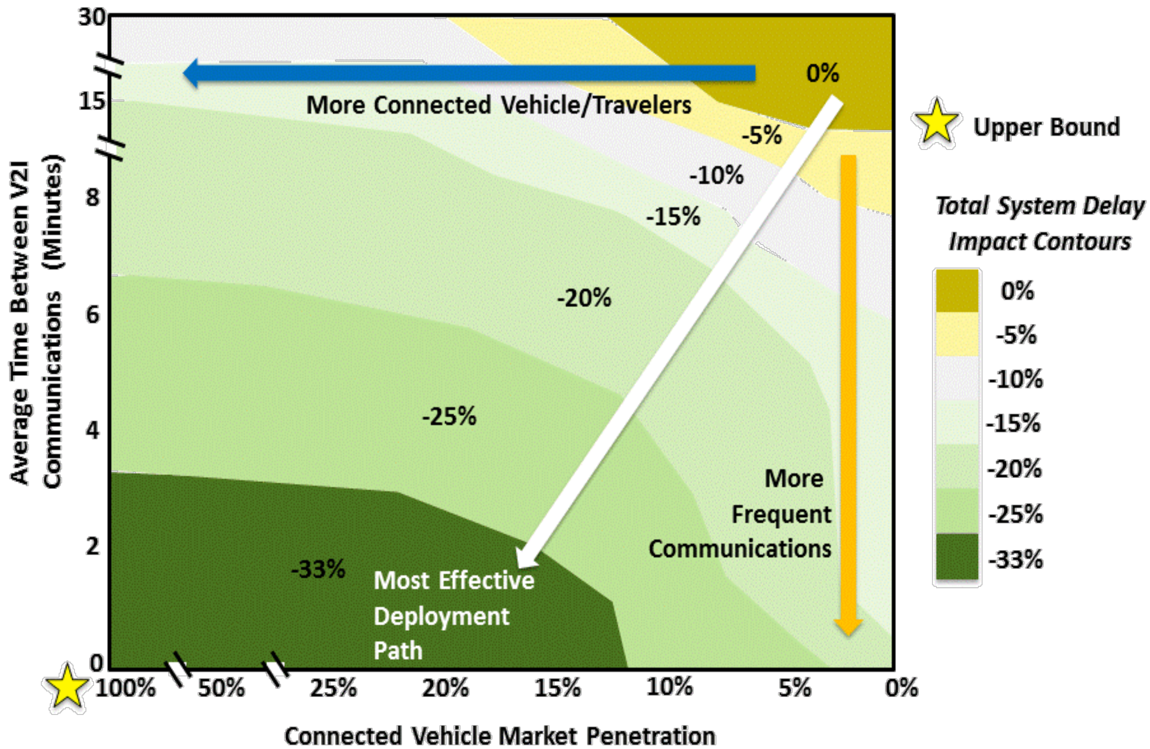

Figure 5-1: What the AMS Testbed Can Reveal: Effect of Connected Vehicle Market Penetration and Communications Latency on System Delay

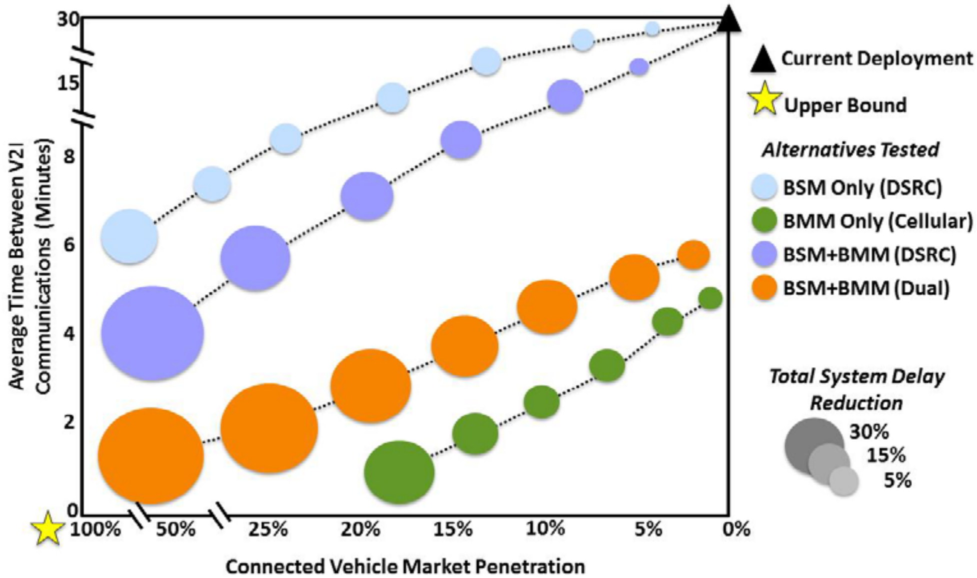

Figure 5-2: What the AMS Testbed Can Reveal: Effect of Connected Vehicle Market Penetration and Communications Latency on System Delay for Alternative Messaging Protocols

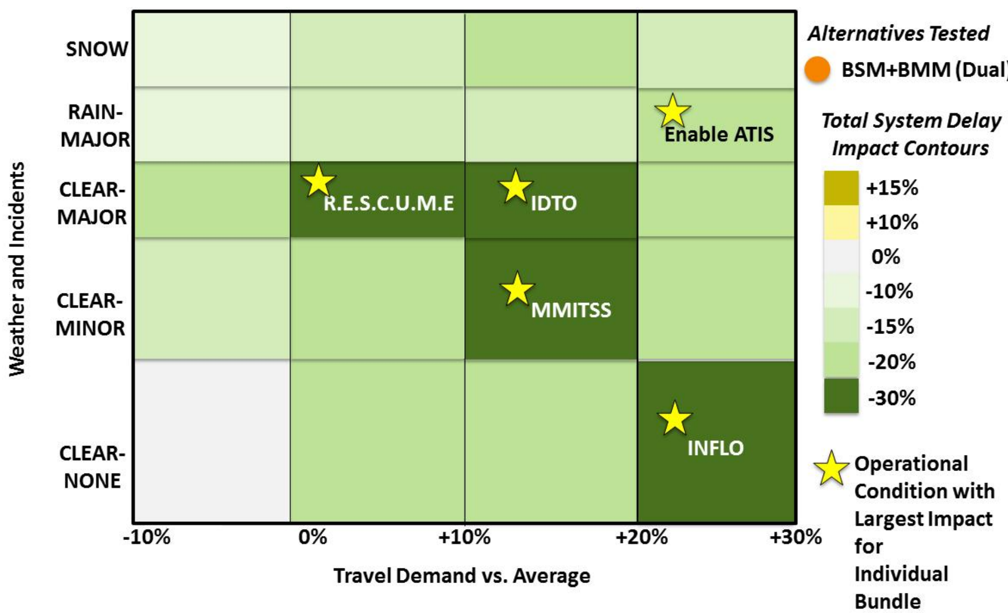

Figure 5-3: What the AMS Testbed Can Reveal: Under What Operational Conditions is Alternative Most Effective

References

1. Active Transportation and Demand Management, http://www.ops.fhwa.dot.gov/atdm/approaches/index.htm, <accessed March 11, 2013>.

2. Yelchuru, B., Singuluri, S., and S. Rajiwade. ATDM Analysis, Modeling, and Simulation (AMS) Concept of Operations (CONOPS): Final Report (DRAFT), Prepared by Booz Allen Hamilton for the Federal Highway Administration, FHWA-JPO-13-020, December 31, 2012.

3. Dynamic Mobility Applications Program, http://www.its.dot.gov/dma/index.htm, <accessed March 10, 2013>.

4. Wunderlich, K, Vasudevan, M, and T. Sandelius. Analysis, Modeling, and Simulation (AMS) Testbed Requirements for Dynamic Mobility Applications (DMA) and Active Transportation and Demand Management (ATDM) Programs, Prepared by Noblis for USDOT, FHWA-JPO-13-098, November 2013.

5. Vasudevan, M, and K. Wunderlich. Analysis, Modeling, and Simulation (AMS) Testbed Preliminary Evaluation Plan for Dynamic Mobility Applications (DMA) Program, Prepared by Noblis for USDOT, FHWA-JPO-13-097, November 2013.

6. Vasudevan, M, and K. Wunderlich. Analysis, Modeling, and Simulation (AMS) Testbed Framework for Dynamic Mobility Applications (DMA) and Active Transportation and Demand Management (ATDM) Programs, Prepared by Noblis for USDOT, FHWA-JPO-13-095, November 2013.

7. Shah, V., Vasudevan, M, and R. Glassco. Analysis, Modeling, and Simulation (AMS) Testbed Initial Screening Report, Prepared by Noblis for USDOT, FHWA-JPO-13-094, November 2013.

8. Society of Automotive Engineers (SAE) standard J2735, Dedicated Short Range Communications (DSRC) Message Set Dictionary, November 2009.

9. Wunderlich, K., INTEGRATED CORRIDOR MANAGEMENT (ICM) PROGRAM: CALCULATING MULTI-MODAL CORRIDOR PERFORMANCE MEASURES FROM SIMULATION OUTPUTS, Proceedings of the 18th World Congress on Intelligent Transportation Systems, October 2011, Orlando, Florida, TS118-1334.

10. Federal Highway Administration. Traffic Congestion and Reliability: Trends and Strategies for Advanced Mitigation, prepared by the Cambridge Systematics and Texas Transportation Institute for the Federal Highway Administration, September 2005.

11. Dowling, R. Traffic Analysis Toolbox Volume VI: Definition, Interpretation, And Calculation Of Traffic Analysis Tools Measures of Effectiveness, Prepared by Prepared by Cambridge Systematics, FHWA-HOP-08-054, January 2007

12. Vasudevan, M., Larkin, J., and K. Wunderlich. Performance Measurement Application for the Dynamic Mobility Applications Program: Software Guidelines (FINAL), Prepared by Noblis for USDOT, March 16, 2012.

13. MATLAB: The Language of Technical Computing, The MathWorks Inc., http://www.mathworks.com/products/matlab/.

14. WEKA, The University of Waikato, New Zealand, http://www.cs.waikato.ac.nz/ml/weka/.

15. Alexiadis, V., Sallman, D., and A. Armstrong. Traffic Analysis Toolbox Volume XIII: Integrated Corridor Management Analysis, Modeling, and Simulation Guide, Prepared by Cambridge Systematics, FHWA-JPO-12-074, May 2012.

16. Kittelson, W., and Vandehey, M. SHRP2 Project L08 – Incorporation of Travel Time Reliability into the Highway Capacity Manual, Draft Final Report, September 2012.

APPENDIX A. Key Performance Measures and 10-Year Targets for DMA Bundles

Table A-1: Key Performance Measures and 10-Year Targets for EnableATIS

Performance Measure	10-Year Target
Multi-modal end-to-end trip planning information (time of departure, cost, mode, route, parking) integrated with search results	Common for major metropolitan areas
Corridor or regional transportation management systems utilizing systematically obtained traveler trip data	Emerging state-of-practice (one or more)
Predictability and reliability of travel	Total unanticipated late arrivals reduced by 50%

Table A-2: Key Performance Measures and 10-Year Targets for FRATIS

Performance Measure	10-Year Target
Travel time	Reduce by 17%
Fuel consumption	Reduce by 10%
Level of criteria pollutants and greenhouse gas equivalents	Reduce by 10%
Number of bobtail trips	Reduce by 15%
Terminal queue time	Reduce by 35%
Number of freight-involved incidents (e.g., bridge strikes)	Reduce by 35%
Number of weight-compliance infractions (Percentage of vehicles over legal gross weight limit)	Reduce by 20%

Table A-3: Key Performance Measures and 10-Year Targets for IDTO

Application	Performance Measure	10-Year Target
T-CONNECT	Percentage of successful connections involving more than one agency	Increase to 95%
	Percentage of successful connections involving more than one mode	Increase to 95%
	Percentage of successful connections involving fixed and flexible modes	Increase to 90%
T-DISP	Duration of time from making a request to receiving a trip confirmation	Approximately 45 seconds
	Duration of time between passenger pickup and trip confirmation	
	Percentage of no shows and cancellations	
D-RIDE	Passenger waiting time	Reduce to 10 minutes or less
	Percentage of ride matches to requests	
	Number of riders per vehicle	

Table A-4. Key Performance Measures and 10-Year Targets for INFLO

Application	Performance Measure	10-Year Target
SPD-HARM	Number of shockwaves formed	Reduce by 25%
	Length of formed shockwaves	Reduce by 25%
	Propagation speed of formed shockwaves (backwards)	Reduce by 25%
	Compliance rate of posted or recommended speed limit	75% compliance
	Variability (spread) of speeds within traffic stream (in-lane, between-lane, and over time)	1 standard deviation of traffic speeds are within 2 mph of average stream speed
	Average travel time (delay)	Reduce by 10%
	Travel time reliability (buffer or planning time index)	Reduce by 25%
	Ratings on public opinion surveys	75% positive ratings of system
	Number of primary crashes	Reduce by 25%
	Severity of crashes	Reduce by 25%
	Number of secondary crashes	Reduce by 50%
	Level of CO_2 (equivalent) emissions	Reduce by 25%
	Amount of energy consumed (MPG/fuel efficiency)	Reduce by 25%
	Cost of SPD-HARM infrastructure and related systems construction	Reduce by 25%
	Cost of SPD-HARM infrastructure and related systems operations and maintenance	Reduce by 25%
Q-WARN	Number of secondary crashes at fixed queue point locations	Reduce by 50%
	Number of secondary crashes at non-fixed queue point locations	Reduce by 50%

Application	Performance Measure	10-Year Target
Q-WARN	Severity of crashes	Reduce by 25%
	Length (distance) of formed queues at variable locations	Reduce by 50%
	Duration of formed queues at variable locations	Reduce by 50%
	Number of shockwaves formed	Reduce by 25%
	Length of formed shockwaves	Reduce by 25%
	Propagation speed of formed shockwaves (backwards)	Reduce by 25%
	Ratings on public opinion surveys	75% positive ratings of system
	Number of false positive queue detection alerts	5% rate of false positive queue detection alerts
	Number of non-detected queue events	10% rate of non-detected queue events
	Cost of Q-WARN infrastructure and related systems construction	Reduce by 25%
	Cost of Q-WARN infrastructure and related systems operations and maintenance	Reduce by 25%
CACC	Vehicles per hour	50% increase
	Average vehicle headways	25% decrease
	Number of shockwaves formed	Reduce by 25%
	Length of formed shockwaves	Reduce by 25%
	Propagation speed of formed shockwaves (backwards)	Reduce by 25%
	Variability (spread) of speeds within traffic stream (in-lane, between-lane, and over time)	1 standard deviation of traffic speeds are within 2 mph of average stream speed
	Average travel time (delay)	Reduce by 10%
	Travel time reliability (buffer or planning time index)	Reduce by 25%
	Ratings on public opinion surveys	75% positive ratings of system
	Number of primary crashes	Reduce by 25%
	Severity of crashes	Reduce by 25%
	Number of secondary crashes	Reduce by 50%
	Level of CO_2 (equivalent) emissions	Reduce by 25%
	Amount of energy consumed (MPG/fuel efficiency)	Reduce by 25%
	Cost of ATM infrastructure and related systems construction	Reduce by 25%
	Cost of ATM infrastructure and related systems operations and maintenance	Reduce by 25%

Table A-4: Key Performance Measures and 10-Year Targets for MMITSS

Performance Measure	10-Year Target
Overall Vehicle Delay	Reduce by 25%
Throughput	Increase by 15%
Queue Length	Reduce by 15%
Average Pedestrian Wait Time	Reduce by 20%
Average Transit Delay	Reduce by 35%
Average Commercial Vehicle Delay	Reduce by 15%
Average Emergency Vehicle Delay	Reduce by 40%
Extent of System-Wide Congestion (i.e., failure to clear queue in a cycle)	Reduce by 25%
Duration of System-Wide Congestion	Reduce by 40%

Table A-5: Key Performance Measures and 10-Year Targets for R.E.S.C.U.M.E.

Performance Measure	10-Year Target
Duration of Response to a Traffic Incident (overall incident clearance time)	Reduce Total Response Time by 30%
Responders to vehicle incidents will be provided with comprehensive information regarding the incident prior to dispatch (incident dynamics, condition of the victims, materials involved, etc.)	Increase the amount of comprehensive information available by 25%
Number of incidents where additional equipment and/or responders post-first responder arrival need to be dispatched due to on-scene triage (i.e., secondary dispatch)	Reduce Secondary dispatch events by 20%
Equipment staging impact on travel conditions (e.g., throughput, delay)	Reduce congestion as measured by throughput and delay times by 20%
En-route time for responders during congested conditions	Improve En-Route travel times by 10%
Number of incidents involving on-scene emergency responders	Reduce secondary incidents by 15%
Number of incidents involving construction and maintenance staff	Reduce primary incidents by 15%
Number of secondary incidents due to congestion	Secondary incidents will be reduced by 15%
System throughput (end-to-end throughput of the system, not just a specific facility)	End-to-End system throughput will be maintained during severe traffic incidents
Ability to employ dynamic dispatching and routing of available resources (e.g., vehicles) across agencies during an evacuation	Use of mixed agency vehicles for evacuation of special needs population will be widespread
Evacuation time needed for all persons, including special needs populations	Reduce total evacuation time for large-scale populations by 25%

APPENDIX B. DMA Analytical Roadmap

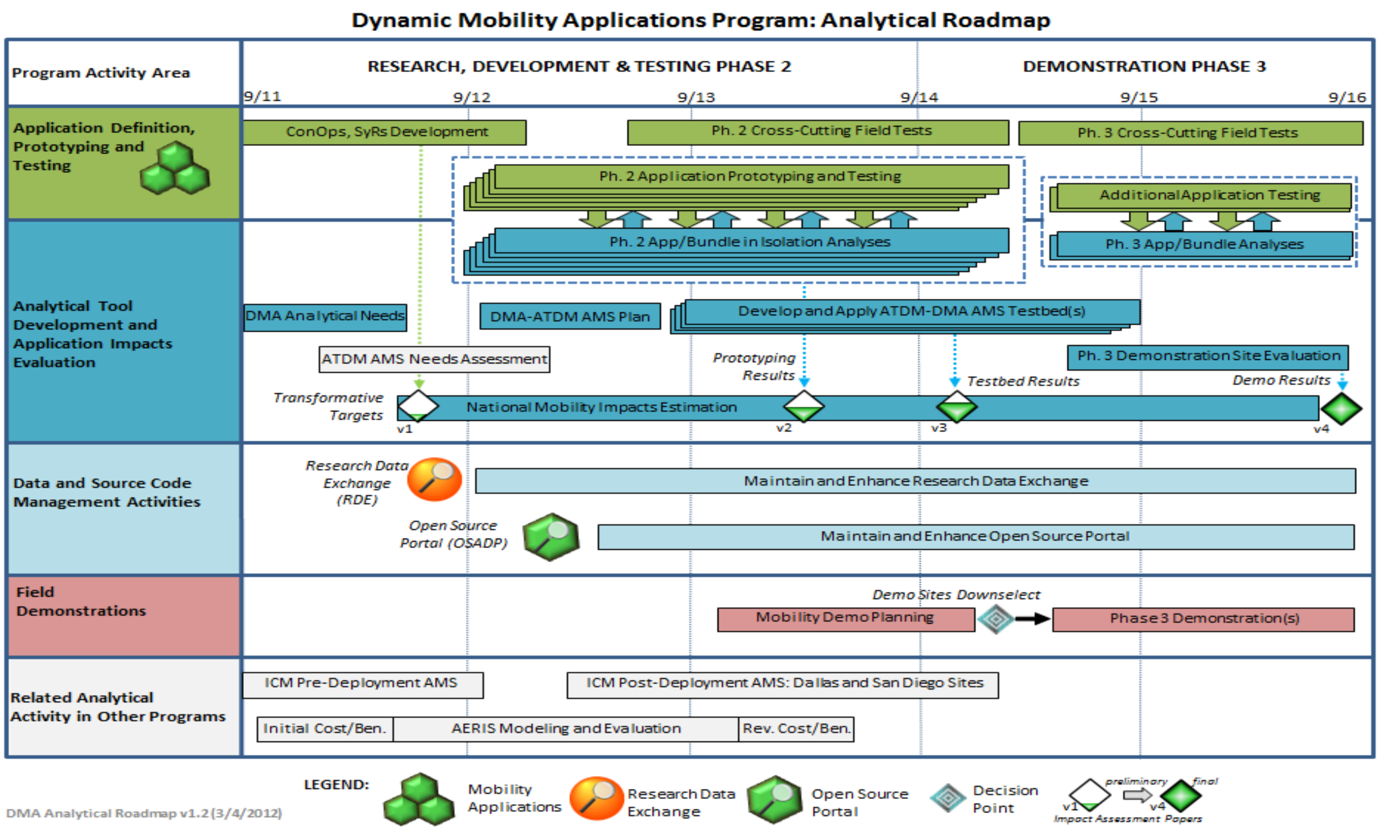

Figure B-1: Dynamic Mobility Applications Program: Analytical Roadmap

APPENDIX C. Technical Approaches to Identifying Operational Conditions

This section presents two data-driven approaches are suggested for grouping the days based on similar travel or operational conditions - one that makes use of a pre-determined bins (Option 1: Pre-Determined Binning) and another that makes use of cluster analysis to identify the bins or clusters (Option 2: Cluster Analysis). The preferred option is Option 2, which uses cluster analysis.

Option 1: Pre-Determined Binning Approach

This approach makes use of pre-determined groups based on operational conditions identified by the analyst in the data. In this approach the analyst identifies factors, which are revealed by the data, that influence the operational or travel conditions at the site; defines bins or groups of operational conditions; and assigns days into different bins or groups. An **example approach** for grouping days into pre-determined bins is given below

Step 1: Data Assembly and Influencing Factors Identification

The goal of this step is to assemble and analyze data to determine the factors that will influence operational conditions for the site. The example below assumes the presence of inclement weather and incidents in the data.

<u>Demand</u>: Screenline counts or volumes may be used. If only BSM or probe data messages are available, without supplementary traffic sensor data, GPS traces, or OD data from Bluetooth sensors, license plate readers, etc., then the total number of messages generated may be used as a surrogate for traffic demand. This is because as demand or congestion increases, the number of messages generated increases. These measures may be calculated for the entire network or the principal corridors. Averages should be calculated for each day; these may be averages for the entire day, or just the peak periods, depending on the goals of the analysis. If the analysis includes an assessment of the FRATIS or IDTO bundle, then in addition to calculating the traffic demand for each day, it is also necessary to calculate the dray orders or transit ridership for each day.

<u>Weather</u>: Contextual weather data, including precipitation, rain, wind, etc., may be obtained from: http://www.weather.gov. Average or maximum (worst case) precipitation levels and wind speed should be calculated for the entire network or region as a whole for each day. These may be averages or the maximum for the entire day, or just the peak periods, depending on the goals of the analysis.

<u>Incident</u>: Incident reports should be available from each site's state department of transportation. Incidents may be classified in the incident databases by day, location, time (notification, arrival, and clearance), type (e.g., debris, non-injury collision, injury collision, disabled), and impacted lanes (e.g., single lane, multiple Lanes, shoulder, HOV, total closure).

Step 2: Bin Definition

The goal of this step is to define bins. In our example, each bin is defined as a combination of a specific congestion index (measure of level of demand), weather index (measure of level of disruption due to weather), and incident index (measure of level of disruption due to incident). Hence, the total number of bins is the product of the number of congestion indices, number of weather indices, and number of incident indices. Although examples are provided on how indices might be chosen, the number and definitions of indices should be identified based on the data. It is critical to not choose too many indices to avoid the problem of several nearly empty bins. Having a limited number of days in a bin will not produce statistically significant results. If there are too many indices, an option is to develop a composite index that combines disruption due to weather and incident (supply disruption index).

<u>Congestion Index</u>: Example congestion indices for each day could be as follows:

1. Low demand
2. Medium demand
3. High demand

<u>Weather Index</u>: Analyze data to identify the types and severity of adverse weather that are experienced by the site. Example weather indices could be as follows:

0. Clear, sunny day
1. Low impact due to weather (e.g., precipitation of < 0.25” or fog)
2. Medium impact due to weather (e.g., precipitation of >= 0.25” and < 0.5”)
3. High impact due to weather (e.g., blowing snow, precipitation of >= 0.5”)

NOTE: The text in parenthesis are examples. The definitions should be based on the observed data. For example, if the region experiences very little rain and no snow, then two indices may be sufficient (0 and 1).

<u>Incident Index</u>: Analyze data to identify the types and severity of incidents experienced by the site. Example incident indices could be as follows:

1. No incidents
2. Low impact (e.g., non-blocking incidents, vehicle on shoulder)
3. Medium impact (e.g., single blocked lanes, police activity for non-blocking incident)
4. High impact (e.g., all or multiple blocked lanes, single blocked lane with police activity)

NOTE: The text in parenthesis are examples. The definitions should be based on the observed data. If the site has only 2 types of incidents, the indices would be 0, 1, and 2.

In the example above, we defined 3 congestion indices, 4 weather indices, and 4 incident indices, resulting in a total of 48 bins (3 x 4 x 4).

Step 3: Grouping Days

The goal of this step is to group days into bins defined in Step 2. In the example, we have defined 48 bins. If the analyst discovers that some of the bins have limited number of days, then the bins should be re-defined so that the number of values that an index can assume is reduced or the number of indices are reduced by defining composite indices as mentioned previously.

Option 2: Cluster Analysis Approach

In this option, an external template of bins is not imposed on the data; rather cluster analysis is used to identify the number and composition of clusters that minimize variation within each cluster (i.e., between component days in a cluster) and maximize variation between clusters.

As a first step, the analyst should assemble the data using the process described in Step 1 under Option 1. Once the data are assembled, cluster analysis may be performed over all days using cluster analysis algorithms or a statistical package that offers cluster analysis. Examples of statistical and data mining tools that offer cluster analysis are the commercial tool, MATLAB [9], or the open source data mining software, WEKA (Waikato Environment for Knowledge Analysis) [10].

The ICM Program [11] and the SHRP 2 L08 effort [12] have developed approaches for identifying operational conditions and their associated probabilities of occurrence. Similar approaches may also be used when developing the AMS Testbed.

APPENDIX D. List of Acronyms

Table D-1: List of Acronyms

Acronym	Name
AMS	Analysis Modeling and Simulation
ATDM	Active Transportation and Demand Management
ATIS	Advanced Traveler Information Systems
ATM	Advanced Traffic Management
BMM	Basic Mobility Message
BSM	Basic Safety Message
CACC	Cooperative Adaptive Cruise Control
CO2	Carbon Dioxide
DMA	Dynamic Mobility Applications
PMA	Performance Measurement Application
DOT	Department of Transportation
DRG	Dynamic Routing of Vehicles
D-RIDE	Dynamic Ridesharing
DR-OPT	Drayage Optimization
DSRC	Dedicated Short Range Communications
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
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRATIS	Freight Advanced Traveler Information Systems
FSP	Freight Signal Priority
FTA	Federal Transit Administration
GPS	Global Positioning System
HOV	High-Occupancy Vehicle
ICM	Next Generation Integrated Corridor Management
IDTO	Integrated Dynamic Transit Operations
INC-ZONE	Incident Scene Workzone Alerts for Drivers and Workers
INFLO	Intelligent Network Flow Optimization
I-SIG	Intelligent Traffic Signal System
ITS	Intelligent Transportation Systems
JPO	Joint Program Office
LTE	Long Term Evolution
MATLAB	Statistical and data mining tool that offers cluster analysis
MAYDAY	Mayday Relay
MDSS	Maintenance Decision Support System
MMITSS	Multi-Modal Intelligent Traffic Signal System
NHTSA	National Highway Traffic Safety Administration
NPV	Net Present Value
OMB	Office of Management and Budget

Acronym	Name
OSADP	Open Source Application Development Portal
PDM	Probe Data Message
PED-SIG	Mobile Accessible Pedestrian Signal System
PII	Personally Identifiable Information
PREEMPT	Emergency Vehicle Priority
Q-WARN	Queue Warning
R.E.S.C.U.M.E	Response, Emergency Staging and Communications, Uniform Management
RESP-STG	Incident Scene Pre-Arrival Staging and Guidance for Emergency Responders
RITA	Research and Innovative Technology Administration
RSE	Roadside Equipment
SAE	Society of Automotive Engineers
SHRP2	Strategic Highway Research Program
SPaT	Signal Phasing and Timing
SPD-HARM	Dynamic Speed Harmonization
T-CONNECT	Connection Protection
T-DISP	Dynamic Transit Operations
T-MAP	Universal Map Application
TMC	Transportation Management Center
TSP	Transit Signal Priority
USDOT	U.S. Department of Transportation
USDOT	United States Department of Transportation
VMT	Vehicle Miles Traveled
WEKA	Waikato Environment for Knowledge Analysis
WX-INFO	Real-Time Route Specific Weather Information for Motorized and Non-Motorized Vehicles
WX-INFO	Real-Time Route Specific Weather
WX-MDSS	Enhanced MDSS Communication

U.S. Department of Transportation
ITS Joint Program Office-HOIT
1200 New Jersey Avenue, SE
Washington, DC 20590

Toll-Free "Help Line" 866-367-7487
www.its.dot.gov

FHWA-JPO-13-096

U.S. Department of Transportation
Research and Innovative Technology Administration