Dynamic Mobility Applications Analytical Needs Assessment

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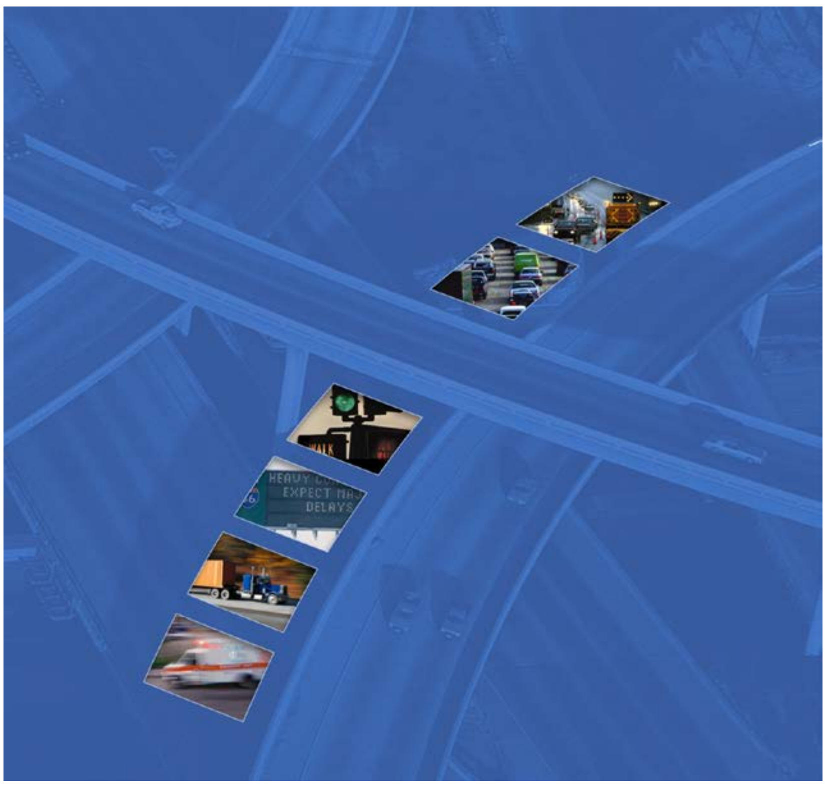

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16. Abstract

Dynamic Mobility Applications Analytical Needs Assessment was a one-year project (July 2011 to July 2012) to develop a strategy for assessing the potential impact of twenty-eight applications for improved mobility across national transportation systems. The purpose was to outline a modeling approach for each application that can be implemented that would allow federal stakeholders to determine the potential benefits of investing in a particular application or group of applications. This project was conducted by Science Applications International Corporation (SAIC), with technical support from the Civil Engineering Department of the University of Virginia (UVA). This document presents the final report of the DMA project, to include an overview of the applications, their data, performance measures and modeling needs, an assessment of current transportation analytics capabilities, a traceability matrix for each application to highlight the gaps between existing capabilities and modeling needs, identified challenges for the implementation of impact assessments, a recommended modeling approach for each application, and finally a research implementation plan and summary of findings.

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Table of Contents

List of Tables

List of Figures

Executive Summary

The Federal Highway Administration's Office of Operations, Research and Development is considering investment in various Dynamic Mobility Applications and requested assistance in the impact assessment of each application being considered, as well as several bundles of applications. The purpose of this report is to identify the gaps and challenges that might hinder implementation and to propose a high-level modeling approach for each application. Twenty-eight applications, grouped into six different bundles, are considered in this report, which outlines a multi-scale modeling approach for use in future impact assessments.

The report consists of nine sections that address existing knowledge and capabilities, known gaps and challenges, and recommended approaches for modeling, collective impact assessment, and implementation.

Objectives

The first section introduces the Dynamic Mobility Applications program, which seeks to apply Connected Vehicle technologies to transportation operations to improve safety, mobility and environmental performance. In 2009, congestion alone cost Americans $115 billion for the 4.8 billion hours of wasted time. The level of cost and wasted time due to congestion are both up 35 and 26 percent, respectively, from the previous decade and will continue to climb unless the transportation system sees enormous improvements. Implementing these high priority applications could be a major component of this improvement, and the subsequent sections (i) review each application and their data, performance measures, and modeling needs assessment; (ii) assess the transportation analytics capabilities, including available modeling tools and current practices; (iii) outline traceability assessment matrices; (iv) describe the potential challenges implied by the gaps; (v) recommend an approach for modeling each application and for collective impact assessment; and, finally, (vi) outline a research implementation plan and summary of findings.

It should be clearly noted that model development, implementation and assessment were outside the scope of this work, but can be accomplished in future projects using the recommendations provided in this report.

Challenges

In Sections 2 through 5, the project team examined the analytical needs for each application and investigated the analytic capabilities of modeling tools to support analytical needs. This project dealt with a variety of modeling tools, including sketch, macroscopic, mesoscopic, microscopic, activity-based and hybrid modeling tools.

From the revealed analytical capability and needs for each tool, the project team built a traceability assessment matrix of each application. These matrices facilitated the identification of gaps between existing capabilities and future needs for successful implementation of the models. The most notable gaps and challenges identified included:

- **Handling individual vehicles**. The most crucial modeling element, but many of the larger-scale tools are unable to handle this component.
- **Separating the traveler from the vehicles**. Only two of the existing modeling tools have attempted this, and both lack the microscopic modeling fidelity. Consequently, there is a need to combine these agent-based demand modeling tools with microscopic traffic simulation software.
- **Modeling traveler behavior**. This includes route selection, mode choice, and driver compliance rates. It is critical for precise impact assessment of the applications, but existing modeling tools require customized enhancement to accommodate the traveler models.
- **Handling wireless communication performance.** The Connected Vehicle technologies utilized in these applications are dependent upon wireless communication. Consequently, the ability to model wireless performance is crucial for assessing the impact of each application, however; no modeling tools are currently able to handle the wireless communication performance precisely. An additional module must be developed to estimate the real-time performance.
- **Multi-scale modeling.** Microscopic modeling tools are identified as most suitable for almost all of the dynamic mobility applications, however; this does not consider the larger network impact. To overcome this challenge will require the simultaneous integration of agent-based traveler behavior tools with multi-level traffic modeling tools. There is an urgent need to integrate activity-based models with a multi-level vehicle modeling framework.
- **Microscopic vehicle movement behavior.** The modeling of vehicle longitudinal and lateral movement behavior within microscopic traffic simulation tools must be enhanced to allow for the capture of unique vehicle capabilities and their interaction with in-vehicle systems.

Solutions

In Section 6, the project team proposed modeling approaches for the evaluation of each dynamic mobility application based on their analytic needs and modeling capabilities; almost every application is therefore tied to multiple approaches, tied together in a multi-scale modeling approach. These recommendations lean heavily on microscopic modeling because of the precision in handling vehicle movement in real-time as well as the ability to incorporate external modules such as APIs and plug-ins, making it much more versatile than larger scales. However, because microscopic approaches do not capture large scale impacts, the project team proposes the incorporation of activity-based modeling tools in order to assess these impacts effectively. The report also overviews alternative modeling approaches, which in many cases capture impacts omitted by microsimulation, but also point to functional limitations such as the inability to model individual vehicle trajectories. Section 7 then outlines an approach for collective impact assessment, in which the applications and bundles are considered in parallel to determine how implementation of multiple applications could have positive or negative impacts. For each bundle, Section 7 maps out the data feeds between applications to give a clear picture of how the inputs and outputs of each application facilitate the implementation of other applications.

- In Sections 8 and 9, the project team outlined a research implementation plan and a summary of findings. The most important components of future work in this area will be (1) government leadership of studies needed on traveler behavior models and Connected Vehicle environments, and (2) vendor/developer cooperation via open source development to facilitate the necessary customization of modeling tools for both impact assessment and implementation. The lack of adequate data and modeling capabilities underpin all of the gaps and challenges identified by this report, and only with coordinated and cooperative efforts will these be alleviated. Background studies on traveler behavior models are needed to provide modeling tools with inputs on decision making behavior in response to information provided by the application. These studies must be overseen by public officials to ensure a high level of quality and reliability. Similarly, the Connected Vehicle data needed to model these applications requires public financial and administrative support because these efforts are being coordinated by the government to ensure a high standard of safety is maintained.

1. Introduction

Traffic congestion in major cities in the United States is becoming worse, resulting in reduced mobility, more energy consumption, and higher emissions. Unless such congestion is adequately controlled and/or mitigated, the transportation system could become a key barrier for economic growth/recovery and a threat to quality of life. Astoundingly, Americans spent 4.8 billion hours of extra time and 3.9 billion gallons of extra gas due to congestion in 2009; an increase of 26 and 30 percent, respectively compared to the previous decade. Nationwide, the United States wasted about $115 billion due to congestion, a 35 percent increase from the previous decade. In addition, transportation accounted for about 30 percent of all carbon-dioxide emissions (EPA, 2007). Recognizing that this is a harmful situation that threatens public safety and health, the U.S. Department of Transportation (USDOT) has leveraged advanced technologies to improve the efficiencies of existing transportation systems. The recent Connected Vehicles initiative (formerly known as IntelliDrive), incorporates wireless vehicular networking technology to enhance dynamic mobility and to achieve sustainable transportation efficiencies.

The Dynamic Mobility Applications program, powered by Connected Vehicles and travelers, seeks to take full advantage of high-quality, integrated, multi-source data to support multiple applications at various network levels (e.g., arterial, freeway, corridor, regional networks) for multiple modes (e.g., freight, transit, passenger cars). In an effort to take full advantage of Connected Vehicle technology, US DOT identified high-priority dynamic mobility applications comprising six bundles that include 21 applications.

The purpose of this project is to assess those high priority dynamic mobility applications' analytical needs. This project completed (i) the review of dynamic mobility applications and their data, performance measures, and modeling needs assessment; (ii) the assessment of transportation analytics capabilities, including available modeling tools and their current practices; (iii) the traceability assessment matrices; (iv) the description of potential challenges implied by the gaps; (v) a recommended modeling approach for each application and collective impact assessment; and (vi) the research implementation plan and summary.

2. Applications, Performance Measures, Data Requirements and Modeling Needs

2.1. Description of Applications

Descriptions of the priority applications and the information sources for each are provided below. A brief description of the function of the analytical tool required for the application is also provided.

2.1.1. Enabling Advanced Traveler Information Services (Enable ATIS) Bundle

2.1.1.1. Multimodal Real-Time Traveler Information (ATIS)

This application includes information from users, information from Connected Vehicles and pedestrians, information from multiple modes of transportation, and from multiple methods of information collection, processing, and delivery. The intent is to enable travelers to make better decisions based on more accurate and reliable traveler information. ATIS will develop the best routes and expected trip times using real-time and predicted information. It will include parking information, real-time route-specific weather information, information for non-motorized modes (e.g., bicycle and walk), pricing information for travel options, and user-created information (e.g., intended destinations, experiences encountered en route).

Thus, the application will enhance information traditionally collected from point and probe traffic sensors with connected traveler information for all travel modes and with origin and destination information when available.

<u>Application Example:</u>

Under the ATIS application, traffic information covering roadway congestion, incidents, bus and metro schedules, route-specific weather conditions, and parking facility availability is collected by multiple data-collection sources, including Connected Vehicles, TMCs, transit agencies, and parking facilities. With the collected traffic information, the ATIS application provides travelers with proper route guidance information corresponding to their traveler modes such as passenger car, bus, metro, bicycle, and walk.

Passenger car drivers will receive real-time route information and anticipated arrival time to their destination. To implement the route guidance, the ATIS application will implement an algorithm calculating the best route based on roadway congestion information, incident information, and parking facility information from both Connected Vehicles and a local TMC. Based on a driver's compliance with the guidance, the driver will either accept or deny the route guidance information.

Similarly, other mode users will receive the guide and determine their choice (i.e., accept or decline). For example, for the bus and metro passengers, the ATIS application provides the best transit routes incorporating both bus and metro routes and the transfers between the modes. Based on the objectives of guidance, the guidance information will be generated to minimize travel time, travel fare, or the number of transfers. Passengers will either accept or deny the provided guidance information based on their compliance.

Bicyclists and pedestrians will receive route-specific weather information and guidance on mode shift (e.g., bicycle to transit or auto, walk to bicycle). The decisions will be made by their compliance with the provided guidance information.

The performance of the ATIS application can be determined by measuring not only the travel time reliability but also travel time savings for each mode, throughputs, and fuel saving and emissions reductions.

Sources:
Updated Descriptions on USDOT High Priority Dynamic Mobility Applications (August 10, 2011)
http://www.its.dot.gov/presentations/MW_Mobility_Breakout_files/slide0306.htm

Function of Analytical Tools:

Traffic flow for all vehicle classes and pedestrians will be simulated. Measures will be computed. Diversion fractions (for which research is required) will be used to model traveler response to information. Errors in information-gathering devices will be modeled.

2.1.1.2. Smart Park-and-Ride (S-PARK)

S-PARK will develop information on the predicted availability of parking spaces for park-and-ride facilities, and will provide this information to motorists along with connecting transit departure times. When lots are full or predicted to be full at the time of the vehicle's arrival, it will provide parking information at alternate transit stops. It will provide for coordinated transit schedule operation and will support parking reservation services. Information will be provided to the motorist using hands-free, voice recognition.

Application Example:

An example of S-Park application will track in-and-out of park-and-ride parking facilities and estimate new arrivals based on information available from opted-in navigation system. In addition, S-Park will advise drivers based on the estimated travel times and user costs between auto-only trips and park-and-ride trips. Algorithms will estimate/predict travel times and user costs from current vehicle location to destination with and without transit. User compliance should be modeled and dynamic route guidance, including transit modes, should be used.

Source:
http://www.its.dot.gov/presentations/MW_Corridor_Breakout_files/slide0261.htm

Function of Analytical Tools:

S-PARK will model parking facility utilization and will predict the number of available parking spaces for future time periods. It will develop message classes for motorists. Diversion fractions (for which research is required) will model incremental demands on the parking facilities. Algorithms estimating/predicting travel times and user costs from current vehicle location to destination with and without transit use are needed.

2.1.1.3. Universal Map Application (T-MAP)

This application combines information on transit vehicle locations with real time traffic information and such highway-related information as maintenance locations and detours. It is supported by information from transit CAD/AVL systems and the Connected Vehicle technology. It incorporates incidents, detours, street closures and other data on transit map applications. Transit agencies provide vehicle locations, passenger amenities, and service level to agencies scheduling street repairs or other road closures.

Application Example:

T-MAP, based on an open map concept, will integrate transit locations and roadway anomalies, such as incidents and road closures, on a universal map. Thus, T-MAP will support transit operators' scheduling and travelers' transfers. In addition, T-MAP will help automobile travelers avoid congested areas (stemming from incidents or road closures).

Source:
http://www.its.dot.gov/presentations/MW_Regional_Breakout_files/slide0269.htm

Function of Analytical Tools:

The analytical tools will model diversion fractions (for which research is required) resulting from the use of T-MAP. Route guidance algorithms for avoiding congested areas and transferring to other modes are needed.

2.1.1.4. Real-Time Route-Specific Weather Information (WX-INFO)

WX-INFO gathers and fuses data from radar, satellites, conventional surface sources, and connected passenger vehicles and trucks. It provides highly localized information to the traveling public, freight haulers, EMS responders, and highway maintenance personnel about the following conditions:

- Snow and ice
- Slick roads and low visibility
- Fog, smoke, billowing dust
- High winds
- Thunderstorms, hail, tornadoes
- Hurricanes
- Wildfires

Application Example:

WX-INFO application will use weather information obtained from various sources (e.g., Clarus, Connected Vehicle technology, etc.) and will provide travelers with advanced warning about icy or slippery roads near bridges/tunnels and about alternative routes that do not have road blocks due to heavy snows/rains. In addition, WX-INFO will need to fuse multiple sources of data, including in-vehicle sensors (e.g., speeds of wipers), Clarus data, etc. It will also share road surface information with infrastructure management systems so that traffic signal settings can be adjusted according to weather conditions, which will help develop better route guidance to travelers.

Source:

Chapman, M. and S. Drobot, *Concept of Operations for the Use of Connected Vehicle Data in Road Weather Applications,* FHWA, JPO, December 21, 2011

Function of Analytical Tools:

Weather conditions should be modeled to reflect the impact of weather on traffic, especially drivers' route selection compliance as well as driving behavior (on slippery roads). Advanced route guidance algorithms that reflect weather impacts affecting pre-trip decisions, including the change of departure time and mode shift, need to be developed and implemented.

2.1.2. Intelligent Network Flow Optimization (INFLO) Bundle

2.1.2.1. Queue Warning (Q-WARN)

Q-WARN monitors traffic to identify the presence and location of a stopped or slowly moving queue and provides this information to motorists. It is expected to reduce rear-end collisions, reduce late-stage lane changing, and facilitate diversion. It will assist emergency service providers by identifying routes that may be inaccessible. Using Connected Vehicle information, Q-WARN predicts queue formation and shock wave propagation. It will reduce dangerous and late-stage lane-changing, and may be implemented in conjunction with speed harmonization to provide target speeds by lane in approaching a congested area.

Application Example:

The Q-WARN application provides real-time queue information at intersections and freeways to travelers. Given the queue warning information, travelers will decide whether or not they will follow the warning information based on their compliance behavior. If travelers accept the queue warning, they will change their driving behavior (e.g., deceleration and/or lane changing) to avoid any potential unsafe situation.

The queue information can be captured in real-time by either Connected Vehicles or stationary traffic surveillance sensors, such as loop detectors or video cameras operated by local TMCs. The queue warning message can be disseminated through Connected Vehicles, VMS, and broadcastings.

Sources:

Updated Descriptions on USDOT High Priority Dynamic Mobility Applications (August 10, 2011)

http://www.its.dot.gov/presentations/MW_Freeway_Breakout_files/slide0241.htm

Function of Analytical Tools:

The analytical tool will model the propagation characteristics of queues resulting from incidents or recurrent congestion. Speed changes, lane changes, and diversion resulting from messages will be modeled. Research is required to establish motorist response relationships. This application will be applied at local intersections or freeway corridors.

2.1.2.2. Dynamic Speed Harmonization (SPD-HARM)

SPD-HARM provides a target speed for lanes that optimizes flow based on traffic and weather information. In the event of incidents, the target speed provides safe passage approaching incident sites and extending through them. The target speed may be advisory or enforced and may address both recurrent and non-recurrent congestion. Communication may be through overhead dynamic signs or with vehicle based displays through infrastructure-to-vehicle (I2V) and vehicle-to-vehicle (V2V) communications. It may be applicable to freeways and arterials. Research on alterations in vehicle-following behavior may be required.

Application Example:

The SPD-HARM application provides travelers with dynamic speed advisory information to keep optimal traffic flow conditions for freeways and corridors under both recurrent and non-recurrent congestion incurred by incidents and/or work-zones. Real-time traffic conditions can be captured via multiple data sources, including Connected Vehicles and traffic monitoring facilities such as video cameras and loop detectors operated by local TMCs.

The advisory information can be disseminated through either Variable Message Signs (VMS) or Connected Vehicle technology in real-time. Based on drivers' travel behaviors, the advisory information can be either accepted or denied. Once the drivers accept the speed advisory messages, they will manipulate their vehicles to meet the provided speed before they enter congestion areas.

Sources:

Updated Descriptions on USDOT High Priority Dynamic Mobility Applications (August 10, 2011)

http://www.its.dot.gov/presentations/MW_Prod_Breakout_files/slide0268.htm

Function of Analytical Tools:

The functions are similar to those for Q-WARN.

2.1.2.3. Cooperative Adaptive Cruise Control (CACC)

There are three ways in which CACC can be implemented. First, CACC can be implemented as a V2V application, wherein the leader informs the follower of its location, speed, and acceleration, allowing the follower to follow the leader safely at a shorter gap. The follower can safely and quickly respond to speed changes by the leading vehicles, thereby reducing the risk of rear-end collisions.

CACC can also be implemented as an I2V application, wherein a traffic manager sets a gap policy to keep traffic flow at or below the road capacity to prevent flow breakdown. Speeds will be automatically adjusted by the vehicle based on communications from the traffic management center. Speeds and gaps will be adjusted by vehicle weight and performance. Finally, it can be implemented as an *ad hoc* platooning concept, wherein several vehicles form a “platoon” that behaves as a single unit. Strategies accommodate the weight and performance characteristics of different vehicles. CACC may be applicable to freeways and arterials.

Application Example:

CACC enables leading and following vehicles equipped with proper V2V communication devices on the same lane to keep shorter time headways (e.g., 1-second or less) while they cruise at high speeds (e.g., 60 MPH or higher). The real-time driving information (e.g., position, speed, and acceleration/deceleration rates) of each vehicle will be shared among the Connected Vehicles by using V2V wireless communications. Optimal driving maneuvers to maintain headway will be cooperatively generated based on the driving information of both leading and following vehicles.

Sources:
Updated Descriptions on USDOT High Priority Dynamic Mobility Applications (August 10, 2011)
http://www.its.dot.gov/presentations/MW_Prod_Breakout_files/slide0288.htm

Function of Analytical Tools:

The analytical tool will be able to model various CACC control strategies for Connected Vehicles by using an external module. A new function will be required to deal with the behaviors of the drivers of equipped vehicles in response to the control strategies.

2.1.3. Multi-Modal Intelligent Traffic Signal System (M-ISIG) Bundle

2.1.3.1. Intelligent Traffic Signal System (ISIG)

This application will make use of high-fidelity data collected from vehicles through wireless communications to predict accurately lane-specific platoon flow, platoon size, and other characteristics. It will also consider transit vehicles, pedestrians, and freight vehicles in designing signal timing plans. New systems that use vehicle-derived data via V2V and V2I wireless communications to maximize flow in real-time can significantly improve traffic signal operations. The ISIG application also plays the role of an over-arching signal system optimization application, accommodating transit or freight signal priority, preemption, and pedestrian movements to maximize overall arterial network performance.

Application Example:

Real-time traveling information of each vehicle (e.g., passenger car, truck, and bus) containing onboard equipment (OBE) is collected through the Connected Vehicle environment. Once the information covering the position, speed, route, and characteristics of such equipped vehicles approaching an intersection is captured by roadside equipment (RSE) connected to an intelligent traffic signal controller, the ISIG application estimates the number of vehicles in a platoon, length of the platoon, and arrival and departure times of the platoon for each lane. With such estimated lane-specific platoon information, the traffic controller of the intersection finds an optimal signal phase operation in real-time to reduce the total delay time at the intersection.

Sources:

Updated Descriptions on USDOT High Priority Dynamic Mobility Applications (August 10, 2011)

http://www.its.dot.gov/presentations/MW_Env_Breakout_files/slide0273.htm

Function of Analytical Tools:

The analytical tool includes vehicle, pedestrian, and bicycle flows and their interactions. It accommodates transit and freight signal priority strategies. It includes objective functions for all traveler modes and an algorithm and solution approach to optimize real-time traffic signal control. A new function optimizes traffic signal control to improve network performance with consideration to all modes in case there exist competing requests from each mode.

2.1.3.2. Transit Signal Priority (TSP)

This application provides a mechanism by which transit vehicles equipped with on-board equipment can communicate information such as passenger count data, service type, door status, passenger stop requests, scheduled and actual arrival time, and heading information to roadside equipment via V2I and V2V communications. The application can better establish priority requirements among transit vehicles based on passenger loads and intersection arrival time. Connected Vehicle technology facilitates earlier detection of and communication with transit vehicles, and better position tracking.

Application Example:

Given a Connected Vehicle environment, traffic signal controllers equipped with RSE collect real-time transit vehicle information such as current position, speed, schedule, the number of passengers, and passenger stop requests from OBE-equipped transit vehicles (e.g., bus, tram, and taxi) through V2I communications. The collected information is used for estimating the arrival time of each transit vehicle, which enables an implementation of dynamic TSP logic. In addition, unlike existing TSP techniques that rely heavily on loop detectors, it will allow the development of advanced TSP logic based on the collected information by employing various control objectives (e.g., maximizing the passenger throughputs, minimizing passenger delay time, etc.).

Sources:

Updated Descriptions on USDOT High Priority Dynamic Mobility Applications (August 10, 2011)

http://www.its.dot.gov/presentations/MW_Mobility_Breakout_files/slide0312.htm

Function of Analytical Tools:

TSP functions are already included in ISIG modeling requirements.

2.1.3.3. Mobile Accessible Pedestrian Signal System (PED-SIG)

PED-SIG integrates information from roadside or intersection sensors and new forms of data from wirelessly connected pedestrian-carried mobile devices. It wirelessly communicates with the traffic signal controller to obtain real-time signal phase and timing (SPaT) information that will be used to inform the visually impaired pedestrian as to when to cross and how to remain aligned with the crosswalk. The application will allow an “automated pedestrian call” to be sent to the traffic controller from the smart phone of registered blind users after confirming the direction and orientation of the roadway that the pedestrian is intending to cross. By extending similar pedestrian detection to all pedestrians, PED-SIG can provide data to enable pedestrian demand to serve as a signal timing optimization measure. It can also make enabled vehicles aware that a pedestrian is present in the case of blocked line-of-sight.

Application Example:

The PED-SIG application enables a visually impaired pedestrian who possesses a mobile device that enables two-way wireless communications from/to traffic signal controllers to cross intersections safely. By monitoring signals from the pedestrian mobile device in real-time, a traffic signal controller equipped with an RSE can detect pedestrians' approach to the intersection and estimate their arrival times. When pedestrian calls requested from the pedestrian mobile devices are detected, the controller estimates the time required for the pedestrian to safely cross the intersection such that it minimizes the potential disruptions of the signal operations for motorists. The application disseminates the safe crossing time to the pedestrians through mobile devices by using both visual and auditory messages while broadcasting a warning message to vehicles equipped to receive the message alerting them to the presence of pedestrians at the intersection to avoid any potential crashes.

Sources:

Updated Descriptions on USDOT High Priority Dynamic Mobility Applications (August 10, 2011)

http://www.its.dot.gov/presentations/MW_SafSec_Breakout_files/slide0319.htm

Function of Analytical Tools:

From a modeling perspective, PED-SIG is a component of ISIG. The fraction of pedestrians equipped with calling devices is a parameter to be included.

2.1.3.4. Emergency Vehicle Preemption (PREEMPT)

This application replaces existing emergency vehicle preemption equipment with V2Vand V2I communication systems. The application adjudicates preemption requests among competing emergency vehicles and adjusts signal recovery cycles accordingly. It provides information concerning the path requirements for emergency vehicles to other highway users. When coupled with improved emergency vehicle routing strategies, it will better coordinate the preemption of appropriate signal phases with the arrival time of the emergency vehicle at the intersection. PREEMPT provides proximity warnings to Connected Vehicles as the emergency vehicle traverses the facility.

Application Example:

Under an emergency condition, an OBE-equipped emergency vehicle (EV) disseminates an Emergency Vehicle Preemption Call messages along with its driving information such as position, speed, route, and destination. Once an RSE-equipped traffic signal controller at an intersection receives the Emergency Vehicle Preemption Call message, the controller estimates EV's arrival time based on its driving information and seeks an optimal signal timing strategy to guarantee the EV's quick departure such that it minimizes the intersection delay. Other OBE-equipped vehicles receiving the Emergency Vehicle Preemption Call messages provide drivers with a guidance message (i.e., "Yield-to-EV") if the subject vehicle is identified to be on the route of the EV. For un Connected Vehicles, the intersection controller located on the EV's route provides them with a visual signal to inform the approach of the EV.

Sources:

Updated Descriptions on USDOT High Priority Dynamic Mobility Applications (August 10, 2011)

http://www.its.dot.gov/presentations/MW_SafSec_Breakout_files/slide0322.htm

Function of Analytical Tools:

The analytical tools incorporate the modified preemption algorithms and modified signal recovery algorithms into the ISIG model.

2.1.3.5. Freight Signal Priority (FSP)

The FSP concept provides signal priority along an arterial corridor near a freight facility based on current and projected freight movements into and out of the freight facility. The goal of the FSP application is to reduce delays and increase travel time reliability for freight traffic. It will enhance safety and reduce environmental impacts at intersections around the freight facility by reducing congestion and idling. Priority requests will be provided by V2I communications.

Application Example:

Similar to the TSP application, FSP provides OBE-equipped freight vehicles (FVs) with signal priorities. An OBE-equipped FV broadcasts messages containing not only real-time driving status, such as current position, speed, route, and the final destination, but also freight information such as type, amount, and price. If a RSE-equipped traffic signal controller at an intersection captures the messages requesting a priority signal, it estimates FV's arrival time to the intersection based on its driving status and finds an optimal priority strategy by considering the freight information. It is also possible that the signal priority strategy can be associated with route guidance for freight vehicles.

Sources:

Updated Descriptions on USDOT High Priority Dynamic Mobility Applications (August 10, 2011)

http://www.its.dot.gov/presentations/MW_Prod_Breakout_files/slide0290.htm

Function of Analytical Tools:

The analytical tools incorporate the FSP priority algorithms into the ISIG model. An arrival time estimation and signal priority control logic corresponding to Connected Vehicle technology equipped freight vehicles should be developed.

2.1.4. Integrated Dynamic Transit Operations (IDTO) Bundle

2.1.4.1. Connection Protection (T-CONNECT)

If transit vehicles are late, passengers that need to connect to another transit vehicle often miss their planned connection. Connection protection reduces the frequency of this occurrence by holding the connecting transit vehicle when the vehicle scheduled to meet it is late. Current systems generally provide for a fixed waiting time for the connecting vehicle in the event of a late arriving vehicle. With T-CONNECT, travelers can initiate a request for connection protection. The system will take into account the overall state of the system, including all connection protection requests, as well as real-time and historical travel conditions for the services affected and pre-determined connection protection rules agreed upon by participating agencies and transit modes. The system will provide feedback to the passenger on the expected success of meeting the connection protection request. The system will maximize reliable trip time in the corridor and will then continue to monitor the situation and provide connection protection status updates to travelers as appropriate.

Application Example:

In case of the late arrival of transit vehicles (e.g., bus and metro), a transit traveler whose connection can be affected by the late arrival can request a connection protection for his/her safe transfer using a mobile device. Once an information center operated by local transit authorities receives such a request, it examines the potential impacts of the connection protection to the operation of transit vehicles. If the connection protection appears to have insignificant impacts, the request is accepted and the control center sends a hold message to the transit vehicle that the traveler requested to hold.

Sources:

Updated Descriptions on USDOT High Priority Dynamic Mobility Applications (August 10, 2011)

http://www.its.gov/presentations/MW_Mobility_Breakout_files/slide0314.htm

Function of Analytical Tools:

Simulate the path of transit vehicles in the network and incorporate T-CONNECT algorithms into the simulation. Evaluate through the use of system transit passenger delay and travel time reliability measures.

2.1.4.2. Dynamic Transit Operations (T-DISP)

Traditional fixed route/fixed schedule transit is inherently cost-inefficient to deliver service and time for the traveler in certain conditions, such as in low density, low ridership, and dispersed origin/destination environments. T-DISP better matches travelers' needs with fixed and flexible route services. It will advance the concept of demand-responsive transportation services by using the global positioning system (GPS) technology and mapping capabilities of personal mobile devices to enable a traveler to input a desired destination and time of departure tagged with their current location. A system would dynamically schedule and dispatch or modify the route of an in-service vehicle by matching compatible trips. The application may incorporate both public and private (e.g., taxi) transportation providers and may include paratransit, fixed-route bus, flex-route bus, and rail transit services. A central system could dynamically schedule and dispatch or modify the route of an in-service vehicle by matching compatible trips.

Application Example:

The T-DISP application enables flexible operations of transit vehicles (e.g., bus, tram, and taxi) by dynamically adjusting transit schedules, departure times, and routes to accommodate travelers' real-time demands to use transit vehicles. A control center dealing with the operation of the T-DISP application continuously collects individual travelers' demand calls and real-time transit vehicle information. With the collected information, the control center not only adjusts the schedules or the routes of transit vehicles but also dispatches a new transit vehicle to respond to the demands as long as such remedies are revealed to be cost-effective.

Sources:

Updated Descriptions on USDOT High Priority Dynamic Mobility Applications (August 10, 2011)

http://www.its.dot.gov/presentations/MW_Env_Breakout_files/slide0275.htm

Function of Analytical Tools:

Simulate the path of transit vehicles in the network and incorporate T-DISP algorithms into the simulation. Evaluate the performances through the use of not only system transit passenger delay and travel time reliability measures but also total costs required to operate the T-DISP application.

2.1.4.3. Dynamic Ridesharing (D-RIDE)

Currently security issues and the need to establish reservations considerably in advance limit the effectiveness of computer-based ridesharing services. In-vehicle technology and hand-held communication devices have the potential to address these issues and expand the usefulness of ridesharing services. By integrating carpooling functions into a vehicle computer, voice-activated ridesharing technology can be built into the vehicle's interface, thereby enabling the driver to find and accept potential ride-matches along his or her route without having to divert concentration from the roadway.

Application Example:

Travelers who need carpools and who are willing to provide ride sharing can exchange their information through Connected Vehicle technology. A traveler who needs a carpool sends his/her request message along with personal information such as current position, destination, and willingness to pay through a mobile device. If the request message is captured by a driver who is willing to share the car through the Connected Vehicle environment, an in-vehicle device displays the information of the requester and asks whether the driver accepts the request or not. Once the driver accepts the request, he/she sends an acceptance message to the requester and performs any necessary manipulations of the vehicle (e.g., route change) to pick up the requester.

Sources:

Updated Descriptions on USDOT High Priority Dynamic Mobility Applications (August 10, 2011)

http://www.its.dot.gov/presentations/MW_Env_Breakout_files/slide0272.htm

Function of Analytical Tools:

A model to simulate the carpool assignment process will be embedded in roadway traffic flow models such as those described in the ATIS and ISIG applications.

2.1.5. Freight Advanced Traveler Information System (FRATIS) Bundle

2.1.5.1. Freight Real-Time Traveler Information with Performance Monitoring (F-ATIS)

F-ATIS will provide traveler information such as real-time travel estimates with route guidance to freight facilities and basic incident alert, road closure, and work zone information to freight operators and drivers. Enhanced freight-specific information such as route restrictions (oversize/overweight) with associated time periods, tailored weather information (high winds) as well as "concierge" services and maintenance locations will be provided. Intermodal connection information, container disposition, and schedule updates will be available to support more efficient freight operations resulting in reduced traffic congestion and increased air quality in metropolitan areas. The freight real-time traveler information application will be used for long-and short-haul freight movement.

Application Example:

The F-ATIS application provides freight vehicles (FVs) with real-time traveler information. The information includes i) typical real-time traffic information (e.g., work-zone, incident, and roadway congestion), ii) weather condition (e.g., pavement status, visibility, wind speed, and precipitation), and iii) freight-specific information (e.g., terminal status, congestion at shipyards, and restricted routes or areas depending on the size, weight, and hazmat risk of freight vehicles). It also provides FV drivers with real-time route guidance from their instant positions to their destinations. By showing the real-time status of freight vehicles for factors such as travel time, fuel consumption, and emission, the F-ATIS application enables FV drivers to keep monitoring the performance of their vehicles while driving. In response to the given traveler information, FV drivers will make a decision as to whether they accept the information or not based on their own traveler behaviors.

The information required for the guidance can be collected through multiple sources, including Connected Vehicles (e.g., passenger cars, transit vehicles, and trucks), local TMCs, weather stations, port authorities, and freight operators. The guidance information is disseminated to only FV drivers through their on-board equipment or other available communication devices.

Sources:

Updated Descriptions on USDOT High Priority Dynamic Mobility Applications (August 10, 2011)

http://www.its.dot.gov/presentations/MW_Prod_breakout_files/slide0293.htm

Function of Analytical Tools:

The functions described above will generally have the effect of restricting truck route choices, and, in some cases, will restrict speeds. The ATIS and ISIG models will be modified to include these restrictions, and freight movement-oriented measures such as freight ton miles, on-time delivery, etc. will be included.

2.1.5.2. Drayage Optimization (DR-OPT)

Vehicles that carry freight between terminals or at ports are commonly overbooked and expend considerable time waiting. Using the DR-OPT application, individual trucks will be assigned time windows within which they will be expected to arrive at a pickup or drop-off location. Early or late arrivals to the facility will be dynamically balanced. It is envisioned that a web-based forum for load matching will be provided to reduce empty or unproductive moves. The drayage optimization application will be used for short-haul (local) freight movement.

Application Example:

Unlike existing drayage scheduling methods based on pre-determined shipment schedules that are insufficient to reflect real-time line-haul traffic conditions, the DR-OPT application generates the most efficient drayage operations strategies. Under Connected Vehicle technology, a control center implementing the DR-OPT application at terminals or ports collects the information of individual freight vehicles (e.g., trucks, trailers, and trains) such as current position, route, traffic congestion status, and freight type and amount. With the collected information, the DR-OPT application estimates the arrival time of the freight vehicles and generates the dynamic optimal drayage schedules that can minimize the idling time of freight vehicles during the trans-shipment period and decrease the rate of empty vehicles. The optimal drayage schedule showing the shipment timetable of each freight vehicle will be disseminated through wireless communications devices.

Sources:

Updated Descriptions on USDOT High Priority Dynamic Mobility Applications (August 10, 2011) http://www.its.dot.gov/presentations/MW_Prod_Breakout_files/slide0291.htm

Function of Analytical Tools:

The ATIS and ISIG models will be modified to include the drayage optimization algorithm.

2.1.5.3. Freight Dynamic Route Guidance (F-DRG)

F-DRG will determine the best route between freight facilities or destinations. Routes will be calculated based on current and predicted conditions. As road conditions change, alternate routing will be provided to avoid the problem or to minimize the impact of the delay. Routing will reflect route restrictions on trucks and itinerary requirements. The freight dynamic route guidance application will be used for long-and short-haul freight movement.

Application Example:

In addition to a general route guidance system, the F-DRG application provides FVs with FV-dedicated real-time route guidance. The route guidance strategies can vary based on the guidance objectives. These include: 1) travel time minimization, 2) fuel consumption and emission minimization, 3) weather-related safety improvement, and 4) the removal of hazmat risk. Therefore, the information collected for the guidance must cover real-time traffic information, weather conditions, and freight-specific information, as noted in the F-ATIS application. The selection of guidance strategy will be determined by FV driver's own travel behavior.

The information can be collected through multiple sources, including Connected Vehicles (e.g., passenger cars, transit vehicles, and trucks), local TMCs, weather stations, port authorities, and freight operators. The guidance information is disseminated to only FV drivers through their on-board equipment or other available communication devices such as cellular phones via wireless data network.

Sources:

Updated Descriptions on USDOT High Priority Dynamic Mobility Applications (August 10, 2011)

http://www.its.dot.gov/presentations/MW_Prod_Breakout_files/slide0292.htm

Function of Analytical Tools:

The ATIS and ISIG models will be modified to include F-DRG functions, and freight movement oriented measures will be included.

2.1.6. Response, Emergency Staging, Communications, Uniform Management and Evacuation (R.E.S.C.U.M.E.)

2.1.6.1. Emergency Communications and Evacuation (EVAC)

The EVAC application focuses on providing evacuees with a range of en-route information to assist in helping them evacuate as safely and efficiently as possible. Information delivered from roadside units, transportation management centers, and other applicable sources to the in-vehicle devices could be of significant assistance to evacuees. Such information includes:

- Dynamic route guidance information
- Current traffic and road conditions

- Location of available lodging
- Location of fuel, food, water, cash machines and other necessities.

EVAC functions include:

1. Integrating information from existing databases to identify and locate people who are more likely to require guidance and evacuation assistance. It also identifies existing service providers and other available resources. Additionally, individuals will be able to register themselves for evacuation assistance or perhaps be registered, with their permission, by the database owners.
2. The second function addresses evacuation assistance that aims to improve the evacuation operations of persons who are already registered in the human services databases to receive subsidized transportation and to set up services to provide transportation to those who are not in those databases but, for whatever reason, cannot evacuate by themselves.

Application Example:

In the event of a no-notice evacuation, as soon as an event is confirmed and an evacuation area is determined, travelers within the evacuation area are notified to evacuate as soon as possible. Furthermore, travelers who might pass through or arrive at/near the evacuation area are notified to change their destination or divert to a different route. These communications are implemented by DSRC and/or cellular data network. Traffic management centers determine designated shelter locations and provide evacuation routes to travelers, including those who need public transportation services. Travelers who have applicable devices (e.g., smart phone or OBU) can request the best route/mode to arrive at their desired destination, including evacuation shelter.

Source:

Updated Descriptions on USDOT High Priority Dynamic Mobility Applications (August 10, 2011)

Function of Analytical Tools:

ATIS and ISIG models will be populated with emergency response plans. Together with the additional evacuees and earlier response start times resulting from EVAC strategies, evacuation times will be estimated.

2.1.6.2.Incident Scene Pre-Arrival Staging Guidance for Emergency Responders (RESP-SIG)

Providing situational awareness to public safety responders while en route can help establish incident work zones that are safe for responders, travelers, and crash victims alike while less disruptive to traffic. Situational awareness information can also provide valuable input to responder and dispatcher decisions and actions. A range of data elements related to situational awareness is currently available from public and private sources and could be accessed, processed, and provided to public safety responders. This application would provide a range of data to responders through their mobile devices to help support public safety responder vehicle routing, staging, and secondary dispatch decision-making. Examples of these data include staging plans, satellite imagery, and GIS data related to the incident scene location, still and video images of the incident scene, real-time traffic information, current weather conditions, electronic manifest data collected from commercial vehicles, and crash data generated though in-vehicle systems.

Application Example

When a crash occurs on a freeway, RESP-SIG application collects data related to situational awareness (e.g., staging plans, images and GIS data showing crash scene location, real time traffic and weather information, crash data generated by in-vehicle systems, etc.) and provides them to public safety responders so that they can establish an incident work zone.

Source: *Updated Descriptions on USDOT High Priority Dynamic Mobility Applications (August 10, 2011)*

Function of Analytical Tools:
Detailed development of RESP-SIG strategies may lead to the requirement for analytical tools.

2.1.6.3. Incident Scene Work Zone Alerts for Drivers and Workers (INC-ZONE)

Incident scenes, traffic stops, and work zones are high-risk areas for vehicle incident responders, crash victims, and travelers alike. Enhancing the safety of such work zones requires that real-time notifications be delivered to both the driver of the vehicle operating near the incident or work zone and the responders working in the area. The first component alerts and warns drivers of lane closings and unsafe speeds for the areas that surround traffic incidents, work zones, or law enforcement traffic stops that may impact traffic flow by using in-vehicle messaging. The second component would, through communication to the emergency vehicle or its personnel, warn on-scene workers of vehicles with trajectories or speeds that pose a high risk to their safety.

Application Example:
In the case of a work zone, an INC-ZONE application will establish a work zone area and provide warnings to in-coming vehicles/drivers. The warnings are intended to ensure the safety of people around the work zone. The system will estimate anticipated trajectories of in-coming vehicles and provide real-time warning and possibly automatic braking to those who opted-in.

Source: *Updated Descriptions on USDOT High Priority Dynamic Mobility Applications (August 10, 2011)*

Function of Analytical Tools:
The first function described above requires a speed change and lane change model to be used in conjunction with the ATIS application. The compliance fraction requires research. The second function requires a model that includes human reaction times and safety clearance criteria.

2.1.6.4.Mayday Relay

Single vehicle, run-off-the-road crashes represent a significant percentage of vehicle crashes nationwide. When these occur in rural areas, dispatching public safety assistance can be delayed or problematic due to limited access to communications infrastructure, lack of crash notification, lack of crash location information, and limited response from law enforcement due to infrequent patrolling on rural roads. When an enabled vehicle is involved in a crash, this application will automatically send a mayday message. When a passing enabled vehicle receives the mayday message, it will deliver it to a roadside hot spot. Data may include vehicle location, number of passengers, airbag status, point of impact, vehicle’s final resting position, and/or infrastructure damage. This information will then be relayed to the appropriate 911 center based on the crash location through V2V or V2I communication.

Application Example:

As noted, mayday relay is only used when a mayday message is received by a passing vehicle. Upon conveying the mayday message to an authority, depending on the information embedded in the mayday message, appropriate actions such as dispatching an emergency management vehicle or tow truck are taken.

Sources: *Updated Descriptions on USDOT High Priority Dynamic Mobility Applications (August 10, 2011)*
http://www.its.dot.gov/presentations/MW_SafSec_Breakout_files/slide0323.htm

Function of Analytical Tools:
While it is anticipated that detailed development of strategies may lead to the requirement for analytical tools, a function emulating mayday relay communications and an algorithm estimating crash/damage severity are necessary.

2.2. Performance Measures

Performance measures were identified for each application. Key sources for these measures include Gordon (2011), Park (2005) and Shaw (2003). Certain additional measures were included. Performance measures are shown in Tables 2-1 and 2-2.

Measures identified by the "O" symbol are applicable to that cell. The first column describes the general type of measure, and the second column further classifies the measure. An identifier is provided in the third column that is used for traceability purposes later in the project. The DMS applications in the subsequent columns are classified by bundles.

Rows shaded in yellow indicate measures that are useful, but that cannot be obtained by modeling techniques. These measures are not treated further in this project.

Table 2-1. Performance Measures' Current Modeling Capability

Type of Measure		ID	Current Modeling Capability
System Delay Measures	Vehicle system delay*	D.a	Readily available
	Private passenger vehicle occupant delay*	D.b	With known or average occupancy rate
	Commercial vehicle occupant delay*	D.c	
	Goods inventory delay*	D.d	
	Transit vehicle occupant delay*	D.e	With known or average occupancy rate
	Pedestrian delay*	D.f	Only available for microscopic modeling tool
	Total traveler delay	D.g	Readily available
	Commercial vehicle delay	D.h	
	Drayage delay	D.i	
Safety	Freeway crashes*	S.a	Surrogate safety with external models (e.g., Safety Surrogate Assessment Model)
	Crashes at intersections*	S.c	
	Work zone related crashes	S.d	
*Fuel consumption		F.a	With external Model (e.g, VT-Micro, MOVES)
Throughput		T.a	Readily available

Type of Measure		ID	Current Modeling Capability
Emissions		E.a	With external Model (e.g, VT-Micro, MOVES)
Service quality	Route travel time	Q.a	Readily available
	Route travel time reliability	Q.b	Post processing
	Emergency vehicle route travel time	Q.c	
Average incident clearance time		C.a	Need new tool to model incident and post processing
Perceived adequacy of traveler information		I.a	Not available with the model

*Measures commonly used for benefit and cost analysis.

Table 2-2. Measures of Effectiveness for Priority Applications

Type of Measure	Sub-Measure	Applications																					
		ATIS				FRATIS			RESCUME				INFLO			IDTO			M-ISIG				
		ATIS	WX-INFO	T-MAP	S-PARK	F-ATIS	DR-OPT	F-DRG	EVAC	RESP-SIG	INC-ZONE	MAYDAY	Q-WARN	SPD-HARM	CACC	T-CONNECT	T-DISP	D-RIDE	ISIG	TSP	PED-SIG	PREEMPT	FSP
System Delay Measures	Vehicle system delay*	O	O		O	O	O	O	O	O	O		O	O	O				O			O	O
	Private passenger vehicle occupant delay*	O	O		O				O	O	O		O	O	O			O	O	O	O	O	O
	Commercial vehicle occupant delay*	O	O			O	O	O		O	O		O	O	O				O	O			O
	Goods inventory delay*					O	O	O															O
	Transit vehicle occupant delay*	O	O	O	O				O	O	O		O	O	O	O	O		O	O			O
	Pedestrian delay*	O								O	O								O		O	O	O
	Total traveler delay	O	O	O	O	O	O	O	O	O	O		O	O	O	O	O	O	O	O	O	O	O
	Commercial vehicle delay		O			O	O	O		O	O		O	O	O								
Safety	Freeway crashes*	O	O		O				O		O		O	O	O			O					
	Crashes at intersections*	O	O		O				O	O	O		O					O	O	O	O	O	O
	Work zone related crashes	O	O								O		O	O	O			O	O				O
*Fuel consumption		O				O	O	O					O	O	O			O	O	O	O	O	O
Throughput		O	O		O	O		O		O	O		O	O	O			O					
Emissions		O			O	O	O	O					O	O	O			O	O	O	O	O	O
Service quality	Route travel time	O	O		O	O		O					O	O	O	O	O	O	O	O		O	O
	Route travel time reliability	O	O		O	O		O					O	O	O	O	O	O	O	O	O	O	O
	Emergency vehicle route travel time		O						O	O									O			O	
Average incident clearance time		O				O		O	O	O	O		O	O	O			O	O				
Perceived adequacy of traveler information		O	O	O	O	O		O	O		O	O	O	O	O	O	O	O	O				

O= The measure may be appropriate for this application.

*=Measures commonly used for benefit and cost analysis.

Notes: ♦The use of these measures depends on the specific functions implemented by the applications. ♦ Yellow shading indicates measures that must be obtained by techniques other than modeling.

2.3. Application Data Needs

Tables 2-3 through 2-8 summarize the general data inputs required for the applications. These tables provide a general overview, and the particular inputs required for each model class will vary by application. Section 4 provides the detailed data needs as a function of the model class. That section also identifies the model classes that are feasible for the application. It is expected that many of the applications will build on the network and flow models that are required for the ATIS and ISIG applications. Macroscopic models and sketch planning tools generally employ a benefits database (a set of stored benefit parameters for the application) to assist in computing the benefits. Macroscopic models may require a link performance function to facilitate the computation.

In this section, the following symbols are used:

- O : Required Data
- E : Need an external model and requires calibration with field data
- Blank : Not needed

Table 2-3. Data Needs for Enabling ATIS Bundle

Data Need	ATIS	WX-INFO	T-MAP	S-PARK
Network information (roadways, traffic signal, transit route, etc.)	O	O	O	O
Time dependent travel demand by modes	O	O	O	O
Static assignment by mode (for macroscopic models and sketch planning tools)	O	O		
Driving behavior (vehicle following characteristics)	E	E		
Traffic composition	O			
Effect of traffic information on route choice and driving behavior	O	O	O	O
Weather (snow, rain, fog, etc.) and its effect on motorist behavior and roadway capacity	O	O		
Map availability to traveler			O	
Benefits database (for macroscopic models and sketch planning tools)	O	O	O	O
Transit Schedule	O		O	O
Park and ride opportunities	O		O	O

Table 2-4. Data Needs for IDTO Bundle

Data Need	T-CONNECT	T-DISP	D-RIDE
Network information (roadways, traffic signal, transit route, etc.)	O	O	O
Time dependent travel demand by modes	O	O	O
Traffic composition		O	
Transit schedule	O	O	

Table 2-5. Data Needs for INFLO Bundle

Data Need	Q-WARN	SPD-HARM	CACC
Network information (roadways, traffic signal, transit route, etc.)	O	O	O
Time dependent travel demand by modes	O	O	O
Driving behavior (vehicle following characteristics)	E	E	E
Traffic composition	O	O	O
Weather (snow, rain, fog, etc.) and its effect on motorist behavior and roadway capacity	O	O	O

Table 2-6. Data Needs for M-ISIG Bundle

Data Need	ISIG	TSP	PED-SIG	PREEMPT	FSP
Network information (roadways, traffic signals, transit routes, etc.)	O	O	O	O	O
Time dependent travel demand by modes	O	O	O	O	O
Traffic composition	O	O	O		O
Pedestrian Crossing Demands	O		O		
Transit Schedule	O	O			
Emergency vehicle route				O	

Table 2-7. Data Needs for FRATIS Bundle

Data Need	F-ATIS	DR-OPT	F-DRG
Network information (roadways, traffic signal, transit route, etc.)	O	O	O
Time dependent travel demand by modes	O	O	O
Driving behavior (vehicle following characteristics)	E	E	E
Traffic composition	O	O	O
Weather (snow, rain, fog, etc.) and its effect on motorist behavior and roadway capacity	O		O
Freight train schedule	O	O	
Incident Information	O	O	O
Work zone information	O	O	O
Trip chain		O	O
Shipment arrival schedule		O	

Table 2-8. Data Needs for RESCUME Bundle

Data Need	EVAC	RESP-SIG	INC-ZONE	Mayday
Network information (roadways, traffic signal, transit route, etc.)	O	O	O	O
Time dependent travel demand by modes	O	O		
Driving behavior (vehicle following characteristics)	O	E	E	
Traffic composition	O	O		
Evacuation scenarios	O			
Current location and availability of emergency responders		O		
Work zone scenarios and locations			O	

2.4. Modeling Functions and Needs

Tables 2-9 through 2-30 summarize the modeling functions needed for the evaluation of each DMA and their current modeling capability. These are identified in Section 4 for each model class (e.g. microscopic, etc.). Many of the applications require the basic functions and needs described for the ATIS and ISIG applications, and the descriptions provided in the tables assume that these basic functions will be in place.

Table 2-9. Modeling Functions and Current Modeling Capability for EATIS Bundle: ATIS

Modeling Function	Current Modeling Capability
Detect real-time traffic information	It is available within the Dynamic Traffic Assignment Model framework.
Develops minimum time path for travelers based on dynamic assignment (single mode and multi modes)	Minimum path algorithm has been implemented. Might need to obtain link information on the fly.
Accommodates route diversion, speed changes and modal shift to travel condition information.	Need to use travelers' behavior model to implement this function (currently not available)
Implements dynamic route assignment and route shifts for each mode.	DTA is available and route choice model needs to be added into the model and should be calibrated with field data
Provides for off-line demand adjustment by mode choice	Implementing mode shifts should be easy as long as the mode choice model is ready
Provides static assignment of route and mode for macroscopic and sketch planning tools	Readily available
Develops estimate of travel time under various traffic condition scenarios	Readily available as long as link costs can be updated for various traffic conditions

Table 2-10. Modeling Functions and Current Modeling Capability for EATIS Bundle: WX-INFO

Modeling Function	Current Modeling Capability
Detect real-time traffic information	It is available within the Dynamic Traffic Assignment Model framework.
Develop dynamic minimum time path for travelers based on off-line weather condition(capacity and speed change)	Minimum path algorithm has been implemented with various objective functions.
Control Traveler behaviors (compliance rate, route diversion, speed changes and modal shift) based on travel condition information and weather condition	Need to use travelers' behavior model to implement this function (currently not available)
Multiple traveler compositions reflecting service market penetration rate and vehicle type	Readily available
Off-line demand adjustment by weather condition	Implementing mode shifts should be available as long as weather-based mode choice model is ready

Table 2-11. Modeling Functions and Current Modeling Capability for EATIS Bundle: T-MAP

Modeling Function	Current Modeling Capability
Implement dynamic transit assignment by transit schedule	Schedule-based Transit DTA has been implemented (e.g., Dynus-T).
Develop minimum time path for travelers (Route Guidance) with adjusted demand by off-line T-MAP utilization ratios	Minimum path algorithm has been implemented. Might need a demand adjustment model reflecting the impact of T-MAP (currently not available).
Control Traveler behaviors (route diversion and mode shift) based on T-MAP information	Need to use travelers' behavior model to reflect traveler's response to the T-MAP information(currently not available)
Multi traveler compositions including T-MAP-enabled traveler group	Readily available
Sketch level travel time estimation under two different map availability scenarios	No T-MAP-related travel time estimation data exist

Table 2-12. Modeling Functions and Current Modeling Capability for EATIS Bundle: S-PARK

Modeling Function	Current Modeling Capability
Model parking facility (e.g., location, available spaces)	Readily available
Calculate minimum time paths (Route Guidance) considering multi modes based on real-time parking information, transit schedule, and highway congestion.	Minimum path algorithm has been implemented. The objective functions can be modified to deal with transit schedule, parking lot information, and congestion.
Dynamically track available parking spaces and predicts availability on vehicle's expected arrival time at parking facility.	It has not been implemented with existing modeling tools.
Control Traveler behaviors (i.e., route diversion, destination change, and modal shift) based on parking lot information	Need to use travelers' behavior model responding to parking lot information(currently not available)
Multi traveler compositions including S-PARK users	Readily available
Sketch level travel time estimation under two different park and ride scenarios given proper database	No Parking facility-related travel time estimation data exist

Table 2-13. Modeling Functions and Current Modeling Capability for INFLO Bundle: Q-WARN

Modeling Function	Current Modeling Capability
Model non-recurrent congestion (e.g., incident, work zone).	Available as long as proper scenarios and models to create incidents and/or work zone are ready
Detect existing queues in real-time	Available within the framework of DTA-enabled model
Generate warning messages for upstream vehicles.	Need to develop proper algorithm to generate warning messages.
Provide upstream vehicles with Queue warning messages	Readily available
Control Traveler behaviors (driver compliance, route diversion, speed change) in response to queue warning information	Need to use travelers' behavior model (currently not available)

Table 2-14. Modeling Functions and Current Modeling Capability for INFLO Bundle: SPD-HARM

Modeling Function	Current Modeling Capability
Model non-recurrent congestion (e.g., incident, work zone).	Available as long as proper scenarios and models to create incidents and/or work zone are ready
Detect traffic congestion conditions	Available within the framework of DTA-enabled model
Determine target speed based on detected recurrent and non-recurrent traffic conditions	A proper algorithm has been implemented (PATH's VSL)
Provide target speed information to drivers.	Readily available
Control Traveler behaviors (e.g., driver compliance, speed change) in response to target speed information	Need to use travelers' behavior model (currently not available)

Table 2-15. Modeling Functions and Current Modeling Capability for INFLO Bundle: CACC

Modeling Function	Current Modeling Capability
Model non-recurrent congestion (e.g., incident, work zone).	Available as long as proper scenarios and models to create incidents and/or work zone are ready
Detect existing traffic congestion conditions in real-time	Available within the framework of DTA-enabled model
Calculate target speed and gap guidance for CACC-enabled vehicles based on traffic and incident conditions.	A proper algorithm has been implemented (PATH's CACC)
Provides target speed and gap guidance to CACC drivers	Readily available
Control Traveler behaviors (e.g., driver compliance, speed change) in response to target speed information	Need to use travelers' behavior model (currently not available)

Table 2-16. Modeling Functions and Current Modeling Capability for IDTO Bundle: T-CONNECT

Modeling Function	Current Modeling Capability
Model a hold request from a pedestrian.	It has not been modeled within any of transportation modeling tools.
Model transit vehicles (e.g., positions of transit vehicles and their schedules and passenger loads).	Readily available.
Determine feasibility of holding based on minimizing the total passenger delay (with proper logic and constraints).	It has not been implemented. Available as long as a proper algorithm is ready.
Manipulate dynamic transit operation based on pedestrian hold requests based on proper logic to determine its feasibility; Grants, if feasible the hold so that a passengers can make the connection; If	It has not been implemented within the basic functionalities of existing transportation modeling tools

not feasible, an alternative transit itinerary will be provided)	

Table 2-17. Modeling Functions and Current Modeling Capability for IDTO Bundle: T-DISP

Modeling Function	Current Modeling Capability
Provide travelers with dynamic transit route using fixed route and flexible route service based on real-time requests.	It has not been implemented within the basic functionalities of concurrent modeling tools
Determine the best route based on traffic conditions as well as the transit pick-up and drop-off requests.	Optimal path algorithms (e.g., Traveling Salesman Problem) can be used to find the best route.
Control Traveler behaviors (driver compliance and route diversion) based on T-DISP information	Need to use travelers' behavior model (currently not available)

Table 2-18. Modeling Functions and Current Modeling Capability for IDTO Bundle: D-RIDE

Modeling Function	Current Modeling Capability
Multiple vehicle compositions including ridesharing-enabled vehicle types.	Readily Available
Model ride sharing requests on short notice (locations, request frequency and time)	It has not been implemented within the basic functionalities of concurrent modeling tools
Search for ridesharing vehicles to serve the requests	It is available as long as a proper searching logic is ready
Develop the best ridesharing option incorporating the information of transit schedule, availability, and location and real-time traffic condition.	It is available with proper algorithms to find the best ridesharing option
Control Traveler behaviors (ridesharing driver's compliance and route diversion)	Need to use travelers' behavior model (currently not available)

Table 2-19. Modeling Functions and Current Modeling Capability for M-ISIG Bundle: ISIG

Modeling Function	Current Modeling Capability
Detect real-time traffic congestions	Available within the framework of DTA-enabled model
Model traffic compositions to consider various modes (auto, transit, pedestrian, freight)	Readily available
Determine optimal traffic signal timing by incorporating proper optimization algorithms that consider all traveler modes (vehicle, transit, pedestrian, freight)	It is available given that proper optimization algorithms are ready
Provides optimal signal timing control to travelers in real-time	Available with any DTA-enabled modeling tools
Control Traveler behaviors (driver compliance, route diversion, speed change) in response to optimal traffic signal controls	Need to use travelers' behavior model (currently not available)

Table 2-20. Modeling Functions and Current Modeling Capability for M-ISIG Bundle: TSP

Modeling Function	Current Modeling Capability
Dynamic transit simulation based on transit schedule	Schedule-based Transit DTA has been implemented (e.g., Dynus-T).
Detect real-time traffic congestions	Available within the framework of DTA-enabled model
Detect real-time transit vehicle information (e.g., position, speed, passenger load)	Available within the framework of any transit-enabled DTA model
Determine optimal transit priority strategy by incorporating proper algorithms that consider auto, transit, and pedestrian modes	Simple TSP logics have been implemented.
Real-time intersection traffic signal control based on the optimal TSP strategy	Available within the framework of any transit-enabled DTA model

Table 2-21. Modeling Functions and Current Modeling Capability for M-ISIG Bundle: PED-SIG

Modeling Function	Current Modeling Capability
Model multiple pedestrian types (e.g., normal pedestrian and visually impaired pedestrian)	Need to use behavior models for visually impaired pedestrian(currently not available)
Model pedestrian on-demand calls	Possibly available within pedestrian-enabled modeling tool
Real-time intersection traffic signal control based on pedestrian demand calls	Available within the framework of any transit-enabled DTA model

Table 2-22. Modeling Functions and Current Modeling Capability for M-ISIG Bundle: PREEMPT

Modeling Function	Current Modeling Capability
Model emergency vehicles (e.g., departure time, desired speed, origin-destination)	Available with modeling tools enabling to handle the movement of individual vehicles
Detect real-time emergency vehicle information (e.g., position, speed, passenger load)	Available with DTA-based modeling tools enabling to handle the movement of individual vehicles
Generate preemption calls	Available with modeling tools enabling to handle the movement of individual vehicles
Real-time intersection traffic signal control based on the preemption calls	Available within the framework of any transit-enabled DTA model

Table 2-23. Modeling Functions and Current Modeling Capability for M-ISIG Bundle: FSP

Modeling Function	Current Modeling Capability
Model freight modes (e.g., type, departure time, desired speed, origin-destination)	Available with modeling tools enabling to handle the movement of individual vehicles
Detect real-time freight vehicle or train information (e.g., position, speed, passenger load)	Available with DTA-based modeling tools enabling to handle the movement of individual vehicles
Generate preemption calls	Available with modeling tools enabling to handle the movement of individual vehicles
Real-time intersection traffic signal control based on the preemption calls	Available within the framework of any transit-enabled DTA model

Table 2-24. Modeling Functions and Current Modeling Capability for FRATIS Bundle: F-ATIS

Modeling Function	Current Modeling Capability
Model freight vehicles (e.g., truck or train and departure time, desired speed, origin-destination)	Available with modeling tools enabling to handle the movement of individual vehicles
Model non-recurrent congestion (e.g., incident, work zone, weather condition).	Available as long as proper scenarios and models to create incidents and/or work zone are ready
Detect real-time traffic information	Available with DTA-based modeling tools enabling to handle the movement of individual vehicles
Provide freight operators with traffic information	Readily available
Model freight operator behaviors (compliance, route diversion, and speed changes) based on traffic Information.	Need to use travelers' behavior model (currently not available)
Multiple vehicle compositions (auto, transit, and freight)	Readily Available

Table 2-25. Modeling Functions and Current Modeling Capability for FRATIS Bundle: DR-OPT

Modeling Function	Current Modeling Capability
Model drayage vehicles (e.g., freight arrival time, loading/unloading time)	It has not been implemented with transportation modeling tools.
Determine optimal drayage vehicle operation by incorporating proper optimization algorithms	

Table 2-26. Modeling Functions and Current Modeling Capability for FRATIS Bundle: F-DRG

Modeling Function	Current Modeling Capability
Model freight vehicles (e.g., truck or train and departure time, desired speed, origin-destination)	Available with modeling tools enabling to handle the movement of individual vehicles
Model non-recurrent congestion (e.g., incident, work zone, weather condition).	Available as long as proper scenarios and models to create incidents and/or work zone are ready
Detect real-time traffic information and create route-guidance by using a proper algorithm that considers the real-time traffic condition, restricted roadways, special weather issues, itinerary constraints	Available with DTA-based modeling tools enabling to handle the movement of individual vehicles
Provide freight operators with the route guidance information	Readily available
Model freight operator behaviors (compliance, route diversion, and speed changes) based on traffic Information.	Need to use travelers' behavior model (currently not available)
Multiple vehicle compositions (auto, transit, and freight)	Readily Available

Table 2-27. Modeling Functions and Current Modeling Capability for RESCUME Bundle: EVAC

Modeling Function	Current Modeling Capability
Model passive evacuees who are not able to evacuate by their own by using proper database	It has not been implemented
Model special vehicles for passive evacuees (e.g., route, schedule)	It has not been implemented
Develop optimal path information for evacuees based on shelter location, grocery location, lodge information, ATM location	Optimal path algorithms can be used to find the best route.
Provide active evacuees with the optimal path information	Available
Provide passive evacuees with proper evacuation modes	Available as long as passive evacuees are properly modeled
Control evacuee behaviors (e.g., compliance, route diversion) based on the path information	Need to use evacuees' behavior model (currently not available)
Multiple traveler compositions reflecting active and passive evacuees	Available as long as evacuees are properly modeled

Table 2-28. Modeling Functions and Current Modeling Capability for RESCUME Bundle: RESP-SIG

Modeling Function	Current Modeling Capability
Model emergency responder vehicles (e.g., route, departure time)	
Model Incidents (e.g., location, occurrence time, duration, severity)	Available as long as proper scenarios and models to create incidents are ready
Detect real-time traffic congestions	Available within the framework of DTA-enabled model
Detect incidents in real-time	Available within the framework of DTA-enabled model
Develop optimal route guidance for emergency responders such that responders, travelers, and crash victim are safe while less disruptive to traffic.	Optimal path algorithms can be used with modified objective functions
Provide route guidance with emergency responders	Available

Table 2-29. Modeling Functions and Current Modeling Capability for RESCUME Bundle: INC-ZONE

Modeling Function	Current Modeling Capability
Model incident scene (occurrence time, location, work zone size, severity)	It has not been implemented
Detect real-time traffic congestions	Available within the framework of DTA-enabled model
Detect incidents in real-time	Available as long as proper scenarios and models to create incidents and/or work zone are ready
Detect vehicles near the incident scene and identify dangerous vehicles	It has not been implemented
Determine safe speed for the vehicles near the incident scene	Existing logic(e.g., VSL) can be used
Provide the vehicles near the incident scene work zone with safe speed advisory	Available
Control Traveler behaviors (e.g., compliance, speed change) in response to the speed advisory information	Need to use travelers' behavior model (currently not available)

Table 2-30. Modeling Functions and Current Modeling Capability for RESCUME Bundle: MAYDAY

Modeling Function	Current Modeling Capability
Model run-off crash situation (e.g., location, occurrence time, mayday dissemination)	Not available
Model wireless communications (e.g., coverage)	Available with external wireless communications models
Multiple vehicle types (normal vehicles vs. communication device-equipped vehicles, market penetration rates)	Readily available.

3. Transportation Analytics Capabilities Summary

3.1. Modeling Tool Overview

This section presents a brief overview of the modeling tools for the evaluation of Dynamic Mobility Applications. The overview in this section deals with high-level description. Thus, the description does not cover specific characteristics of each modeling tool.

3.1.1. Sketch Planning Tool

Sketch Planning Tools (SPTs) aim to estimate the high level benefits and costs of transportation projects. With an input data set (e.g., network, static origin-destination matrix), SPT performs static traffic assignments to capture the change of network performances (e.g., total travel time, total travel distance-VMT) based on various project scenarios. Given benefits and costs reported from similar completed projects, SPT performs high-level estimations for the benefits and costs by interpolating and/or extrapolating the network performance changes.

No SPTs consider detailed traveler behaviors (e.g., en-route choice, departure time selection); users are required to simplify such behaviors by assuming proper rates, factors, or manual adjustments to account for changes in travel behavior based on project scenarios. Due to such a simple architecture, SPTs are capable of handling an extremely large-scale network covering national and State-level transportation projects.

3.1.2. Macroscopic Modeling Tool

Macroscopic models have been widely used for demand forecasting, transportation impact analysis, and the feasibility studies of transportation projects based on the four-step approach. They perform trip generation, trip distribution, mode choice, and traffic assignment in a sequential manner. The macroscopic model needs such input data as network (zone, node, and link information), static origin-destination (OD) matrix by different modes (e.g., auto, transit, pedestrian), and supply side models (e.g., link performance functions). Unlike SPT, the macroscopic model supports not only multi-class static traffic assignments enabling users explicitly to consider diverse types of travelers (e.g., auto, HOV, HOT), but also transit assignment based on transit operation schedules. The macroscopic model provides vehicle-hour traveled (VHT) and vehicle-mile traveled (VMT) at both the network-wide and OD-pair levels as model outputs. In addition, given external models for the environment (e.g., MOVES) and safety (Crash Estimation Model), the macroscopic model can also produce such output measures.

The macroscopic model is incapable of handling travelers' behavior, such as en-route path choice, pre-trip departure time selection, and on-line mode choice, and drivers' driving characteristics, such as car-following and lane changing behaviors. Accordingly, the macroscopic model is insufficient to deal properly with several dynamic mobility applications requiring to model travelers' response to the traffic information such as real-time traveler guidance applications.

3.1.3. Mesoscopic Modeling Tool

The mesoscopic model combines macro-scale speed-density relationships for the simulation of vehicles' movements and time-dependent OD demand matrices to implement dynamic traffic assignment (DTA). Thus, the mesocopic model is able to capture the dynamic changes of network performances such as travel time, speeds, density, and the propagation of queues. By adopting the speed-density relationships to improve the computation performance, the mesoscopic model can perform DTA modeling for mid- to small-sized networks covering up to the MPO-level study area.

Mesoscopic models have been used for various transportation projects dealing with the dynamic aspects of traveler behavior, such as real-time traveler information systems, weather-responsive traffic management strategies, and mass evacuation plans. Accordingly, the mesoscopic models require more input data sets than SPT and macroscopic modeling tools; they require information on network (e.g., zone, node, and link information), time-dependent OD demands, traffic management strategy scenarios (e.g., variable message sign, ramp metering and weather conditions), and traveler behavior models (e.g., the route-choice model). However, mesoscopic models do not explicitly model the intricate interactions of multi-modal transportation systems. This results in critical challenges for transit- and/or freight- related dynamic mobility applications. Furthermore, mesoscopic models do not model lane-changing behavior and thus are unable to capture such effects on system performance.

The mesoscopic models provide not only the network-wide and OD-pair level of mobility performances such as VHT and VMT l as do the macroscopic models but they also provide time-dependent measures for travel times, speeds, and delays for each OD pair. Furthermore, users may employ external safety and environment models to assess the impacts of such sustainability measures.

3.1.4. Microscopic Modeling Tool

Microscopic models handle every individual vehicle's movement based on stochastic travel and driving behavior models. The user determines the unique modeling characteristics such as departure time, route choice, car following, lane changing, degree of aggressiveness, and desired speed. While the microscopic model uses a time-dependent OD demand matrix as input data (similar to the mesoscopic models), it assigns an identity to each individual vehicle in the network by using each vehicle's network departure time. It tracks the hypothetical vehicle and keeps it moving based on car-following logic. Mesoscopic models use speed-density relationships to perform this function. Handling individual vehicles enable the microscopic models to be extended to cover various transportation applications: e.g., route guidance systems, traffic signal controls, and safety assessments.

Microscopic models require more input data than SPT, macro, and mesoscopic models to set up the simulation environment, such as network information (node and links), time-dependent demand matrix and turning volume designations at intersections, vehicle-type compositions, intersection control strategies, driving behavior models.

Almost all off-the-shelf microscopic modeling tools support an Application Programing Interface or API that provides great expandability, enabling users to develop advanced simulation modeling that is not supported by out-of-the-box functionalities in microscopic modeling tools.

3.1.5. Hybrid Modeling Tool

As reviewed in the previous sections, each modeling tool has its unique advantages and disadvantages. For example, the microscopic models provide high-fidelity simulation outputs that are crucial for the precise evaluation of dynamic mobility applications. They are, however, challenged to cover large- or medium-scale study areas due to the computational burden that is correlated to the number of vehicles being simultaneously tracked. The macroscopic model is capable of handling a large-scale study area, but is insufficient to treat individual drivers' behaviors. The hybrid modeling tool was initiated to overcome such issues. To this end, the hybrid modeling tool integrates microscopic and macroscopic models into a single simulation framework. Thus, the hybrid modeling tool supports analytical functionalities found in the microscopic tools that include time dependent demand, dynamic traffic assignment, and API capabilities. Assuming the same network coverage as macro and micro modeling tools, it is likely that the hybrid model requires more time and efforts for the calibration of the model as it incorporates two heterogeneous models into a single simulation framework.

3.1.6. Activity-based Modeling Tool

All the modeling tools reviewed in the previous sections are trip-based models that do not account for the trip chain of a traveler for a day. The activity-based modeling tool handles the travel patterns of each individual traveler based on the trip chain that is more close to actual traveler behavior.

The following summarizes the advantages for activity-based models over conventional trip-based models:

- In the determination of trip production, activity-based travel patterns consider numerous inter-relationships, trade-offs, and substitution effects between different tours as a function of time-of-day. Daily activities are sensitive to the travel environment and accessibility. They are not fixed.
- The activity-based model is fully consistent in modeling time-of-day choices.
- Network assignment procedures are implemented in the same manner as they are modeled in four-step models. The outputs of an activity-based, tour-based micro-simulation model are converted and aggregated into a conventional trip table for trip assignment. However, with the recent rapid progress of DTA modeling, DTA can effectively handle a large network and should be integrated with the activity-based model.

Typically, the activity-based model requires a more complicated data set, as it considers every individual traveler's trip schedule. The size and quality of the household survey data are the most crucial factors, and the relative complex and time-consuming process of developing a new activity-based model are obvious disadvantages to practitioners and agencies.

3.2. Analytic Capability Summary Table

Table 3-1 summarizes the list of each modeling tool based on its category. The software list presented in the table was categorized based on each tool's known characteristics that can represent the nature of the tool at best. For example, TRANSIMS could be categorized as a micro modeling or meso modeling tool as it utilizes cellular automata approach to modeling individual vehicles. However, TRANSIMS is categorized as an activity-based modeling tool in this report because it was originally developed as an activity-based model.

Table 3-1. Software List for Modeling Tools

Category	Acronym	Example Modeling Tool
Sketch Planning Tool	SP	IDAS
Macro Modeling Tool	MA	Cube Voyager, EMME/3, VISUM, TransCAD
Meso Modeling Tool	ME	DYNASMART, DynaMIT, Dynus-T, Cube Avenue, DynaMEQ
Micro Modeling Tool	MI	CORSIM, INTEGRATION, VISSIM, AIMSUN, PARAMICS, CUBE Dynasim, MITSIM, SUMO, GROOVNET, TransModeler, SimTraffic
Hybrid Modeling Tool	HY	TransModeler
Activity-based Modeling tool	AC	TRANSIMS and the Multi-Agent Transportation Simulation (MATSim) software

Table 3-2. Summary of Input, Functionality and Output for Modeling Tool

Tool	Input	Modeling Tool Functionality	Output
SP	• Network (node/link) • Static OD matrix	• Static traffic assignment	• Network-wide mobility performances: total travel time (VHT) and total travel distance (VMT)
MA	• Network (node/link) • Static OD matrix by modes (auto, transit, truck) • Transit schedule • Off-line mode choice model	• Static multi-class traffic assignment • Static transit assignment	• Network-wide mobility performances(VHT, VMT) by OD-pair
ME	• Network (node, link, traffic signal) • Time-dependent OD matrix • Route choice model • Traffic management scenario (VMS, Ramp Metering)	• Dynamic traffic assignment	• Network-wide mobility performances(VHT,VMT) by OD-pair • Link-based time-dependent speed, volume, density, queue length
MI	• Network (node, link, traffic signal) • Time-dependent OD matrix • Time-dependent trip chain • Transit Schedule and Route • Intersection turning volumes • Vehicle compositions • Route choice model	• Dynamic traffic assignment • En-route path choice (route guidance) • Schedule-based transit assignment • Application Program Interface(API) or Component Object Model (COM)	• Network-wide mobility performances(VHT, VMT) by OD-pair • Link-based time-dependent speed, volume, queue length • Time-dependent vehicle trajectories • Time-dependent Emission and Fuel Consumption
HY	• Network (node, link, traffic signal) • Time-dependent OD matrix • Transit Schedule and Route • Intersection turning volumes • Vehicle compositions • Route choice model	• Dynamic traffic assignment • En-route path choice (route guidance) • Schedule-based transit assignment • Application Program	• Network-wide mobility performances(VHT, VMT) by OD-pair • Link-based time-dependent speed, volume, queue length • Time-dependent vehicle

Tool	Input	Modeling Tool Functionality	Output
		Interface(API)	trajectories
AC	• Network (node, link, traffic signal) • Transit Schedule and Route • Time-dependent trip chain	• Dynamic traffic assignment • Pre-trip route guidance • Emission estimation	• Network-wide mobility performances(VHT, VMT) • Link-based time-dependent speed, volume, queue length • Time-dependent individual vehicle trajectory • Time-dependent Emission and Fuel Consumption

Table 3-3. Summary of Modeling Tool Performance Measure Capability

		Performance Measure	ID	SP	MA	ME	MI	HY	AC
Mobility		Vehicle system delay	D.a	√	√	√	√	√	√
Mobility		Private passenger vehicle occupant delay	D.b	√	√	√	√	√	√
Mobility		Commercial vehicle occupant delay	D.c				√	√	
Mobility		Goods inventory delay	D.d						
Mobility		Transit vehicle occupant delay	D.e		√		√	√	√
Mobility		Pedestrian delay	D.f				√		√
Mobility		Total traveler delay	D.g		√	√	√	√	√
Mobility		Commercial vehicle delay	D.h				√		
Mobility		Throughput	T.a	√	√	√	√	√	√
Mobility	Service Quality	Route travel time	Q.a	√	√	√	√	√	√
Mobility	Service Quality	Route travel time reliability	Q.b	√	√	√	√	√	√
Mobility	Service Quality	Emergency vehicle route travel time	Q.c				√	√	
safety		Freeway crashes*	S.a	√(P)	√(P)	√(P)	√(P)	√(P)	√(P)
safety		Crashes at intersections+	S.c				√(P)	√(P)	√(P)
safety		Work zone-related crashes	S.d						
Environment		Fuel Consumption*+	F.a	√(P)	√(P)	√(P)	√(P)	√(P)	√
Environment		Emission*+	E.a	√(P)	√(P)	√(P)	√(P)	√(P)	√
Average Incident Clearance Time			C.a						
Perceived adequacy of traveler information			I.a						

√ : Available

√(P) : Available with Post-Processing, API

* : Highway Safety Manual

+ : Surrogate Safety Assessment Model (SSAM)

*+: MOVES, CMEM. VT-Micro 2.0

Table 3-4. Summary of Modeling Tool Analytic Capability Needs

Analytic Capability Needs		SP	MA	ME	MI	HY	AC
Scale Needs	National	√					
	State	√	√				
	Regional	√	√	√		√	√
	Corridor			√	√	√	√
	Intersection				√	√	√
	Parking Facility				√	√	√
Visualization			√	√	√	√	√
Open Source				Dynus-T	MITSIM		MATSim, TRANSIMS
API				√	√	√	
Cost/Benefit Analysis.		√	√				
Maturity level[1]		low	high	medium	high	high	Medium
Setup Cost		low	low	medium	high	high	High
Complexity		low	low	medium	medium	medium	High
Calibration Complexity[2]		low	low	medium	medium[3]	high	High
Driver Behavior Model					√	√	√
Traveler's Behavior Model				√	√	√	
Multi-modal Needs	PC Only	√	√	√	√	√	√
	PC+T		√		√	√	√
	PC+F				√	√	
	PC+F+T				√	√	
	PC+Ped				√	√	√
	PC+Ped+T				√	√	√
	PC+Ped+T+F				√	√	
FACTOR	Market Penetration Rate				√	√	
	Compliance Rate			√	√	√	

[1] The maturity level was determined by whether the subject tool provides user-friendly interface for network editing, data reduction, and access to external programs such as API or Script language.
[2] The complexity of calibration is compared in terms of same modeling scale.
[3] In case of VISSIM, AIMSUN, and PARAMICS.

Table 3-5. Summary of Modeling Tool Data Needs

Data Needed	SP	MA	ME	MI	HY	AC
Benefit database	√					
Current location and availability of emergency responders				√		
Driving behavior (Car following characteristic)				√	√	
Driving behavior of emergency responders				√		
Traveler behavior (route choice, mode choice)			√	√	√	
Emergency vehicle route				√	√	
Evacuation scenarios		√	√	√		√
Freight train schedule				√		
Incident Information			√	√	√	
Link performance function	√	√				
Map availability scenarios	√					
Network information : Roadways (Node, Link)	√	√	√	√	√	√
Network information : Traffic Control (sign, signal, etc.)			√	√	√	√
Network information : Transit Route		√		√	√	√
Park and ride scenarios	√					
Pedestrian Crossing demands				√	√	√
Shipment arrival schedule				√	√	
Static Demand (Auto)	√	√	√	√	√	√
Static Demand (Transit)		√		√	√	√
Static Demand (Freight)		√		√	√	
Static Demand (Pedestrian)		√		√	√	√
Time-Dependent Demand (Auto)			√	√	√	√
Time-Dependent Demand (Transit)				√	√	√
Time-Dependent Demand (Freight)				√	√	
Time-Dependent Demand (Pedestrian)				√	√	√
Trip chain for each mode				√		√
Traffic composition				√	√	
Traffic information scenarios	√					
Transit Schedule		√		√	√	√
Weather scenarios (precipitation, speed reduction, etc.)	√	√	√	√	√	
Work zone information				√	√	
Work zone scenarios and locations	√	√	√	√	√	
Summary	9	11	10	27	22	13

4. Traceability Assessment

This section presents traceability assessment tables integrating the application needs reviewed in Section 2 and analytical capabilities summarized in Section 3 to examine whether or not the modeling tools can satisfy the application needs properly. The traceability tables are divided into three categories: i) performance measures (i.e., Section 4.1 and Tables A-1 through A-6 in Appendix A); ii) data needs (i.e, Section 4.2 and Table B-1 through in Appendix B); and iii) functions needed for modeling applications (Section 4.3 and Table C-1 through in Appendix C).

4.1. Traceability Matrix for Performance Measure

4.1.1. EATIS

- ATIS: The performance measures of goods inventory delay, commercial vehicle delay, and emergency vehicle route travel time appear to be unrelated to the ATIS application. The MI tool appears to support 13 out of 16 performance measures while the SP tool appears to handle 8 performance measures.
- WXINFO: All the modeling tools are not able to handle the measures of work-zone crashes and traveler information adequacy. Except for those measures, the MI tool supports the other measures but the SP tool is not able to deal with any delay-related measures.
- T-MAP: 16 out of 19 performance measures appear to be unrelated to the evaluation of the T-MAP application. The SP tool is incapable of producing any performance measures for the T-MAP evaluation. The MA, MI, HY and AC tools can support 2 measures out of 3.
- S-PARK: 8 out 19 performance measures are not related to the S-PARK. Except for the measure of adequacy of traveler information, the MI, HY, and AC tools appear to support all the required performance measures for the S-PARK application.
- In-depth information on application-based performance measures for each modeling tool is tabulated in Table A-1 in Appendix A.

4.1.2. INFLO

- Q-WARN: Measures related to the delays of goods and pedestrians, emergency vehicles, and intersection crashes are unnecessary to be considered for the evaluation of the Q-WARN application. The MI tool is capable of 12 out of 15 performance measures while the SP tool can produce 8 measures.
- SPD-HARM and CACC appear to have same performance measure requirements as Q-WARN.
- Detailed information for each performance measure at the level of modeling tools is summarized in Table A-2 in Appendix A.

4.1.3. M-ISIG

- ISIG: It is appeared that the measures of freeway crashes, commercial vehicle delay, and goods inventory delays are not related to the evaluation of the ISIG application. The MI tool covering 13 out of 16 measures is unable to produce three measures such as work-zone related crash, average incident clearance time, and the adequacy of traveler information. In addition to the uncovered measures of the MI tool, the HY tool is able to handle the pedestrian delay measure. The SP tool is incapable of supporting 9 measures out of 16.
- TSP: 9 performance measures out of 19 appear to be unnecessary for the TSP evaluation. All the performance measures required for the evaluation of the TSP application can be supported by both the MI and HY tools while the SP tool can produce 6 measures out of 10.
- PED-SIG: For the evaluation of the PED-SIG application, 10 out 19 performance measures are identified to be unnecessary. The MI and AC tools can produce all the performance measure except for the adequacy of traveler information. The SP tool covers 5 out of 8 performance measures including private vehicle delay, throughputs, route travel time reliability, and emission and fuel consumption.
- PREEMPT: Transit and freight-related delay measures and crashes at freeways and work-zones are not related to the performance of the PREEMPT application. The MI tool appears to cover all the performance measures for the evaluation of PREEMP. The AC tool has similar coverage as the MI tool but it is unable to measure the travel time of emergency vehicle.
- FSP: Except for unrelated performance measures for the FSP application, the MI tool can produce 12 out 14 performance measures while the SP tool is able to cover 7 measures. The HY and AC tool show similar performance measures coverage except for the measures of pedestrian delay and commercial vehicle delay, respectively.
- The details of the performance measure for each modeling tool are summarized in Tables A-3 and A-4 in Appendix A.

4.1.4. IDTO

- T-CONNECT and T-DISP: 14 performance measures out of 19 appeared to be unnecessary for the evaluation of both applications. Except for the perceived traveler information adequacy (i.e., I.a), all the required performance measures can be supported by the MA, MI, HY and AC tools.
- D-RIDE: The MI, HY, and AC tools are able to produce performance measures for the D-RIDE evaluation except for the perceived traveler information adequacy measure.
- The details of the performance measure for each modeling tool are summarized in Table A-5 in Appendix A.

4.1.5. FRATIS

- F-ATIS and F-DRG: 12 performance measures are identified to be crucial for the evaluation of both applications. The MI, too, appeared to support 10 measures out 12 while the SP tool can cover 6 measures.

- DR-OPT: The MI tool might be able to produce all the required 7 performance measures out of 19 with the supports of external models for emission and fuel consumptions. The HY tool can cover all the measures except the measure of commercial vehicle delays.
- Performance measures for each modeling tool are identified as Table A-6 in Appendix A.

4.1.6. RESCUME

- EVAC: 9 performance measures out 19 were identified to be required to evaluate the EVAC application. The MI and HY tools appeared to handle 7 measures out of 9 but the SP tool can support 3 measures.
- RESP-SIG: The MI tool is able to produce 10 out of 11 required performance measures. The SP tool can produce 3 measures, including delay-related measures for auto modes.
- INC-ZONE: Except the measures of perceived travel time adequacy and incident clearance time, the MI tool is able to cover all the required performance measures (10 out of 11 measures). The HY tool appeared to support 9 measures.
- MAYDAY: A total of 18 out 19 performance measures identified in this research are not related to the MAYDAY application. No modeling tools are able to handle the perceived travel time adequacy measure.
- Detailed information for each performance measure at the level of modeling tools is summarized in Table A-7 in Appendix A.

4.2. Traceability Matrix for Modeling Data Needs

4.2.1. EATIS

- ATIS and WX-INFO: The MI and HY tools appeared to support all the data needs for the evaluation of the ATIS application. The other tools are not able to handle the time-dependent demand data which are crucial for the implantation of ATIS evaluation.
- S-PARK and T-MAP: There are 6 data items needed for the evaluation of S-PARK and T-MAP, including transit schedule, time dependent modal demands, and traveler behaviors. The MI and HY tools are able to deal with such data, but the SP, MA, and ME tools appeared able to cover only 3 of the 6 needed data items.
- Detail information on the data need for the EATIS bundle is summarized in Tables B-1 and B-2 in Appendix B.

4.2.2. INFLO

- The MI and HY tools are able to handle all the data items required for the implementation of each application in the INFLO bundle.
- The SP and MA tools appeared to be unsuitable for the evaluation of this bundle as they are not able to handle most of data items as summarized in Table B-3 in Appendix B.

4.2.3. IDTO

- One of the most essential data item for the evaluation of the IDTO bundle would be time-dependent pedestrian demands. It appears that the MI, HY and AC tools are able to handle pedestrian demand data, but the AC tool is unable to accommodate multiple traffic composition data, as shown in Table B-4 in Appendix B.
- The SP, MA, and ME tools which are not able to handle pedestrian data appeared to be inadequate for the IDTO evaluation.

4.2.4. M-ISIG

- The most crucial data item needed throughout the M-ISIG bundle is time-dependent auto demand, but the SP and MA tools are not suitable to handle them.
- The MI and HY tools appeared to deal with all the data item required for the evaluation of each M-ISIG application as shown in Tables B-5 and B-6 in Appendix B.

4.2.5. FRATIS

- Throughout the entire bundle, the MI tool appeared to deal with all the data items required for the bundle evaluations. The HY tool is also identified as a proper modeling tool that can support the required data items for the F-ATIS application.
- Table B-7 summarizes the data needs for each application by each modeling tool in Appendix B.

4.2.6. R.E.S.C.U.M.E

- For the EVAC application, the data describing the driving behavior of emergency responders might be crucial, but no modeling tools other than the MI tool handle the data item.
- The MI tool appeared to accommodate all the data needs for the evaluation of the applications of RESP-STG, INC-ZONE, and MAYDAY.
- Detail information on the data need for the RESCUME bundle is summarized in Tables B-8 and B-9 in Appendix B.

4.3. Traceability Matrix for Functions needed for modeling applications

This section presents traceability matrix for the functions needed for each application.

4.3.1. EATIS

- The traveler behavior control appeared to be one of crucial elements for evaluating each EATIS bundle application. However, no modeling tools are capable of handling the traveler behaviors except for the MI and ME tools, which are possible through API and program customization, respectively.

- ATIS and WX-INFO: With the support of API capability, the MI tool is able to handle all the functions needed for modeling both applications. The SP and MA tools are unable to deal with real-time traffic information and to create route guidance information within their modeling capabilities.
- Through customization, the ME tool might be able to implement dynamic transit assignment, which is essential for the evaluation of the T-MAP application. The MI tool appeared to support all the modeling functions for the T-MAP application.
- Modeling parking facilities is a crucial element for the evaluation of the S-PARK application, and it can be implemented by developing new APIs within the capability of the MI tool. The SP and MA tools are not able to handle most of required functions for S-PARK.
- Detail information on the modeling function for each modeling tool is summarized in Tables C-1 and C-2 in Appendix C.

4.3.2. INFLO

- The SP and MA tools, which are unable to handle the individual vehicles in real-time, are insufficient to support all the INFLO bundle applications.
- The ME tool is unsuitable for providing upstream vehicles with the information of each application (e.g, queue and target speed)
- MI appeared to be the most suitable tool for the INFLO bundle as two sub-applications have been implemented by existing research efforts employing the AIMSUN program (VSL, PATH; CACC, PATH).
- Detail information on the modeling function for each modeling tool is summarized in Table C-3 in Appendix C.

4.3.3. IDTO

- Modeling real-time transit operation is the most crucial piece for the evaluation of the IDTO bundle. Thus, the SP, MA, HY, and AC tools are not suitable for the IDTO evaluation.
- It would be difficult for the ME tool to deal with the T-CONNECT application as ME is incapable of handling the pedestrian mode. The ME tool can be customized to be used for the evaluations of the T-DISP and D-RIDE applications, however.
- The MI tool appeared suitable for the IDTO bundle as long as new APIs are developed for several key functions as summarized in Table C-4 in Appendix C.

4.3.4. M-ISIG

- The SP and MA tools are unable to model the M-ISIG bundle as they are based on static traffic assignments, which are incapable of handling individual vehicles and real-time traffic signal control.
- For the ISIG application, a few ME and AC tools can be applied by customizing the program source codes to handle real-time traffic signal control.
- For the TSP application, it appears that the HY and AC tools are usable with new APIs (HY) and customization (AC) for the real-time transit signal control.

- Overall, the MI tool is the most suitable modeling tool for all the M-ISIG applications as long as proper APIs are developed to handle the pedestrian (PED-SIG), emergency vehicle (PREEMPT), and freight modes (FSP).
- Detail information on the modeling function for each modeling tool is summarized in Tables C-5 and C-6 in Appendix C.

4.3.5. FRATIS

- Modeling freight vehicles for the F-ATIS and F-DRG applications might be possible through APIs (MI and HY) and source code customization (AC). The MI, HY, and AC tools appeared to be suitable for the evaluation of such applications as summarized in Table C-7 in Appendix C.
- For the DR-OPT application, the MI tool might be able to model the DR-OPT application with the support of new APIs to handle drayage vehicle modeling and drayage schedule optimization.

4.3.6. RESCUME

- The RESCUME bundle requires modeling special vehicle types (e.g., emergency responder vehicle, vehicles for passive evacuees, crashed vehicles) that are not supported by the off-the-shelf functions of the existing modeling tools. Thus, the SP and MA tools are not suitable for the evaluation of all the applications.
- The ME and AC tools might be customizable but they are not enough to handle modeling the special vehicle modes.
- No off-the-shelf modeling function in the MI tool are incapable of modeling the RSCUME bundle but it is appeared that proper APIs enable to evaluate the RESCUME bundle applications as summarized in Tables C-8 and C-9 in Appendix C.

5. Gaps and Challenges

In this section, the gaps and the challenges of each Dynamic Mobility Application as categorized by the six modeling tool bundles are identified based on the findings obtained from Sections 2, 3, and 4.

Overall, based on findings obtained from the previous sections, the agent-based and microscopic simulators were identified as the most suitable modeling tool. However, almost all the applications require appropriate APIs to be properly modeled and to produce the necessary performance measures to evaluate the impacts both individually and collectively within the microscopic modeling framework. Notably, only a few applications, such as CACC and SPD-HARM, are readily available to use their APIs. Thus, proper API required for the modeling of each application is identified as the most critical gap in evaluating the impact of the application. No traveler's models are able to handle the driver behaviors within a Connected Vehicle (CV) environment, such as lane changing, car following, and compliance to given information. Since all the applications dealt with in this research are based on the CV environment, the non-existence of the CV-based traveler models remains a crucial gap for modeling DMAs.

While with the supports of APIs, the microscopic modeling tools can handle various modeling capabilities and functionalities that are crucial for the evaluation of the applications, it is challenging for them to cover areas larger than corridors (e.g., Nation-, State-, and regional-level coverage). Thus, for several applications, such as ATIS, WX-INFO, F-DRG, and F-ATIS, which are suitable for large scale networks, the use of the microscopic modeling tools would be insufficient to assess the impacts of these applications properly. To overcome such challenges, it might be possible to use either hybrid modeling tools or mesoscopic modeling tools. However it must be noted that hybrid modeling tools need to be improved to accommodate more APIs while the mesoscopic tools must be customized to fully support required analytical capabilities and functionalities. In addition, modeling traveler route choice behavior is problematic. Typically, modeling route choice behavior, which is mostly based on an econometric modeling approach by using choice theory such as Logit or Probit models, is known as a sophisticated process requiring numerous traveler response data (e.g., revealed preference data or stated preference data). One surrogate method that may be used would be applying scenario-based sensitivity analyses based on multiple experiments designed to cover the various rates of driver choice selection behaviors for given routes.

5.1. Enabling Advanced Traveler Information Services (Enable ATIS) Bundle

The gaps and challenges identified in the EATIS bundle for each modeling tool are summarized as follows.

5.1.1. Multimodal Real-Time Traveler Information (ATIS)

- The sketch planning tool (SPT) does not consider pedestrian-, truck- and transit-related performance measures (i.e., delay). SPT is very limited in modeling traveler behaviors (e.g., driving characteristics, route or mode changes), local traffic control (e.g., signal, sign), time-dependent demand for all the modes required by the application, and transit mode manipulation.
- While the macroscopic modeling tool (MA) supports transit-related performance measures, it is not capable of producing pedestrian- and freight-related measures. Since MA is based on static traffic assignment techniques, it is not able to implement any time-dependent analyses that are crucial for the ATIS application such as real-time traffic information capture and real-time route guidance generation and dissemination. It also is not capable of dealing precisely with signalized intersection operations.
- Like SPT, the mesoscopic modeling tool (ME) is not capable of handling pedestrian, freight, and transit modes, resulting in no performance measure for such modes. Given that ME uses dynamic traffic assignment, it is possible to create route guidance information and disseminate it to individual (or group) of travelers through source code customization.
- With API capability that can provide proper interfaces to overcome the gaps, the microscopic modeling tool (MI) appears to support all the performance measures except for S.d., C.a, and I.a, and functions needed to evaluate the ATIS application.
- Similarly to MI, the hybrid modeling tool is capable of handling transit and freight modes by using its API capability, but the pedestrian delay is not available. The API is not adequate to control multiple traveler behaviors.
- The activity-based modeling tool (AC) has no proper capabilities to create and disseminate route guidance information to travelers in the simulation model. A source code customization would allow the user to implement a route guidance system.
- The measures of work zone-related crashes (S.d), average incident clearance time (C.a), and perceived adequacy (I.a) were identified as gaps for all the modeling tools considered in this project as no existing modeling tools support such measures.
- The gaps and challenges are summarized in Tables D-1 and D-2 in Appendix D.

5.1.2. Real-Time Route-Specific Weather Information (WX-INFO)

- The WX-INFO application needs performance measures for mobility such as pedestrian-, truck-, and transit-related performance measures that are not supported by SPT. SPT cannot handle traveler behaviors (e.g., driving characteristics, route or mode changes), traffic control (e.g., signal, sign), time-dependent demands for all the modes required by the application, or transit mode manipulation.
- While MA is based on static traffic assignment techniques, the WX-INFO must be based on dynamic assignments as it needs to implement time-dependent analysis such as real-time traffic information capture and real-time route guidance generation and dissemination. It is insufficient to deal precisely with intersection operations and to capture pedestrian- and freight-related measures.

- No mesoscopic modeling tools support pedestrian, freight, and transit modes. Given that ME uses dynamic assignment, it is possible to create route guidance information based on weather information and disseminate it to travelers by customizing source code.
- MI appear to cover all the functions and the performance measures required to evaluate the ATIS application, except for the measures such as S.d., C.a, and I.a., due to the API functionality enabling dynamic route guidance, traveler behavior control, and modeling for all modes of transportation. It is problematic for MI to deal with large-scale networks at the MPO, region, or larger scale.
- As with the ATIS application, WX-INFO can be modeled by a hybrid modeling tool as its API capability can handle transit and freight modes. However, its API is insufficient to control multiple traveler behaviors. Unlike MI, the HYT can handle larger network than MI can cover.
- The activity-based modeling tool (AC) has no proper capabilities to create and disseminate route guidance information to travelers in the simulation model. A source code customization would allow for implemention of route guidance system.
- The WX-INFO application appear to have gaps due to some performance measures that are not supported by existing modeling tools such as work zone-related crashes (S.d), average incident clearance time (C.a), and perceived adequacy (I.a).
- The gaps and challenges are summarized in Tables D-3 and D-4 in Appendix D.

5.1.3. Universal Map Application (T-MAP)

- SPT is not able to produce all the required performance measures for T-MAP such as transit vehicle delay (D.e) and total traveler delay (D.g) as it does not support multiple modes. SPT is incapable of not only building optimal paths for the T-MAP application holder but also handling traveler behaviors.
- Except for the adequacy measure (I.a), MA supports all performance measures, although it is not able to create optimal paths for the T-MAP application holder or to control traveler behaviors based on the optimal path.
- ME is insufficient to produce transit-related performance measures as no MEs are known to deal with the transit measures yet. With ME's dynamic traffic assignment capability, it is possible to develop customized path information to be used for T-MAP travelers.
- T-MAP enabled by MI is available with a reasonable network coverage size (e.g., small to medium area). To this end, it is necessary to develop proper APIs to bring about optimal path generation for T-MAP travelers and to control such travelers.
- HYT provides similar functionalities as MI, but HYT is incapable of controlling traveler behaviors.
- The activity-based modeling tool (AC) can support the same performance measures as MI and HYT for the T-MAP application, but not proper methods to develop and disseminate the optimal path information for T-MAP travelers unless its source code is customized.
- The T-MAP application needs the perceived adequacy measure (I.a) to examine the adequacy of the T-MAP information, which is not supported by existing modeling tools.
- The gaps and challenges are summarized in Tables D-5 and D-6 in Appendix D.

5.1.4. Smart Park (S-PARK)

- SPT is not able to produce transit vehicle delay. It is not capable of dealing with several critical modeling items for this application, such as parking facilities, minimum time path for S-PARK travelers, and traveler behavior controls.
- The intersection-level crash is not available with MA. More importantly, like SPT, MA is not capable of explicitly considering several critical modeling items such as parking facilities, minimum time path for S-PARK travelers, and traveler behavior controls.
- ME is not sufficient to examine transit-related measures. Also, no proper interfaces exist to consider parking facilities, minimum time path for S-PARK travelers, or traveler behavior controls.
- MI with proper APIs supports all the performance measures and functionalities required for this application as long as the size of network that this application covers is reasonable. (i.e., small to medium). The intersection-level crash measure can be obtained by using an external crash estimation model (e.g., Surrogate Safety Assessment Model).
- HYT's APIs can model parking facilities, but appear to be incapable of controlling traveler behaviors (e.g., route change, destination change). The intersection-level crash measure can be obtained by using an external crash estimation model (e.g., Surrogate Safety Assessment Model) to produce individual vehicles' trajectories.
- AC is not suitable to produce transit delay. No proper interfaces exist to consider parking facilities, minimum time path for S-PARK travelers, or traveler behavior controls.
- For the S-PARK application, the measures of work zone-related crashes (S.d), average incident clearance time (C.a), and perceived adequacy (I.a) were identified as gaps for all the modeling tools considered in this project as those measures can be obtained by external proper techniques.
- The gaps and challenges are summarized in Tables D-7 and D-8 in Appendix D.

5.2. Intelligent Network Flow Optimization (INFLO) Bundle

This section presents the gaps and challenges identified in the INFLO bundle for each modeling tool.

5.2.1. Queue Warning (Q-WARN)

- SPT is not able to detect queues in real-time that are crucial to creating warning messages. Modeling non-recurrent congestion conditions is not available with SPT.
- No MAs are able to model non-recurrent incidents in their framework. Due to its static assignment nature, it is not possible to capture real-time queues; therefore, developing queue warning is not available.
- Given proper source code customization for some MEs such as DynaMIT and Dynus-T, it might be possible to model non-recurrent congestion, detect real-time queues, and generate queue warning information and disseminate it to travelers.

- MI's APIs can support all the performance measures and functions needed for this application, but MI might be unsuitable if its spatial coverage exceeds corridors, while ME can cover up to regional-level network.
- HYT also provides APIs that would enable non-recurrent congestion modeling and real-time queue detection. However, it is difficult to generate warning messages and disseminate them to travelers as HYT is incapable of controlling traveler behaviors (i.e., driver compliance, route diversion, speed change) in response to queue warning information.
- ACT allows the user to customize its source codes and thus is able to model non-recurrent congestion and detect queues in real-time. But, ACT is insufficient to handle the behaviors of selected individual travelers advised by queue warning messages.
- The measures of work zone-related crashes (S.d), average incident clearance time (C.a), and perceived adequacy (I.a) were identified as gaps for all the modeling tools as no existing modeling tools support such measures.
- The gaps and challenges are summarized in Tables D-9 and D-10 in Appendix D.

5.2.2. Dynamic Speed Harmonization (SPD-HARM)

- SPT is not able to detect the traffic congestion in real-time that is crucial to determining safe speed advisory information. Modeling non-recurrent congestion conditions is also unavailable.
- Like SPT, MA is unable to model non-recurrent incidents or to capture real-time queues for determining safe target speeds.
- Some open-source MEs are able to model non-recurrent congestion, detect real-time congestion, generate target safe speed information, and disseminate it to travelers. Thus, it is necessary to customize such MEs by modifying source codes. For example, Dynus-T, an open-sourced mesoscopic tool, is capable of capturing the real-time traffic information and disseminating it to drivers through VMS. It is also known that it can accommodate external algorithms to generate target speed information by modifying its source code.
- As long as proper APIs are developed, MI appears likely to support all the performance measures and functions needed for this application. However, MI is insufficient to model driver behavior unless proper methods are provided. It is also known that MI finds it challenging to deal with large-scale networks larger than corridor level.
- APIs embedded in HYT can support the modeling non-recurrent congestion and real-time traffic congestion detection. However, it is difficult to generate target speed and disseminate it to travelers as HYT is incapable of controlling traveler behaviors (i.e., driver compliance, route diversion, speed change) in response to the target speed.
- AC might be able to model non-recurrent congestion and to detect queues in real-time by allowing the source code modifications. However, ACT is insufficient to handle the behaviors of selected individual travelers advised by target speeds.
- The measures of work zone-related crashes (S.d), average incident clearance time (C.a), and perceived adequacy (I.a) were identified as gaps for all the modeling tools as no existing modeling tools support such measures.
- The gaps and challenges are summarized in Tables D-11 and D-12 in Appendix D.

5.2.3. Cooperative Adaptive Cruise Control (CACC)

- SPT is not able to monitor real-time traffic conditions that are crucial to calculating target speed for CACC vehicles. Modeling non-recurrent congestion conditions is not available with SPT.
- MA cannot model non-recurrent incident and capture real-time traffic condition. Thus, it is not possible to calculate CACC target speed.
- By customizing the source codes of some MEs, it is possible to develop a simulation test-bed dealing with non-recurrent congestion, detect real-time congestions, and generate target safe speed information for CACC and disseminate it to CACC travelers. ME tools are not available to control driver behaviors responding to CACC information.
- MI's APIs can support all the performance measures and functions needed for this application, but MI might not be able to cover a regional-level network. MI is unable to control the behaviors of drivers in response to the advisory information from CACC within the off-the-shelf modeling capability.
- HYT provides APIs that would enable non-recurrent congestion modeling and real-time queue detection. However, it is difficult to determine optimal target speeds for CACC vehicles and to disseminate it to the CACC travelers as HYT is incapable of controlling traveler behaviors (i.e., driver compliance, route diversion, speed change).
- ACT allows modifying its source codes and thus is able to model non-recurrent congestion and capture real-time traffic condition. But, ACT is insufficient to handle the behaviors of CACC travelers in response to the target speed.
- The measures of work zone-related crashes (S.d), average incident clearance time (C.a), and perceived adequacy (I.a) were identified as gaps for all the modeling tools as no existing modeling tools support such measures.
- The gaps and challenges are summarized in Tables D-13 and D-14 in Appendix D.

5.3. Multi-Modal Intelligent Traffic Signal System (M-ISIG) Bundle

This section presents the gaps and challenges identified in the M-ISIG bundle for each modeling tool.

5.3.1. Intelligent Traffic Signal System (ISIG)

- SPT and MA are not able to capture real-time traffic congestion information that is crucial for determining optimal signal timing plans. Neither modeling tool can control intersection signal operation in real-time.
- ME is capable of capturing real-time traffic congestion. To generate optimal signal timing plans and handle traveler behavior in response to the optimal signal control, ME must be enhanced by customizing its source code. ME is not capable of generating pedestrian-related performance measures.
- MI's APIs enable support for all the crucial functions required for this application while its spatial coverage must be corridor-level or less. However, new APIs must be developed.

- HYT can generate optimal timing plans based on the detected real-time traffic congestion information, but is not able to control traveler behaviors in response to the optimal timing plans. HYT is incapable of capturing pedestrian-related performance measures.
- With proper source code modifications, ACT appear to generate optimal timing plans based on the detected real-time traffic congestion information and to control traveler behaviors in response to the optimal timing plans. However, ACT is insufficient to produce pedestrian-related performance measures.
- The measures of work zone-related crashes (S.d), average incident clearance time (C.a), and perceived adequacy (I.a) were identified as gaps for all the modeling tools.
- The gaps and challenges are summarized in Tables D-15 and D-16 in Appendix D.

5.3.2. Transit Signal Priority (TSP)

- SPT and MA are not able to capture the real-time information of a transit vehicle (e.g., position, speed, and number of passengers) that is crucial for this application. Neither modeling tool can accommodate an intersection's transit priority signal. SPT and MA are insufficient to produce intersection crash measures.
- ME is incapable of detecting the real-time information about a transit vehicle that is needed to determine an optimal TSP.
- There exist numerous off-the-shelf APIs for MI's TSP that can be used with minimum modification to accommodate the wireless communications. MI's API appears to be suitable for real-time intersection signal control and travelers' behavior control. However MI's spatial coverage is insufficient to cover a regional-level or larger study area.
- HYT's API capabilities can cover real-time transit vehicle detection, optimal TSP generation, and traveler behavior control. HYT-based TSP applications can be applied to relatively larger network covering regional area, but new APIs must be developed.
- ACT appears to be capable of modeling transit vehicles for TSP operation and generating the optimal TSP plans. However, to this end, ACT must be customized by modifying its source codes. The successfully customized ACT can cover regional level study area.
- The gaps and challenges are summarized in Tables D-17 and D-18 in Appendix D.

5.3.3. Mobile Accessible Pedestrian Signal system (PED-SIG)

- The most crucial elements of this application are i) modeling pedestrian-based signal on-demand calls and ii) modeling various types of pedestrians (e.g., normal and visually impaired pedestrians). SPT, MA, ME, HYT, and ACT are not able to handle such functional requirements as they are based on aggregated demands. Thus, those tools do not support pedestrian-related performance measures.
- For this application to be implemented within MI, proper APIs must be developed to model pedestrian calls and pedestrian types. However, it is difficult to model the behavior of visually impaired pedestrian within the MI framework.
- The average incident clearance time measure (C.a) was identified as a gap that all the modeling tools cannot support for this application.
- The gaps and challenges are summarized in Tables D-19 and D-20 in Appendix D.

5.3.4. Emergency Vehicle Preemption (PREEMPT)

- SPT, MA, and ME are not able to model emergency vehicles (e.g., departure time, route, and desired speed), which are the key elements of this application. Thus, those modeling tools cannot produce emergency vehicle travel times as one of the required performance measures.
- There exist numerous off-the-shelf methodologies such as API, hardware-in-the-loop simulation (HILS), and software-in-the-loop simulation (SILS) for evaluation of preemption logic. Such methodologies can be easily applied to this application with some efforts to accommodate wireless communications. However MI's spatial coverage is insufficient to cover areas larger than corridors.
- HYT's API capabilities enable not only emergency vehicle modeling, but also capture the real-time information of such emergency vehicles. Through APIs, HYT can place preemption calls and control intersection signals in response to the preemption calls. However unlike MI, no existing APIs handling preemption are reported, so it will be necessary to develop new APIs.
- ACT is capable of handling this application given a customized ACT program that is modified from original source code to capture preemption vehicles, place preemption calls, and control intersection signals in real-time. The successfully customized ACT can cover regional level study areas.
- This application needs the measures of average incident clearance time (C.a) and perceived adequacy (I.a), but those measures are not obtainable with existing modeling tools, resulting in gaps for this application.
- The gaps and challenges are summarized in Tables D-21 and D-22 in Appendix D.

5.3.5. Freight Signal Priority (FSP)

- SPT, MA, and ME are not able to capture the real-time information (e.g., position, speed, number of passengers) of a freight vehicle (e.g., truck, train) that is crucial in this application. Those modeling tools cannot implement an intersection's priority signal.
- There exist numerous off-the-shelf APIs for priority signal logic that have been used for transit signal priority. Such APIs can be converted to FSP logic with some modification efforts to accommodate wireless communications and freight vehicles instead of transit vehicles. MI's API is suitable for real-time intersection signal control, but its spatial coverage is insufficient to cover regional level study areas.
- HYT is insufficient to capture freight vehicles' real-time information, which means it is incapable of generating preemption calls and controlling intersections in response to the preemption of freight vehicle within the HYT framework.
- ACT might be able to model freight vehicles and control the intersection based on preemption calls. However, ACT must be customized by enhancing the original source code to accommodate such special vehicle modes. The successfully customized ACT might cover a larger area than MI.
- The gaps and challenges are summarized in Tables D-23 and D-24 in Appendix D.

5.4. Integrated Dynamic Transit Operations (IDTO) Bundle

This section presents the gaps and challenges identified in the IDTO bundle for each modeling tool.

5.4.1. Connection Protection (T-CONNECT)

- SPT and MA are not able to model pedestrian hold message requests and transit vehicles in response to the hold message. Thus, neither modeling tool is able to determine the feasibility of holding a transit vehicle for passenger delay minimization. SPT is also unable to calculate transit vehicle occupant delay.
- ME is incapable of modeling pedestrian-based hold message requests, but it can determine the feasibility of the holding message by customizing the source codes. Despite this, ME is probably not able to control a transit vehicle in response to the holding message.
- MI's APIs enable it to support all the functions required for this application, although its spatial coverage must be corridor-level or smaller.
- HYT and ACT do not have the proper capabilities, including APIs, to handle functions for this application.
- The measure of perceived adequacy (I.a) was identified as a gap that none of the modeling tools can support for this application.
- The gaps and challenges are summarized in Tables D-25 and D-26 in Appendix D.

5.4.2. Dynamic Transit Operations (T-DISP)

- SPT and MA are insufficient to support this application as they are not able to model dynamic transit route changes in response to real-time requests. They are also unable to develop the best route for transit vehicles to pick up the requesters as they are based on aggregated static traffic assignment.
- With some open-source programs, ME can be customized to handle crucial functional requirements for this application, such as dynamic transit route changes and best transit route selections. However, to this end, it is necessary to modify source codes.
- MI's API appears to be suitable for implementing this application as it enables MI to model dynamic transit route changes and to generate the best paths for specialized transit vehicles. However MI's spatial coverage is insufficient to cover regional level study areas.
- HYT and ACT appear to be incapable of modeling dynamic transit routes changes and best transit route selections.
- The perceived adequacy measure (I.a) was identified as a gap that none of the modeling tools can support for this application.
- The gaps and challenges are summarized in Tables D-27 and D-28 in Appendix D.

5.4.3. Dynamic Ridesharing (D-RIDE)

- In this application, modeling the ride-sharing request and ride-sharing vehicles is crucial. However SPT and MA are not able to meet these critical modeling requirements.
- ME might be able to model the ride-sharing request and ride-sharing vehicles by enhancing some ME programs if the source codes are available. However, significant customization will be required.
- MI's APIs enable it to support all the functions required for this application, although its spatial coverage must be corridor-level or smaller.
- HYT and ACT appear to be incapable of modeling the ride-sharing request (e.g., locations and request frequency and time) and ride-sharing vehicles' behaviors.
- The measures of average incident clearance time (C.a) and perceived adequacy (I.a) were identified as a gap that none of the modeling tools can support for this application.
- The gaps and challenges are summarized in Tables D-29 and D-30 in Appendix D.

5.5. Freight Advanced Traveler information System (FRATIS) Bundle

This section presents the gaps and challenges identified in the FRATIS bundle for each modeling tool.

5.5.1. Freight Real-Time Traveler Information with Performance Monitoring (F-ATIS)

- The sketch planning tool (SPT) does not consider truck-related performance measures (e.g., commercial vehicle occupant delay). SPT cannot handle freight vehicles, operator behaviors (e.g., driving characteristics, route or mode changes), and real-time traffic information detection, which are crucial for route guidance information.
- MA is insufficient to produce freight-related measures. Since MA is based on static traffic assignment techniques, it is not able to implement ATIS applications requiring real-time traffic information capture and real-time route guidance generation and dissemination.
- Due to ME's nature dealing with aggregated demand, unlike MI, ME is not capable of modeling freight vehicles, which need to be properly modeled in this application. Some MEs such as DynaMIT and DynusT can be customized by source code modifications to detect real-time traffic information and generate route guidance information.
- With API capability that can provide proper interfaces overcoming the gaps, the microscopic modeling tool (MI) appears to support all the performance measures except for C.a, I.a, and functions needed to evaluate the ATIS application. However, MI is not suitable to cover state- and regional-level networks.
- HYT's APIs have limitations in modeling freight vehicles (e.g., truck or train and departure time, desired speed, and origin-destination) and controling truck operator behaviors (e.g., route change, destination change).

- It will be necessary to customize AC by modifying source code to deal with freight-related functions (e.g., modeling freight vehicles and freight operator behaviors), performance measures (e.g., commercial vehicle delays) and route guidance for freight modes.
- The measures of average incident clearance time (C.a) and perceived adequacy (I.a) were identified as gaps for all the modeling tools considered in this project as no existing modeling tools support such measures.
- The gaps and challenges are summarized in Tables D-31 and D-32 in Appendix D.

5.5.2. Drayage Optimization (DR-OPT)

- The sketch planning tool (SPT) is not able to produce freight-related performance measures (e.g., commercial vehicle occupant delay and goods inventory delay). SPT cannot model drayage vehicles (e.g., arrival time and loading/unloading time); as a result, incorporating proper drayage optimization methods to determine optimal drayage operations will be problematic for SPT.
- MA is unable to produce freight-related measures and to model drayage vehicles. Like SPT, MA is insufficient to determine optimal drayage operations.
- In order to generate optimal drayage operations using ME, the source code must be customized, but ME may still be unable to model drayage vehicles.MI's API can cover all the functions and the performance measures for this application as long as proper APIs are developed.
- HYT is not able to support drayage vehicle modeling or the incorporation of drayage optimization methods to determine the best drayage optimization strategies.
- Customization of AC by modifying source code will be necessary to model drayage vehicles and to implement optimal drayage operation strategies properly.
- The gaps and challenges are summarized in Tables D-33 and D-34 in Appendix D.

5.5.3. Freight Dynamic route Guidance (F-DRG)

- The sketch planning tool (SPT) cannot consider truck-related performance measures (e.g., commercial vehicle occupant delay). SPT cannot model freight vehicles (e.g., truck or train, departure time, desired speed, origin-destination) and detect real-time traffic information, which is crucial for the development of route guidance information.
- MA is insufficient to produce freight-related measures. Due to MA's static traffic assignment nature, it is not able to implement ATIS applications requiring real-time traffic information capture and real-time route guidance generation and dissemination.
- Some MEs such as DynaMIT and DynusT can be enhanced by customized source code modifications to produce freight-related performance measures, but cannot explicitly control individual freight vehicles. To implement a route guidance feature with such open-source MEs, it is necessary to customize the program by modifying their source codes.
- MI's APIs enable it to consider freight vehicles and implement real-time route guidance for freight operators. However, MI is not suitable if the coverage of this application exceeds a medium-sized area.

- HYT's APIs make it difficult to model freight vehicles (e.g., truck or train, departure time, desired speed, and origin-destination) and to produce freight vehicle delay measures.
- It is necessary to modify source codes for AC to deal with freight-related functions (e.g., modeling freight vehicles and freight operator behaviors), performance measures (e.g., commercial vehicle delays) and route guidance for freight modes.
- The measures of average incident clearance time (C.a) and perceived adequacy (I.a) were identified as gaps for all the modeling tools as no existing modeling tools support such measures.
- The gaps and challenges are summarized in Tables D-35 and D-36 in Appendix D.

5.6. Response, Emergency Staging, Communications, Uniform Management and Evacuation (R.E.S.C.U.M.E.)

This section presents the gaps and challenges identified in the RESCUME bundle for each modeling tool.

5.6.1. Emergency Communications and Evacuation (EVAC)

- SPT cannot model evacuees and special vehicles for evacuees. It is also impossible to create real-time evacuation guidance by using real-time traffic information due to its static assignment nature. SPT does not support the measures of emergency vehicle route travel time and crashes at intersections.
- Since MA is based on static traffic assignment, it is not suitable for this application, which is based on dynamic traffic assignment and requires the capability to capture real-time traffic information and generate real-time route guidance for evacuees. Like SPT, MA is incapable of capturing the measures of emergency vehicle route travel time.
- ME is not suitable for this application because it is unable to deal with individual vehicles.
- MI's API enables explicit modeling of evacuees and special evacuation vehicles. MI also appears to support all the performance measures—except for C.a and I.a—and other functions needed in this application. However, MI is not suitable to cover state- and regional-level evacuation plans due to its computational burden for such large scale networks.
- HYT's APIs are not capable of modeling passive evacuees and controlling special vehicles for evacuations.
- It is very difficult to consider passive evacuees with ACT as it does not support any interfaces to control such specific travelers.
- The measures of average incident clearance time (C.a) and perceived adequacy (I.a) were identified as gaps for all the modeling tools considered in this project as such measures can be evaluated through external models other than existing modeling tools for DMA.
- The gaps and challenges are summarized in Tables D-37 and D-38 in Appendix D.

5.6.2. Incident Scene Pre-arrival Staging Guidance for Emergency Responder (RESP-SIG)

- SPT is not suitable for this application as it is not able to model emergency responders and incidents. SPT does not support transit- or freight-related measures or the emergency vehicle route travel time that is crucial for this application.
- MA is not able to consider emergency responder and incidents in its framework. Like SPT, MA is incapable of capturing the measures of emergency vehicle route travel time.
- ME is not suitable for this application as emergency responders are considered special individual modes.
- MI is able to model emergency responders by developing new APIs. MI also appears to model hypothetical incident situations through new APIs, but its spatial coverage is insufficient to support activity at the regional level or larger.
- HYT's APIs are known to have difficulty modeling emergency responder behaviors and are insufficient to produce the emergency vehicle travel time measure.
- ACT does not have the capability to model either emergency responders or incident situations.
- The measure of average incident clearance time (C.a) was identified as a gap for all the modeling tools.
- The gaps and challenges are summarized in Tables D-39 and D-40 in Appendix D.

5.6.3. Incident scene Work zone Alerts for Drivers & Workers (INC-ZONE)

- SPT is not able to make incident situation and detect it in real-time.
- MA is incapable of modeling incident situation and real-time incident detection. MA is not able to capture vehicles adjacent to the incident scene as it depends on aggregated OD-based static assignment model.
- Despite its open-source feature, ME is not able to control the vehicles near the incident scene. Thus, ME is not suitable for this application.
- It is necessary to develop new APIs to model incident scene (e.g., occurrence time, location, work zone size, severity) and capture and control the vehicles near the incident scene to provide safe speed advisory information. MI would be suitable as the coverage of this application would not exceed a corridor.
- HYT and AC are not able to support incident scene modeling which is crucial element for this application.
- The measures of average incident clearance time (C.a) and perceived adequacy (I.a) were identified as gaps.
- The gaps and challenges are summarized in Tables D-41 and D-42 in Appendix D.

5.6.4. Mayday Relay

- While modeling run-off-road crashes (e.g., location, occurrence time, and mayday dissemination) is the most crucial element for this application, no modeling tools but MI are able to handle its needs.
- MI is able to model the run-off-road crash case with a newly developed API.
- The measure of perceived adequacy (I.a) was identified was a gap for all the modeling tools.
- The gaps and challenges are summarized in Tables D-43 and D-44 in Appendix D.

6. Modeling Approach

6.1. Enable ATIS Bundle

This section presents a modeling approach for the E-ATIS bundle to provide researchers and stakeholders who potentially implement the application in the future with recommendations on how to model each application using the current state-of-the-art and the state-of-the-practice modeling tools.

Figure 6-1 shows a high-level data flow diagram for the E-ATIS bundle. In a Connected Vehicle regime, the data covering traffic information, incidents, weather condition, and parking facilities can be collected by not only a traffic management center but also by communications device-equipped vehicles. The collected data will be used for generating both real-time and predicted guidance information to provide travelers with the route alternatives and the expected travel times of the routes. The guidance information will be disseminated to multi-modal travelers through Connected Vehicles, variable message signs (VMS), broadcasting, and personal mobile devices, with the end result of enabling travelers to make better departure time, mode, and route choices.

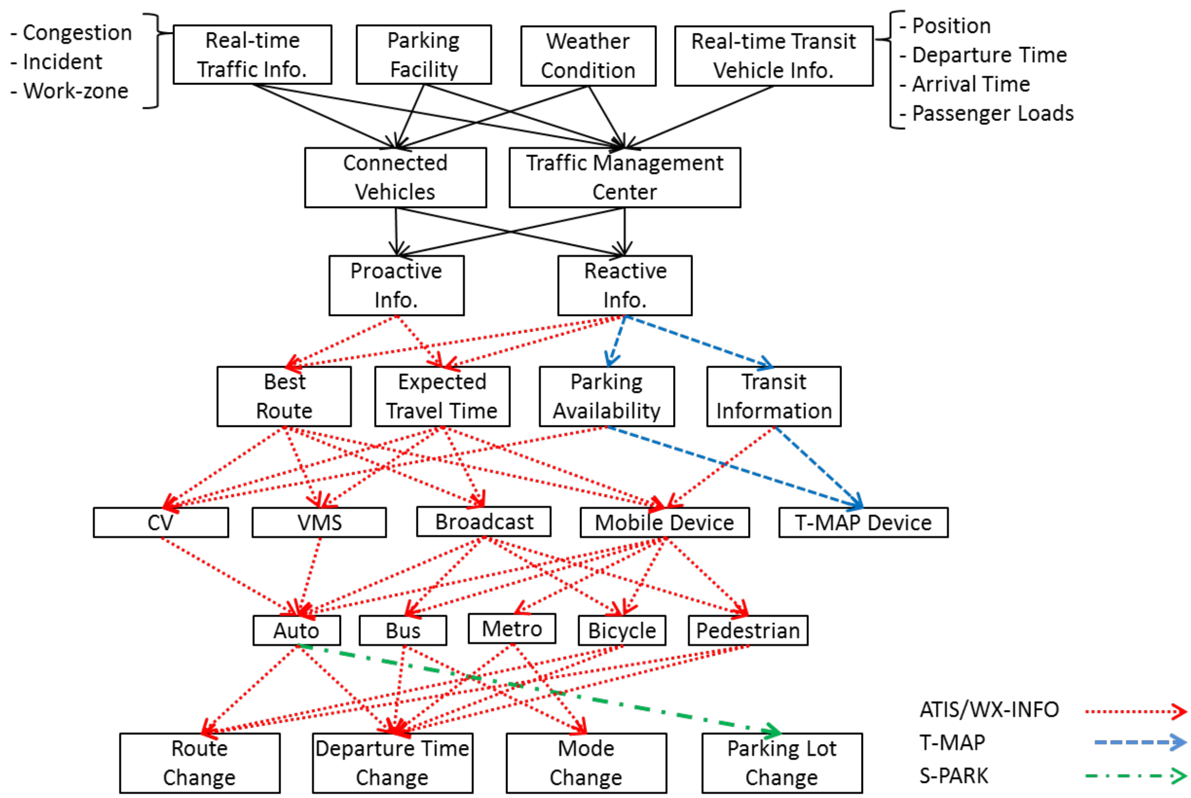

Figure 6-1. E-ATIS Flow Diagram.

The fundamental outcome of E-ATIS applications is to provide travelers with information about available travel alternatives, so the most basic modeling need related to the E-ATIS bundle is the discrete choice model. Each traveler's choice depends on a number of microscopic factors (e.g., origin and destination, trip type, traveler preference, and risk) and the collective impact of these choices will be shifts in demand patterns on the larger system. Thus, modeling E-ATIS could require a hierarchy of modeling approaches. A microscopic model is well-suited to examine the cumulative impact of individual traveler choices on observable transportation variables given the transportation and traveler characteristics at a particular site. For example, a microscopic simulation could provide estimates for changes in demand in response to changes in freeway travel time, taking into consideration the distribution of traveler origins and destinations, available alternatives, etc. Knowledge of how demand will respond to changes in freeway travel time could be used in larger-scale models to estimate more systemic impacts.

With respect to the selection of proper modeling tools to successfully accommodate proposed modeling approaches, it is necessary to note that the applications dealt with in this section are prepared for meso- and micro-scopic as well as activity-based modeling tools based on the findings in Section 5. The modeling approach for a large-scale network proposed in this section for the E-ATIS bundle of applications focuses on the activity-based modeling tool. In addition, the project team suggests a multi-scale modeling approach combining a microscopic and a mesoscopic tool might be suitable for dealing with a large-scale network covering a metropolitan planning organization (MPO) or State-level network. However, both tools are insufficient to capture an individual vehicle's instantaneous information, which is a crucial element for the E-ATIS bundle of applications as it is unable to handle an individual vehicle. It is necessary to note that the hybrid model would also be unable to handle individual vehicles for the entire network because they are considered only for a narrowed area of the network. Thus, it is challenging to model individual vehicle-related features such as obtaining real-time traffic information from equipped vehicles as well as travelers' traveling behaviors (e.g., lane changing, car following, and route selection in response to the E-ATIS information).

Proposed Modeling Tools

For the activity-based model, the project team proposes the TRANSIMS and the MATSim model – two activity-based models – that are open source programs, and it appears to be appropriate for handling large-scale networks while capturing an individual vehicle's instantaneous information; a crucial element for realizing Connected Vehicle-based applications. However, it must be noted that the TRANSIMS and MATSim models do not support any user interfaces (e.g., API or COM) to enable handling individual vehicles during the simulation. Thus, the modeling approach proposed for each E-ATIS application is based on the assumption that the TRANSIMS model can be customized in the near future. Each modeling approach section describes how to accommodate individual vehicular information by TRANSIMS.

The microscopic modeling tool was selected because it can precisely simulate each E-ATIS application as described in its concept of operations while it would be suitable for small scale network such as multiple corridors or a small region. However, as identified in Section 5, there are numerous modeling elements that are beyond the off-the-shelf capabilities of the available microscopic modeling tools, such as real-time route change and user-defined signal adjustment. For those elements, necessary API-type external modules need to be developed. The following sections describe how to design such API modules.

While developing a modeling approach, the study team determined that the most challenging component of modeling applications is how to handle traveler behavior such as route choice, mode choice, car following, and lane changing in response to the information provided by dynamic mobility application. Moreover, modeling such traveler behaviors under a Connected Vehicle environment is challenging due to lack of proper data identifying the relationships between traveler behavior and the Connected Vehicle environment. This report proposes two options to deal with traveler behavior: one is choice model-based approaches proposed by several researchers (Ben-Akiva and Lerman, 1985; Cascetta et al., 1996; Koppelman and Wen, 1998; Ramming, 2002; Bovy et al., 2008) and the other one is scenario-based sensitivity analysis.

The choice model approach, based on either the Logit or the Probit model, estimates the probability of a traveler's decision to select one out of all other competitive alternatives by using the utility function developed for each alternative. Thus, it is crucial to obtain proper utility functions but obtaining and calibrating such models are challenging. While this approach sounds theoretical in explaining the behavior of travelers, it must be noted that it is typically quite expensive and often not reliable when stated preference (SP) data instead of revealed preference (RP) data is used. It is also noted that only SP data can be obtained at this point as each dynamic mobility application is based on the Connected Vehicle, which is not available yet.

The sensitivity analysis assumes the compliance of a traveler for selecting one alternative among other competitive alternatives by simulating a range of plausible compliance rates (e.g., from 10 percent to 90 percent by 10 percent increment). For example, assuming a traveler's compliance rates for choosing the alternative routes are 60 percent, 30 percent, and 10 percent for the best, second, and third shortest paths, respectively, the behavior of traveler's path selection can be simulated based on a Monte Carlo simulation approach. It should be noted that the compliance rates can be obtained by an experimental design approach such as full factorial method and Latin Hypercube Sampling to create unbiased compliance rate scenarios. While the sensitivity analysis sounds like an ad-hoc approach that would be insufficient to precisely capture the behavior of travelers and requires numerous simulation replications to cover the diversity of choice behaviors, this approach enables a dramatic reduction in the cost and effort to build behavior models.

It is worth noting that the use of highway driving simulators (FHWA, 2010; NHSTA, 2011) may be a viable option to support the modeling of driver behavior. For example, for one of its exploratory advanced research (EAR) projects, FHWA has led an innovative research effort employing a highway driving simulator to examine driver behaviors (e.g., lane changing and car following) in response to external stimuli such as an aggressive driving and a sudden stop. With the driving simulator, one might be able to capture how drivers react to guidance information in a Connected Vehicle environment. Such reaction data can be useful for building accurate behavior models.

6.1.1. Multimodal Real-Time Traveler Information (ATIS)

6.1.1.1. Review of existing modeling efforts

While ATIS or route guidance has been widely studied through simulation modeling (Ben-Akiva et al., 1997; Wunderlich, 1998; Bottom et al., 1999; Farver, 2005), the multimodal real-time traveler information system in a Connected Vehicle environment has not been well studied. Lee and Park (2008) developed multiple route-guidance strategies and implemented them in a VISSIM simulation using an API. The study developed a simulation-based Connected Vehicle test-bed. Using the test-bed, the study created four plausible guidance strategies based on probe data: the latest link travel time (LTG), the averaged link travel time (ATG), individual vehicular path travel time (RTG), and predicted link travel times (PTG) by a dynamic traffic assignment (DTA) technique. The study examined the best guidance strategy through an experimental design approach with the following factors: 1) the market penetration rates of communication device-equipped vehicles, 2) drivers' compliance rates to the guided route information, 3) guidance information dissemination interval, and 4) traffic congestion levels. Intensive simulation-based evaluations concluded that the guidance that used the averaged link travel times of roadways outperformed the other strategies for mobility performance measures.

6.1.1.2. Modeling approach

The following are the core modeling components identified in the findings in Section 5:

- Capturing real-time traffic information (to realize Connected Vehicle technology)
- Driving behavior model (e.g., car following, lane changing in response to the ATIS information)

- Traveling behavior model (e.g., pre-trip route selection and mode selection and en-route route selection and mode transfer)
- Multi-modal simulation covering auto, transit (e.g., bus and metro), and pedestrian
- Dynamic k-shortest path algorithm
- Dynamic origin/destination matrix estimation

Incorporating the above modeling components, the ATIS application can be modeled by microscopic and activity-based modeling tools. This section describes the modeling approach and discusses potential research needs for each modeling approach.

Mesoscopic Tool-Based Modeling Approach

While the mesoscopic tool is appropriate for handling large-scale networks, it is not capable of capturing instantaneous information from individual vehicles, which is essential to realizing the Connected Vehicle-based traveler information system. Thus, one challenge is to model individual vehicle-related features such as retrieval of real-time traffic information from equipped vehicles and drivers' travel behaviors (e.g., lane changing, car following, and route selection in response to ATIS information)

To collect real-time traffic information from such equipped vehicles within the mesoscopic modeling framework, it is necessary to use aggregated link-based measures such as average travel time, or delay. Incorporation of the market penetration rate of Connected Vehicle technology is not available because of the uniform treatment of individual vehicles within a mesoscopic simulation. In order to obtain an aggregated link-based measure and develop/implement route guidance, it is necessary to customize the mesoscopic program (only applicable to open source programs such as DynaMIT and Dynus-T) as no API-type external plugins are available. This customization is also necessary to handle the movement of travelers to reflect the en-route route change decisions.

With respect to the traveler behavior, almost all mesoscopic modeling tools provide both pre-trip and en-route route selection models that are based on research conducted by Ben-Akiva and others within the context of given off-the-shelf functionalities. However, neither pre-trip nor en-route mode choice models are available in the mesoscopic tool. It is possible to incorporate the pre-trip/en-route mode shift on top of the mesoscopic modeling tools by employing choice models proposed by several researchers (Ben-Akiva and Lerman, 1985; Cascetta et al, 1996; Koppelman and Wen, 1998; Ramming, 2002; Bovy et al., 2008). For instance, the utility functions given in the mode shift model consist of travel times for each mode competing with each other; thus, as long as it is possible to obtain travel time for each mode at every update interval, both pre-trip and en-route modal shift can be modeled. It must be clearly noted that both route choice and mode shift models should be calibrated based on proper data sets before they are applied; however, collecting such data sets would require tremendous time and effort.

Another challenge for the mesoscopic modeling approach is that existing mesoscopic tools do not support the pedestrian mode. However, for a large-scale evaluation of ATIS, it might be acceptable to ignore the pedestrian mode with the mesoscopic modeling tools.

One of crucial elements in the ATIS application is finding the shortest path based on collected traffic information at every update interval. Existing mesoscopic modeling tools have embedded a proper algorithm to build multiple paths (a.k.a., k-shortest paths). Furthermore, a dynamic OD table for each mode might be the most critical input data for the evaluation of the ATIS application. A few relevant research efforts to obtain the dynamic OD tables exist; the most notable approaches are found in Van Aerde (1997), Ashok and Ben-Akiva (2000), and Bierlaire and Crittin (2004). These approaches can be incorporated as an external module for the mesoscopic modeling tool for estimating dynamic ODs.

Microscopic Tool-Based Modeling Approach

A microscopic simulation model is suitable for the evaluation of ATIS because it requires multimodal modeling, route-guidance to each traveler, and the emulation of traveler behavior. However, it might be inefficient in covering a regional or State-level study area. It is clear that the microscopic simulation model can generate measures needed to assess the ATIS performance, although some measures, including fuel consumption, emissions, and safety, require external modules. As no proper method/data to model traveler behavior is available, the traveler behavior model needs to be developed and calibrated.

Emulated real-time information can be generated relatively easily from a microscopic traffic simulation modeling tool, but the challenges are how to estimate dynamic origin-destination (OD) demand and how to calibrate/validate the simulation. Assuming real sensor counts are available, dynamic OD can be estimated by utilizing existing estimation methods (Ashok and Ben-Akiva, 2002; Van Aerde, et al., 2003). Traffic simulation models can be calibrated and validated using the performance data made available by Connected Vehicle technology and the systematic procedures developed by Park et al. (2005).

There are at least two options available to realize traveler behavior under the ATIS implementation. As mentioned in the previous section, one is to develop and calibrate the traveler behavior model by using existing choice modeling approaches proposed by Ben-Akiva (1985), Ramming (2002), and Bovy et al. (2008) and by collecting behavior data. The other approach is to conduct sensitivity analyses based on assumed traveler behaviors and quantify impacts through a modeling approach. Sensitivity analysis on driver's compliance behavior can be implemented by simulating a range of plausible compliance rates (e.g., from 10 percent to 90 percent by 10 percent increments).

In summary, the following is the list of APIs required for the microscopic modeling approach for the ATIS application.

New API:

- *Real-time traveler control (e.g., en-route path change and departure time adjustment)*
- *Capturing real-time vehicular information(e.g., position, speed, travel time, and route)*

New API to be supported by external models:

- *Choice model-based traveler behavior model (e.g., decision on mode choice, route selection, departure time change, and traveler compliance in response to the given information)*
- *Sensitivity analysis for travel behavior*
- *Optimal path generation based on a k-shortest path algorithm*

Non-API type external module:

- *Performance measure generation (e.g., safety (SSAM), emission and energy (VT-Micro model))*

Activity-Based Modeling Approach

An activity-based modeling tool requires customization of the program source code to handle real-time individual vehicle-related features such as the ability to obtain real-time traffic information from equipped vehicles and drivers' traveling behaviors (e.g., lane changing, car following, and route selection in response to ATIS information).

It is certainly possible to collect real-time traffic information (e.g. delay, travel time, or incident information) from equipped vehicles within the TRANSIMS simulation framework, as long as it is properly customized, and, consequently, to obtain instantaneous vehicular information for individual vehicles, such as position, origin and destination, and speed.

With respect to traveler behavior, the activity-based modeling tool provides both pre-trip and en-route route selection models that are based on a choice modeling approach conducted by several researchers (Ben-Akiva and Lerman, 1985; Cascetta et al, 1996; Koppelman and Wen, 1998; Ramming, 2002; Bovy et al., 2008) within the context of given off-the-shelf functionalities. However, neither pre-trip nor en-route mode choice models are available in the activity-based modeling tool. It is possible to incorporate the pre-trip/en-route mode shift on top of the activity-based modeling tools by employing choice models proposed by several researchers (Ben-Akiva and Lerman, 1985; Cascetta et al, 1996; Koppelman and Wen, 1998; Ramming, 2002; Bovy et al., 2008). For instance, the utility functions given in the mode shift model consist of the travel times for each mode competing with each other; thus, as long as it is possible to obtain travel time for each mode at every update interval, both pre-trip and en-route model shift can be modeled.

One of the crucial elements in the ATIS application is finding the shortest path based on collected traffic information at every update interval. The activity-based modeling tool has embedded a proper algorithm to build multiple paths (a.k.a., k-shortest paths). Furthermore, a dynamic OD table for each mode might be the most critical input data for the evaluation of the ATIS application. There exist a few relevant research efforts to obtain the dynamic OD tables; the most notable approaches are found in Van Aerde, et al. (2003), Ashok and Ben-Akiva (2002), and Bierlaire and Crittin (2004). These approaches can be incorporated as an external module for the activity-based modeling tool for estimating dynamic ODs.

Multi-Scale Modeling Approach

The project team proposes a multi-scale modeling approach to incorporate a microscopic modeling approach with a mesoscopic modeling tool (e.g., Dynus-T, DynaSMART) to assess the impact of the ATIS application on a large-scale network. It should be noted that the mesoscopic modeling tool is considered to be more suitable for the multi-scale modeling approach tool than the activity-based modeling tool. This is because the mesoscopic modeling tool can ensure faster implementation for a large-scale network when it is incorporated with the microscopic modeling tool.

With a network as large as mesoscopic modeling tools can handle, it is possible to evaluate the performance of ATIS by using the microscopic modeling approach based on the various external factors such as Connected Vehicles market penetration rates, traffic congestion levels, and traveler compliance rates to the provided guidance information. Using an experimental design approach, numerous experimental scenarios can be built to cover a variety of external factors to examine the benefits of the ATIS application, such as travelers' travel time savings and travel time accuracy. For example, by capturing the travel times of travelers under the experiment scenario cases for both the ATIS and non-ATIS cases, it is possible to measure how much the ATIS users improved their travel time over the non-ATIS users.

It should be noted that the ATIS performances captured by the microscopic modeling approach can be modeled by either a parametric (e.g., regression model) or nonparametric (e.g., artificial neural network) approach. By examining the relationships between the performances of ATIS (i.e., output) and the external factors (i.e., inputs), a model relating the performance of ATIS and the external factors (e.g., vehicles market penetration rates, traffic congestion levels, and compliance rates) can be built.

With the ATIS performance function, the speed-density functions can be adjusted to reflect the impact of ATIS on the network. To this end, it is recommended to examine the speed-density relationship obtained from the microscopic modeling approach for the combination of external factors under the ATIS application case and find the optimal parameter coefficient set such as jam density, speed intercept, maximum flow rate, and model shape parameters (e.g., α and β). The adjusted speed-density function is fed into the mesoscopic modeling tool covering a large scale network to implement a DTA with initial OD demands. Once the DTA is complete, one can obtain OD travel times and link travel times, which are used for updating OD tables and routes for each OD pair. It is possible to adjust the initial OD demands using mode choice models, which take OD travel time, cost and transfer time as independent variables for their utility functions, if these mode choice models are given by a regional travel demand model. Likewise, with the link travel times obtained from the DTA, the best route for each modal OD pair can be updated. In particular, the travelers who are supposed to have real-time information accessibility through Connected Vehicles, 3G/4G mobile devices, or variable message signs can perform en-route route selection while the pre-trip routes are assigned to the travelers who have no access to the information. With the updated OD demands and routes, the DTA in the mesoscopic modeling approach is repeated until the network converges. Once the convergence is achieved, performance measures (e.g., travel time, throughput) will be calculated to examine the large-scale performance of the ATIS application.

6.1.2. Real-Time Route-Specific Weather Information (WX-INFO)

6.1.2.1. Review of modeling research efforts

Rakha et al. (2009) investigated the impacts of inclement weather on microscopic driving behaviors, such as car following, lane changing, and gap acceptance by using empirical data obtained through nation-wide weather stations. The research team developed several sub-models to be used for the longitudinal, latitudinal, and gap acceptance behaviors under adverse weather conditions and evaluated those models by using microscopic traffic simulation programs such as VISSIM and AIMSUN and mesoscopic simulation software such as INTEGRATION.

Mahmassani et al. (2009) developed a weather-sensitive DTA model for a Traffic Estimation and Prediction (TrEP) application by using DYNASMART-P. In order to accommodate the effect of adverse weather, the authors suggested considering changes from both supply side and demand side. On the supply side, weather conditions would impact the speed-flow-density relationship, capacity, saturation flow rate, and several traffic flow model parameters such as jam density, maximum densities, and model shape term coefficients. On the demand side, the weather conditions would reduce demand when drivers cancel their trips or shift the peak-hour if the drivers choose to either advance or postpone their trips due to the possibility of unsafe driving conditions. It is also worth noting that the research efforts introduced in the ATIS application can conceivably be expanded for the WX-INFO application by employing the same approaches addressed by Mahmassani et al. (2009) to deal with weather impacts on drivers and network.

Park et al. (2010) summarized the concept of operations for weather responsive traffic operations management strategies in the Traffic Analysis Toolbox Volume XI report. The authors addressed three weather responsive management strategies covering advisory, control, and treatment strategies under an inclement weather condition. The advisory strategy is to mitigate the impact of inclement weather by providing drivers with advisory information such as pre-trip and en-route route-guidance. The control strategy includes the manipulation of traffic control devices (e.g., variable speed limit signs, traffic signal controls, and ramp metering). The treatment strategy indicates the cooperation between management center and emergency agencies to keep roadway infrastructure safe under inclement weather conditions (e.g., variable message signs while de-icing a roadway). The report discussed case studies to demonstrate the impacts of the strategies by using DYNASMART-P for a VMS-based advisory strategy and CORSIM for a control strategy based on optimized corridor signal controls.

6.1.2.2. Modeling approach

Based on the findings in Section 5, the following core modeling elements are identified.

- Capturing real-time traffic information
- Weather-responsive traveler behavior model (e.g., car following, lane changing, route selection, mode choice, and departure time shift in response to weather condition)
- Multi-modal simulation covering auto, transit (e.g., bus and metro), and pedestrian
- Dynamic k-shortest path algorithm
- Dynamic origin/destination matrix estimation

This application follows a similar modeling approach as the ATIS application; the most notable distinction from ATIS is that it accommodates weather impacts. Thus, to incorporate the above modeling elements and enable the coverage of various network sizes, the WX-INFO application can be modeled using microscopic and activity-based modeling tools. This section describes the modeling approach and discusses research needs for each modeling approach.

Microscopic Tool-Based Modeling Approach

A microscopic simulation tool was identified as the most appropriate tool for the WX-INFO application because an existing API that simulates route-guidance (Lee and Park, 2008) and modeling fidelity allows for explicit consideration of individual travelers. Given this API, the WX-INFO application can be modeled relatively easily by adding a module dealing with the impact of weather on route-guidance (e.g., optimal path finding and weather-involved travel time estimation). The research results by Mahmassani et al. (2009) can be used for the adjustment of the supply parameters of the microscopic modeling tool (e.g., desired speed and minimum headway). Figure 6-2[4] shows freeway weather adjustment factors (WAFs) to adjust the coefficients of supply model parameters in DYNASMART to reflect various weather conditions. The WAF for free flow speed can adjust the desired speed of vehicles individually. Furthermore, using the flow-density relationship with the adjusted parameters such as jam density, free flow speed, and model shape parameters (i.e., α), it is possible to estimate minimum headway for microscopic modeling tools by adjusting the corresponding parameters (e.g., saturation flow rate adjustment).

Highway	Milemark	Station ID	Weather condition	k_{bp}	u_f	v_f	α	v_0	k_{jam}	RMSE[1]	R-sqrd[2]	# of obs.		Weather Adjustment Factor (WAF)[3]			
				(vpmpl)	(mph)	(mph)		(mph)	(vpmpl)	(reg.1)	(reg.2)	reg.1	reg.2	F_k_{bp}	F_u_f	F_v_f	F_f_{max}
I-64	283.5	48	Normal	25	61.2	205.4	10.5	2	225	7.18	0.80	23611	660	1.00	1.00	1.00	1.00
			Moderate Rain	14	54.1	72.1	4.6	2	225	9.86	0.52	315	64	0.56	0.88	0.35	0.74
			Heavy Rain	19	56.6	118.7	8.6	2	225	8.82	0.73	84	13	0.76	0.93	0.58	0.72
			Light Snow	11	58.1	68.1	3.3	2	225	8.86	0.43	116	88	0.44	0.95	0.33	0.79
I-64	282.2	50	Normal	30	65.7	87.2	2.0	2	225	5.85	0.34	11257	601	1.00	1.00	1.00	1.00
			Light Rain	28	63.1	99.3	3.5	2	225	7.51	0.84	1349	207	0.93	0.96	1.14	0.82
			Moderate Rain	21	61.9	98.2	4.8	2	225	5.07	0.65	224	19	0.70	0.94	1.13	0.77
			Heavy Rain	11	57.6	64.8	2.4	2	225	12.45	0.27	36	12	0.37	0.88	0.74	0.59
I-64	282.2	51	Normal	19	62.5	89.7	4.2	2	225	4.65	0.75	23153	10234	1.00	1.00	1.00	1.00
			Light Rain	15	61.0	81.8	4.4	2	225	6.74	0.80	1347	1968	0.79	0.98	0.91	0.87
			Moderate Rain	10	57.1	71.2	5.0	2	225	9.27	0.84	48	252	0.53	0.91	0.79	0.89
			Heavy Rain	16	61.6	85.5	4.6	2	225	6.11	0.91	36	49	0.84	0.99	0.95	0.72
			Light Snow	14	58.5	83.2	5.6	2	225	6.14	0.82	127	104	0.74	0.94	0.93	0.59

Figure 6-2. Weather Adjustment Factors

Additionally, the microscopic behavioral models obtained from Rakha et al. (2009) would be useful to calibrate the car following and lane changing models of the microscopic modeling tool under adverse weather conditions.

With respect to the weather conditions, microscopic models are incapable of simulating pre-trip travel decisions such as departure time change, trip cancelation, or mode shift. However, since such behaviors are typically modeled by choice modeling approaches (Ben-Akiva and Lerman, 1985), they can be reflected in the weather-responsive behaviors by updating the utility functions' input data (e.g., travel time, delay, or waiting time) as long as proper utility functions for such choice behaviors can be obtained.

With respect to the traveler behavior models crucial for supporting route-guidance simulation, two options are possible: 1) an analytical approach based on a traveler's choice model (e.g., Logit or Probit) and 2) a scenario-based sensitivity analysis. As mentioned above, the choice model-based approach would be the most

[4] Mahmassani H., et al. "Incorporating Weather Impacts in Traffic Estimation and Prediction Systems." FHWA. FHWA-JPO-09-065, EDL# 14497. 2009.

promising method in that it can precisely reflect drivers' route choice behavior. For the choice model approach, the utility functions given in the route choice model consist of travel times of each alternative path competing with each other; thus, as long as it is possible to obtain travel time for each path at every update interval, the real-time route shift can be modeled. On the other hand, the sensitivity analysis on drivers' compliance behavior can be implemented by simulating a range of plausible compliance rates (e.g., from 10 percent to 90 percent by 10 percent increments) in response to the given route information, but this approach requires a relatively large number of simulated scenarios.

In summary, the following is the list of APIs required for the microscopic modeling approach for the WX-INFO application.

Existing API:

- API developed for the ATIS application covering the following capabilities
  - Real-time traveler control (e.g., en-route path change and departure time adjustment)
  - Capturing real-time vehicular information (e.g., position, speed, travel time, and route)
  - Choice model-based traveler behavior model (e.g., decision on mode choice, route selection, departure time change, and traveler compliance in response to the given information)
  - Sensitivity analysis for travel behavior
  - Performance measure generation (e.g., safety (SSAM), emission and energy (VT-Micro model))

New API supported by external models:

- Traveler behavior model based on weather impact: e.g., Mahmassani et al.(2009) and Rakha et al. (2009)
- Capturing real-time weather information (e.g., precipitation, sight distance, and duration)

Activity-Based Modeling Approach

Collecting real-time traffic information from equipped vehicles within the activity-based modeling framework would use the same approach as that proposed for the ATIS application. By customizing the program source codes, it is possible to handle individual vehicle-related features in real-time. For example, with TRANSIMS, it is possible to capture real-time traffic information (e.g. delay, travel time, or incident information) from equipped vehicles as long as it is properly customized to obtain instantaneous vehicular information for individual vehicles, such as position, origin and destination, and speed.

With respect to the traveling behavior, the two approaches (i.e., a choice model-based approach and a sensitivity analysis) proposed for the ATIS application can be employed; however, it is necessary to incorporate the impact of inclement weather, as it affects not only driver behavior in response to the provided guidance information but also roadway traffic conditions. Drivers' microscopic behavior, such as lane changing and acceleration/deceleration, under the adverse weather condition can be easily modeled using an approach proposed by Rakha (2009). The method proposed by Mahmassani (2009) can be applied for adjusting the coefficients of supply function parameters in the activity-based modeling tool to reflect the impact of inclement weather on roadways. An approach suggested by Park and Samba (2010) can be applied to simulate the pre-trip trip decision in response to the weather condition. However, the impact of inclement weather on traveler behavior for mode shift, departure time change, and en-route route choice has not been explicitly investigated; only a few empirical studies demonstrated the effect of the weather impact (Khattak and De Palma, 1997) on the pre-trip mode shift. Knowing that such behaviors are typically represented by choice modeling approaches (Ben-Akiva and Lerman, 1985), it is possible to simulate the weather-responsive behaviors by updating the

utility functions' input data (e.g., travel time, delay, or waiting time) that result from inclement weather conditions.
The optimal paths can be generated based on both collected traffic information and weather conditions at every update interval. The activity-based modeling tool has a proper algorithm to build multiple paths (a.k.a., k-shortest paths). Furthermore, a dynamic OD table for each mode might be the most critical input data for the evaluation of the ATIS application under inclement weather. There exist a few relevant research efforts to obtain the dynamic OD tables; the most notable approaches would be found in Van Aerde et al. (2003), Ashok and Ben-Akiva (2002), and Bierlaire and Crittin (2004). These approaches can be incorporated as an external module for the activity-based modeling tool for estimating dynamic ODs.

Multi-Scale Modeling Approach

The high level performance evaluation for the WX-INFO application can be obtained by the same approach proposed for the ATIS application. Like the modeling approach for ATIS, it is possible to assess the benefits to travelers who use the weather-enhanced route guidance information. Thus, by breaking down the cases of weather conditions which can be treated as additional experimental scenarios, it is possible to estimate the performance of route guidance users under the various external conditions, resulting in a unit benefit for each experiment case. As noted earlier, the mesoscopic modeling tool is considered to be more suitable for the multi-scale modeling approach tool than the activity-based modeling tool. This is because the mesoscopic modeling tool can ensure faster implementation for a large scale network when it is incorporated with the microscopic modeling tool.
In order to properly adjust the speed-density function, one needs to identify the speed-density relationship obtained from the microscopic modeling approach for the combination of external factors under the WX-INFO application case and then find the optimal parameter coefficient set such as jam density, speed intercept, maximum flow rate, and model shape parameters (e.g., α and β). The adjusted speed-density function is fed into the mesoscopic modeling tool covering a large-scale network to implement a dynamic traffic assignment (DTA) with initial modal OD demands. Once the DTA is complete, one can obtain OD travel times and link travel times which are used for updating OD tables and routes for each OD pair. It is possible to adjust the initial OD demands using mode choice models, which take OD travel time, cost and transfer time as independent variables for their utility functions, if these mode choice models are given by a regional travel demand model. Likewise, with the link travel times obtained from the DTA, the best route for each modal OD pair can be updated. In particular, the travelers who are supposed to have real-time information accessibility through Connected Vehicles, 3G/4G mobile devices, or variable message signs can perform en-route route selection while the pre-trip routes are assigned to the travelers who have no access to the information. With the updated OD demands and routes, the DTA in the mesoscopic modeling approach is repeated until the network converges. Once the convergence is achieved, performance measures (e.g., travel time, throughput) will be calculated to examine the large-scale performance of the WX-INFO application.

6.1.3. Universal Map Application (T-MAP)

6.1.3.1. Review of modeling research efforts

No relevant modeling efforts were identified.

6.1.3.2. Modeling approach

The T-MAP application can be an element of the ATIS and WX-INFO applications that assists travelers in making decisions about mode shift and route choice by providing high fidelity traffic information regarding not only passenger cars but also public transportation through the T-MAP service. Consequently, the modeling approach for this application can be imported by either ATIS or WX-INFO, except for modeling travelers' behavior in response to the T-MAP information. This section focuses on how to deal with travelers' behavior with respect to the T-MAP information. Both the ATIS and WX-INFO sections provide a more detailed modeling approach.

Choice-based modeling

The impact of T-MAP information on both pre-trip and en-route travel decisions can be modeled by employing choice model approaches (Ben-Akiva and Lerman, 1985; Cascetta et al., 1996; Koppelman and Wen, 1998; Ramming, 2002; Bovy et al., 2008). Given proper utility functions, including the impact of T-MAP information affecting travelers' decisions, it is possible to evaluate the probability of route choice and mode shift in response to the T-MAP and other traffic information, but the impact of T-MAP on traveler's decisionmaking has not yet been examined. Thus, prior to employing the choice model approach, the impact of T-MAP must be investigated; however, collecting proper revealed preference (RP) data is impossible until the T-MAP application deploys in the field. To overcome this data availability issue, highway driving simulators (FHWA, 2010; NHTSA, 2011) may enable the capture of behavioral characteristics of drivers in response to the given T-MAP information in the near future.

Scenario-based sensitivity analysis can be applied for the simulation of driver's reaction to the T-MAP information. By designing a range of plausible compliance rates (e.g., from 10 percent to 90 percent by 10 percent increments) based on an experimental design approach, the changes of the T-MAP benefits under the various compliance rates can be examined.

In summary, the following is the list of APIs required for the microscopic modeling approach for the T-MAP application.

New API supported by external models:

- *Traveler behavior model (e.g., mode choice, route selection, and traveler compliance to the T-MAP information)*
- *Sensitivity analysis for the travel behavior.*

Multi-Scale Modeling Approach

It might be unnecessary to evaluate the performance of the T-MAP application for a large scale network. Since it is expected that T-MAP would improve the performance of the ATIS application, the magnitude of ATIS improvements identified by the microscopic modeling approach can be adjusted under the number of T-MAP application users and the market penetration rates of Connected Vehicles.

6.1.4. Smart Park-and-Ride (S-PARK)

6.1.4.1. Review of modeling research efforts

Bos et al. (2007) developed a methodology to assess the effect of travel time uncertainty on mode choice. Instead of looking at the benefit on travel time, traffic conditions, or other operational measurements, they emphasized the change of mode share caused by the additional information provided. The simulation model adopted in the research is based on expected-utility theory. In other words, traffic users, when facing an alternative with an uncertain outcome, evaluate the utility of all possible outcomes and weight them by the probability of each outcome. The simulation shows minor migration on mode share as a result of the provision of uncertainty information. However, it could be expected that, as the severity of congestion grows, the benefit of providing uncertainty information would increase significantly.

Caicedo et al. (2006) suggested a parking access revenue and control (PARC) system to simulate patron parking behavior in underground facilities. The commonly known desegregated models based on the random utility theory were adapted to mimic how parking patrons make their decisions. A subroutine was programmed and compiled in Microsoft Visual Basic to simulate patron behavior under many conditions of availability and geometric constraints. The results indicate that an intelligent parking management system that informs patrons with exact locations of available spaces is cost effective and beneficial.

Lu et al. (2009) proposed a new Smart Parking (SPARK) scheme under the Vehicle Ad Hoc Networks (VANETs) environment. The SPARK scheme aims at providing navigation service to patrons in large parking lots so that patrons would be able to find vacant parking spaces easier and faster. To this end, the authors developed a discrete event-based simulation model incorporating both a stochastic wireless communications model and a simple driver behavior model that were developed by the authors.

6.1.4.2. Modeling Approach

The S-PARK application may need to cover a large area (e.g., a city or a region) where multiple modes interact with each other. To examine the impact on such a large area, the activity-based modeling tool is the most suitable option, as the microscopic tool is insufficient for large networks. This section presents modeling approaches for both microscopic and activity-based modeling tools and discusses the research needs for each modeling approach by demonstrating how each modeling tool handles the core modeling components listed below:

- *Capturing real-time parking information (e.g., monitoring parking space availability)*
- *Capturing real-time transit information (e.g., arrival time, departure time, number of passengers)*
- *Multi-modal simulation covering auto, transit (e.g., bus and metro), and pedestrian*
- *Traveler behavior model (e.g., pre-trip route selection and mode selection and en-route route selection and mode transfer in response to parking and transit information)*
- *Dynamic k-shortest path algorithm*

<u>Microscopic Tool-Based Modeling Approach</u>

Parking facilities can be modeled by the microscopic modeling tool with the support of new APIs that can simulate real-time operation of the parking facilities (e.g., monitoring the parking space availability) and the estimated arrival times of automobile and transit vehicles. The information obtained from the parking facilities can be used for the generation of route-guidance information determining the choice behaviors of the S-PARK service holder for their routes, departure time, and modes.

Handling multiple modes is supported by the microscopic modeling tool, and thus transit information can be captured by the microscopic modeling tool with the support of a proper API to obtain real-time transit information such as departure time, arrival time, and the number of passengers in a transit vehicle. A transit vehicle’s dwell time can also be modeled using an estimated average and standard deviation.

It is necessary to develop traveler behavioral models handling the selection of paths, modes, and departure times. Since no modeling tools directly support such models, either an external choice model, based on Logit or Probit models, or a sensitivity analysis-based approach, must be employed as described in the previous section. Given these choice models for the decisions of route, modes, and departure times, such models can be fed into a new API to estimate the probability of choice behaviors. In case no choice models are available, the sensitivity analysis based on multiple scenarios defining various compliance rates can be directly implemented by an external API.

In summary, the following is the list of APIs required for the microscopic modeling approach for the S-PARK application.

New API:

- *Real-time parking facility modeling (e.g., monitoring the parking space availability)*
- *Capturing real-time transit vehicle information (e.g., departure time, arrival time, and the number of passengers)*

New API supported by external models:

- *Traveler behavior model (e.g., mode choice, route selection, departure time change, and traveler compliance)*
- *Sensitivity analysis for travel behavior*

<u>Activity-Based Modeling Approach</u>

The TRANSIMS model was selected to assess the benefits of the S-PARK application for large-scale networks; however, it must be noted that, while the TRANSIMS model adequately handles transit modes, pedestrians, and parking facilities within the predefined route plans, obtaining real-time data from such modes and parking facilities is not possible unless the model is customized. To this end, the program source code of the micro simulator module of TRANSIMS, which deals with the movement of each traveler and transit vehicle, must be modified. With a customized TRANSIMS model, it is possible to capture real-time parking information, such as the number of available parking spaces. Real-time transit information (such as the arrival and departure time of transit vehicles, passenger loads, and the number of boarding and alighting passengers at each station or stop) can also be captured by the customized TRANSIMS model.

The pedestrian mode is crucial for the S-PARK application because the travel time from a parking facility to a transit station would affect the traveler's decision on parking facility choice, route selection, and mode choice. Using the TRANSIMS model, based on an agent-based modeling approach that handles an individual pedestrian as an agent, it is possible to estimate the pedestrian travel time by using the length of link and average walking speed of pedestrian.

With respect to traveling behaviors, such as pre-trip and en-route route change, parking facility selection, and mode choice, it is possible to incorporate choice model approaches proposed by several researchers (Ben-Akiva and Lerman, 1985; Cascetta et al., 1996; Koppelman and Wen, 1998; Ramming, 2002; Bovy et al., 2008). The methodology for pre-trip and en-route route selections and mode choice would be identical to the description in the ATIS and WX-INFO applications; please see the section of *Activity Modeling Tool-B Approach* for ATIS and WX-INFO. The parking facility selection can be also modeled using the choice modeling approach by adding a component indicating the availability of parking spaces to the utility functions. Alternatively, sensitivity analysis could also be adequately employed to model parking facility selection.

The real-time optimal paths for T-MAP travelers can be generated by incorporating not only traffic information but also transit and parking facility information at every update interval. The TRANSIMS model has the proper algorithm to build multiple paths (a.k.a., k-shortest paths) to obtain the best path reflecting the transit schedule and parking facility information.

<u>Multi-Scale Modeling Approach</u>

The microscopic modeling approach enables estimation of the impacts of the S-PARK application on a small area with and without the application. It should be noted that the mesoscopic modeling tool is considered to be more suitable for the multi-scale modeling approach tool than the activity-based modeling tool. This is because the mesoscopic modeling tool can ensure faster implementation for a large-scale network when it is incorporated with the microscopic modeling tool. By measuring the performances of S-PARK users through the microscopic modeling approach, such as travel time reductions per S-PARK-deployed parking facility, it is possible to estimate the travel time reduction ratios of S-PARK users based on various external factors (e.g., market penetration rates and traffic congestion conditions).

It is possible to apply these ratios to a large-scale network covering multiple cities, a region, and a State that can be handled by a mesoscopic modeling tool. For example, by establishing experimental scenarios covering multiple market penetration rates, the number of S-PARK-enabled parking facilities, and the ratio of S-PARK users, DTA can be performed by adjusting the speed-density functions for each scenario in the mesoscopic modeling tool. Since the speed-density function modified for the S-PARK application would shorten the travel time, one needs to adjust proper parameters such as jam density, speed intercept, maximum flow rate, and model shape parameters (e.g., α and β) in the speed-density function.

The adjusted speed-density function is fed into the mesoscopic modeling tool covering a large-scale network to implement DTA with initial modal OD demands. Once the DTA is complete, one can obtain OD travel times and link travel times which are used for updating OD tables and routes for each OD pair. It is possible to adjust the initial OD demands using mode choice models, which take OD travel time, cost and transfer time as independent variables for their utility functions, if these mode choice models are given by a regional travel demand model. Likewise, with the link travel times obtained from the DTA, the best route for each modal OD pair can be updated. In particular, the travelers who are equipped with wireless communications devices can perform en-route route selection while the pre-trip routes are assigned to the travelers who have no access to the real-time parking information. With the updated OD demands and routes, the DTA in the mesoscopic modeling approach is repeated until the network converges. Once the convergence is achieved, performance measures (e.g., travel time, throughput) will be calculated to examine the large-scale performance of the S-PARK application.

6.2. Intelligent Network Flow Optimization (INFLO) Bundle

This section presents modeling approaches for the INFLO bundle covering three sub applications:

1) Queue Warning (Q-WARN),
2) Cooperative Adaptive Cruise Control (CACC) and
3) Speed Harmonization (SPD-HARM).

Figure 6-3 shows a high-level data flow diagram for the INFLO bundle. Under a Connected Vehicle environment, the data covering real-time traffic information and instantaneous vehicular information can be collected not only by a traffic management center but also by communications device-equipped vehicles. The collected data will be used for estimating downstream queues, congestion, and safe gaps for CACC vehicles. The guidance information will be disseminated to drivers through Connected Vehicles, variable message signs (VMS), and personal mobile devices.

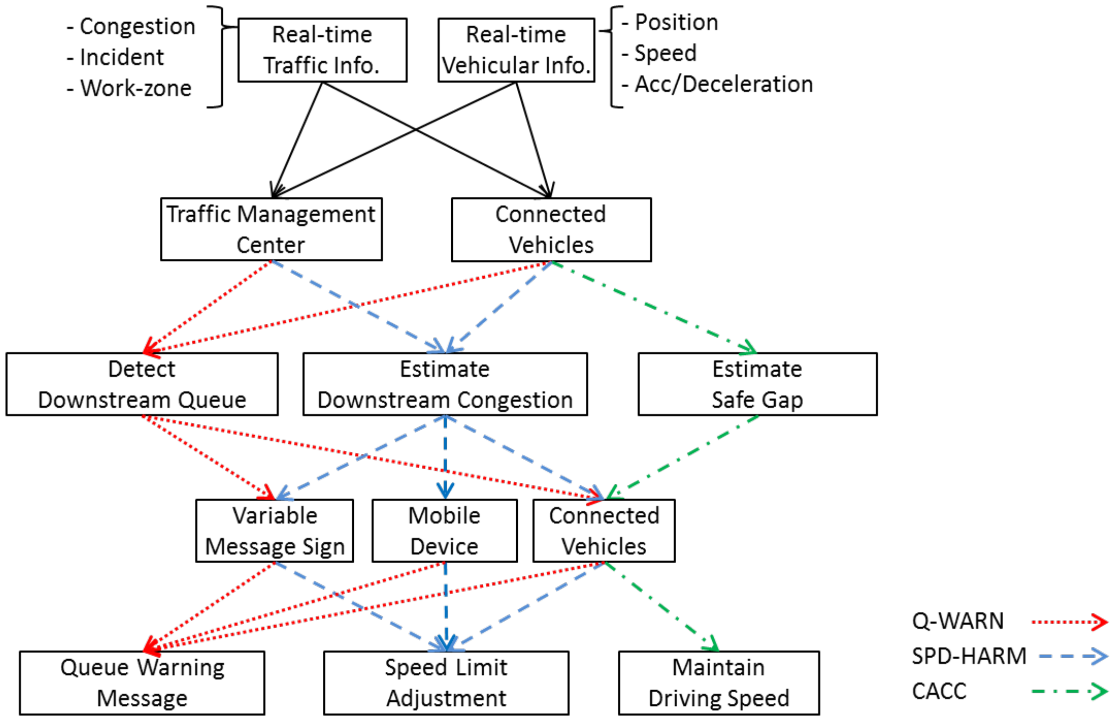

Figure 6-3. INFLO Data Flow Diagram

Proposed Modeling Tools

With respect to the selection of proper modeling tools to successfully accommodate the proposed modeling approaches, the microscopic simulator was selected as the primary modeling tool while the activity-based modeling tool was chosen for handling a large-scale network. The microscopic tool would be suitable for a small-scale network, such as a couple of corridors or a small region, while it enables the capture of individual vehicular information in real-time. Thus, it is most capable of precisely simulating each dynamic mobility application as described in its concept of operations. However, as identified in Section 5, there are numerous modeling elements that are beyond the capability of existing off-the-shelf microscopic modeling tools, such as real-time route change and user-defined signal adjustment. For those elements, this research proposes proper API-type external modules and describes how to design the API modules.

While the mesoscopic and hybrid modeling tools might be suitable for dealing with larger areas, one critical challenge of using such modeling tools is to model individual vehicle-related features, such as instantaneous driving information from equipped vehicles, drivers' traveling behaviors (e.g., lane changing and accelerating or decelerating), and the impact of wireless communications performance for the equipped vehicles. It is necessary to note that the hybrid model would also be unable to handle individual vehicles for the entire network because its microscopic modeling capability is designed to cover only a small-scale network. Collecting instantaneous vehicular data, such as position, speed, and acceleration or deceleration, is crucial for the implementation of the INFLO bundle application. However it is not possible to collect such data from the mesoscopic modeling tools.

The wireless communications among Connected Vehicles would be the most crucial element of each INFLO bundle application. Thus, the modeling tool used for its modeling must accommodate the impact of wireless communications performance. For the microscopic modeling tool, the project team proposes two optional approaches: one is to incorporate a wireless communication simulator into the traffic simulation tool (Park et al., 2010) and the other is to employ a hybrid V2V/V2I communications model proposed by Assenmacher et al. (2011). In the case of the activity-based modeling tool for the larger network, the project team suggests a radio propagation model-based approach. The radio propagation models (Rappaport, 2001) are used for the estimation of signal strengths under various propagation conditions resulting from the fundamental mechanisms of radio propagation: reflections, diffractions, and scatterings. The radio propagation models are divided into large-scale propagation models and small-scale propagation (or fading) models. On one hand, large-scale propagation models deal with the fact that the signal strength would be gradually weakened as the distance between transmitters and receivers becomes longer. On the other hand, the small-scale fading models, in addition to the large scale propagation effects, take into consideration micro-level fading phenomena, such as the small movements of mobile nodes and receiving time differences due to multipath radio propagations resulting from radio signals' reflections or scatterings.

An obvious challenge in developing a modeling approach is handling travelers' behavior in response to the guidance information they receive, such as queue warnings and optimal speed limit messages. The most critical traveler behavior would include lane changing, driving maneuver decisions (e.g., acceleration or deceleration), and en-route route changes. The project team proposes two options to deal with traveler behavior: one is a choice model-based approach proposed by several researchers (Ben-Akiva and Lerman, 1985; Cascetta et al., 1996; Koppelman and Wen, 1998; Ramming, 2002; Bovy et al., 2008) and the other is a scenario-based sensitivity analysis.

The choice model approach, based on either the Logit or the Probit model, estimates the probability of a traveler's decision to select one out of all other competing alternatives by using a utility function developed for each alternative. Thus, it is crucial to obtain proper utility functions, but obtaining and calibrating such models are challenging. While this approach theoretically explains the behavior of travelers, it must be noted that it is typically quite expensive and often not reliable when stated preference (SP) data instead of revealed preference (RP) data is used. It is also noted that only SP data can be obtained at this point, as each dynamic mobility application is based on the Connected Vehicle, which is not available yet.

It is worth noting that the use of highway driving simulators (FHWA, 2010; NHSTA, 2011) might be applicable for modeling of driver behavior. For example, as one of its exploratory advanced research (EAR) projects, FHWA has led the way in innovative research, using a highway driving simulator to examine driver behaviors (e.g., lane changing and car following) in response to external stimuli such as aggressive driving and sudden stop. With the driving simulator, it might be possible to capture how drivers react to guidance information such as speed harmonization and queue warnings under a Connected Vehicle environment. Such captured driver reaction data can be useful for building the utility functions of the choice model.

The other option for handling traveler behavior in the simulation model is to use sensitivity analysis. Assuming the compliance of a traveler for selecting one alternative among other competing alternatives, it is possible to simulate a range of plausible compliance rates (e.g., from 10 percent to 90 percent by 10 percent increments). Notably, unbiased compliance rate scenarios can be obtained by experimental design approaches such as full factorial method and Latin Hypercube Sampling. While the sensitivity analysis may seem like an ad-hoc approach that would not sufficiently capture the precise behavior of travelers and requires numerous simulation replications to cover the diversity of choice behaviors, this approach dramatically reduces the cost and effort of building behavior models.

6.2.1. Queue Warning (Q-WARN)

6.2.1.1. Review of existing modeling efforts

Middleton et al. (2011) evaluated the performance of a queue warning system by using a VISSIM-based simulation test-bed. The authors suggested using two types of data sources for the implementation of a queue warning system: one is loop detector-based spot speed data and the other is Bluetooth-based point-to-point travel time data. While the VISSIM program is able to model the spot speed-based queue warning system using its internal function, it is challenging to simulate the Bluetooth-based travel time estimation without a proper external API module. To overcome such a technical challenge, the project team employed an API for V2V/V2I communications provided by the VISSIM vendor. The performance of the queue warning system was assessed using the test-bed, which demonstrated mobility measures such as queue length and throughputs.

6.2.1.2.Modeling approach

From the findings in Section 5, the following core modeling elements were identified for the Q-WARN application.

- *Non-recurrent traffic condition (e.g., incident, work zone)*
- *Real-time traffic information*
- *The impact of wireless communications performance for capturing traffic information and disseminating the warning message*
- *Traveler behavior in response to the warning information (e.g., route changing, lane changing, acceleration or deceleration)*

To incorporate the above modeling elements, the Q-WARN application can be modeled by the microscopic and activity-based modeling tools. This section describes the modeling approach and discusses research needs for each modeling approach.

<u>Microscopic tool-based modeling approach</u>

The microscopic modeling tool enables the precise modeling of the Q-WARN application for a small network, such as a few corridors or a diverse freeway section covering merge and/or diverge areas.

The real-time recurrent traffic condition can be captured by the microscopic modeling tool within its off-the-shelf modeling capability. To handle non-recurrent traffic conditions, a scenario-based modeling approach can be considered by creating hypothetical incident scenarios covering occurrence time, duration, and severity (e.g., capacity reduction).

The traffic congestion information for issuing queue warnings is collected through Connected Vehicles that can be defined by traffic compositions covering various types of vehicles based on pre-defined scenarios. Again, the API developed in the research of Middleton et al. (2011) can be modified to deal with the generation of queue warning messages, which is triggered by a predefined speed threshold (e.g., 25 mph) based on the collected congestion information and the dissemination of the warning messages to the Connected Vehicles. Assuming the queue warning messages can be disseminated to equipped vehicles located on upstream roadways, the drivers would either change their paths or reduce their speeds to avoid the congestion, but their behaviors will be determined by either external choice models or a sensitivity analysis-based approach discussed earlier.

The quality of wireless communications might affect the performance of the Q-WARN application, as collecting real-time traffic data and disseminating warning messages rely on the Connected Vehicles. However, it should be noted that the impact of imperfect wireless communications performance such as packet drops and/or long communications lags would be insignificant for the safety aspect of the Q-WARN application. Thus, it would be unnecessary to model the wireless communications for the Q-WARN application precisely. Instead, the project team suggests a hybrid V2V/V2I communications model proposed by Assenmacher et al. (2011). The VISSIM program supports the hybrid V2V/V2I communications model as an external API module.

In summary, the following is the list of APIs required for the microscopic modeling approach for the Q-WARN application.

New API:

- *Real-time vehicle manipulation in response to the queue warning (e.g., route change, lane change, and speed adjustment)*

- *Capturing real-time vehicular information (e.g., position, speed, travel time, and route)*

New API supported by external models:

- *Choice model-based traveler behavior model (e.g., decision on route selection, lane change, and traveler compliance in response to the given information)*
- *Sensitivity analysis for travel behavior*
- *Hybrid V2V/V2I wireless communication performance estimation model (e.g., Assenmacher et al. (2011)).*

Non-API type external module:

- *Performance measure generation (e.g., safety (SSAM), emission and energy (VT-Micro model))*
- *Scenario-based non-recurrent congestion modeling (e.g., hypothetical incident scenarios covering occurrence time, duration, and severity (e.g., capacity reduction)).*

<u>Activity-Based Modeling Approach</u>

The activity-based model has been selected for assessing the impact of the Q-WARN application on a large-scale network. However it should be noted that TRANSIMS model is incapable of capturing individual vehicle-related features in real-time, such as real-time traffic information from equipped vehicles, drivers' traveling behaviors (e.g., lane changing, car following, and route selection in response to the queue warning message), and the impact of wireless communications performance for the equipped vehicles.

To collect real-time traffic information from such equipped vehicles within the TRANSIMS framework, it is necessary to customize the program source code, as it does not provide any external programming interfaces such as API or COM. Customizing the program source codes is also necessary to handle the behavior of drivers in response to the warning message. It should be noted that within the current TRANSIMS framework, real-time handling of an individual vehicle's lane changing or speed adjustment in response to the warning message cannot be modeled.

With respect to modeling a traveler's decision in response to the warning message, it is possible to incorporate an en-route route selection model by employing choice model approaches. Assuming proper utility functions are available for all the alternative paths that a driver group can choose, it is possible to estimate the probability of selecting each path. It is also possible to apply the sensitivity analysis approach for the simulation of a traveler's behavior. For example, assuming a traveler's compliance rate for a given warning message for a downstream queue is 50 percent, the behavior of the traveler's acceptance to the provided warning message can be determined by generating a random number at every moment in which the information was given.

Because the activity-based modeling tool can deal with individual vehicles, it would be possible to include the performance of wireless communications. As it is not expected that the quality of the wireless communications would seriously affect the safety of the Q-WARN application, the project team suggests the use of a radio propagation model, such as free-space, two-ray ground, and/or Nakagami fading models (Rappaport, 2001) to reflect the quality of the wireless communications in the activity-based modeling tool under a large-scale network. The radio propagation model estimates the strength of radio signals based on the distance between transceivers and probability distributions, resulting in communications performances (success or failure).

To handle non-recurrent traffic conditions, a scenario-based modeling approach can be considered by creating hypothetical incident scenarios covering occurrence time, duration, and severity (e.g., capacity reduction).

<u>Multi-Scale Modeling Approach</u>

With the microscopic modeling approach, it is possible to estimate the benefits of Q-WARN for corridor or freeway sections, such as travel time savings, delay time reductions, and throughput increase, under varying market penetration rates, compliance rates, and traffic congestion levels. It is possible to identify the relationships between the external factors and the benefits by using either a parametric (e.g., regression model) or a nonparametric (e.g., artificial neural network) to build a performance model for a roadway section where the Q-WARN application deploys.

The benefit model can be utilized for the large scale evaluation of the Q-WARN application by using mesoscopic modeling tools. The mesoscopic modeling tool is considered to be more suitable for the multi-scale modeling approach tool than the activity-based modeling tool. This is because the mesoscopic modeling tool can ensure faster implementation for a large scale network when it is incorporated with the microscopic modeling tool. Assuming there are certain numbers of Q-WARN links in a large scale network covering multiple cities or a state, the speed-density function of Q-WARN links can be adjusted to reflect the impact of the application.

The adjusted speed-density function is fed into the mesoscopic modeling tool covering a large-scale network to implement a DTA with initial modal OD demands. Once the DTA is complete, one can obtain OD travel times and link travel times that are used for updating OD tables and routes for each OD pair. It is possible to adjust the initial OD demands using mode choice models, which take OD travel time, cost and transfer time as independent variables for their utility functions, if these mode choice models are given by a regional travel demand model. Likewise, with the link travel times obtained from the DTA, the best route for each modal OD pair can be updated. With the updated OD demands and routes, the DTA in the mesoscopic modeling approach is repeated until the network converges. Once the convergence is achieved, performance measures (e.g., travel time, throughput) will be calculated to examine the large scale performance of the Q-WARN application.

It should be noted that assessing the impact of the Q-WARN application for a regional scale transportation network is possible by setting up experimental scenarios dealing with various ranges of some factors such as Connected Vehicle market penetration rates, compliance rates, the frequency of queue warnings, and congestion levels.

6.2.2. Dynamic Speed Harmonization (SPD-HARM)

6.2.2.1. Review of modeling research efforts

Lu et al. (2011) proposed using dynamic speed harmonization strategies including a combination of variable speed limit (VSL) logic and a coordinated ramp metering technique based on a linear programming (LP) approach to determine the optimal harmonization strategy. They evaluated the strategies by using both METANET (Messmer and Papageorgiou, 1990), a macroscopic traffic flow model, and AIMSUN. The METANET model can easily be tied into the Linear Programming (LP) model, but its current version does not handle individual drivers' lane changing behavior. Though using AIMSUN-based modeling, they were able to handle driving behavior, which required the development of a proper API in order to implement the LP-based harmonization strategies.

6.2.2.2. Modeling approach

This section deals with the modeling approaches of the SPD-HARM application for both the microscopic and activity-based modeling tools by addressing how each modeling tool handles the core modeling components listed below:

- Modeling non-recurrent traffic conditions (e.g., incident, work-zone)
- Capturing real-time traffic information
- Modeling the impact of wireless communications performance for capturing traffic information and disseminating the speed limit information
- Traveler behavior model in response to speed limit information

Knowing that the SPD-HARM application relies on real-time traffic information from Connected Vehicles, the microscopic modeling tool would be promising, even if it is insufficient to cover large-scale networks. To deal with large-scale networks, the project team proposes an activity-based modeling framework as it enables the handling of individual vehicles across various lanes in a large network, unlike mesoscopic tools that do not model the movement of individual vehicles in specific lanes or hybrid modeling tools that are insufficient to cover a large-scale network due to complexity in their model implementation. This section describes the modeling approach and discusses potential research needs for each.

Microscopic Tool-Based Modeling Approach

A microscopic modeling tool is suitable for the precise modeling of the SPD-HARM application, which enables modeling individual vehicle-related features, such as real-time traffic information from equipped vehicles, and the impact of wireless communications performance for equipped vehicles. It should be noted that the off-the-shelf capability of the microscopic tool is not able to handle all the required modeling elements summarized above, and, consequently, it will be necessary to develop external modules by using APIs.

To handle non-recurrent traffic conditions, a scenario-based modeling approach can be considered by creating hypothetical incident scenarios covering occurrence time, duration, and severity (e.g., capacity reduction). Speed harmonization has been modeled with the support of a new AIMSUN-based API developed by California PATH (Lu et al., 2011). This API deals with several crucial functionalities, such as gathering traffic information, generating optimal speed limits, and handling the desired speed of individual drivers, required for the implementation of the SPD-HARM application, except for modeling travelers' behavior in response to the speed advisory information. The API gathers traffic information by using traffic data such as speed, occupancy, and volume, collected from loop detectors every 20 seconds, ensuring that the collected information is accurate in real-time. That is, by enhancing the data-gathering part of the original API, the traffic information data from Connected Vehicles in real-time can be obtained to adequately support the SPD-HARM application. The collected data are fed into a module designed to solve the Linear Programming-based optimization problem to obtain optimal speed advisory information. Once the optimal speed information is available, the API adjusts drivers' desired speed to have them follow the advisory speed based on compliance rates. The way the API handles the travelers' compliance is based on a scenario-based sensitivity analysis, but statistical models, based on choice theory, can be embedded into the API to control the compliance of drivers as long as the proper models are prepared.

The driver's behavior in reacting to the speed limits can be modeled using a choice model approach. For example, assuming a binary choice model and its utility function are ready, producing 0 and 1, indicating accept and reject for a given choice alternative, the acceptance rate of the given speed limit information can be modeled for each individual driver. It is also available to apply the sensitivity analysis approach for the simulation of traveler behavior.

The quality of wireless communication might affect the performance of the SPD-HARM application as real-time traffic information is collected in a Connected Vehicle environment. However, it should be noted that the impact of imperfect wireless communications performance, such as packet drops and/or long communications lags would be insignificant for the safety aspect of the SPD-HARM application. Thus, it would be unnecessary to model the wireless communications for the SPD-HARM application precisely. Instead, the project team suggests a hybrid V2V/V2I communications model proposed by Assenmacher et al. (2011). The VISSIM program supports the hybrid V2V/V2I communications model as an external API module.

In summary, the following is the list of APIs required for the microscopic modeling approach for the SPD-HARM application.

Existing API:

- Speed harmonization logic API developed by Lu et al. (2011)

New API:

- *Real-time vehicle manipulation in response to the variable speed limit information (e.g., route change, lane change, and speed adjustment)*

- *Capturing real-time vehicular information (e.g., position, speed, travel time, and route)*

New API supported by external models:

- *Choice model-based traveler behavior model (e.g., decision on route selection, speed change, lane change, and traveler compliance in response to the given information)*
- *Sensitivity analysis for travel behavior*
- *Hybrid V2V/V2I wireless communication performance estimation model (e.g., Assenmacher et al. (2011))*

Non-API type external module:

- *Performance measure generation (e.g., safety (SSAM), emission and energy (VT-Micro model))*
- *Scenario-based non-recurrent congestion modeling (e.g., hypothetical incident scenarios covering occurrence time, duration, and severity (e.g., capacity reduction))*

<u>Activity-Based Modeling Approach</u>

The SPD-HARM application may need to be modeled for a large area (e.g., a city or a region) to examine its large-scale impact. To this end, the activity-based modeling tool would be the most suitable option because the microscopic tool is insufficient to deal with a large network. However, without source code modification, the activity modeling tool is incapable of modeling individual vehicle-related features such as real-time traffic information from equipped vehicles and the impact of wireless communications performance for the equipped vehicles. Thus, the project team proposes the TRANSIMS model, which can be customized by users, as the primary activity modeling tool.

The real-time traffic information from equipped vehicles within the TRANSIMS framework can be obtained by customizing the program source code to incorporate the market penetration rate of Connected Vehicle technology. Thus, the variable speed limit information can be generated from individual vehicular information. Customizing the program source codes is also necessary to handle the effect of drivers reacting to the provided speed limit information.

With respect to modeling travelers' decisionmaking in response to the speed limit guidance, it is possible to incorporate choice model approaches. Assuming a Logit-based binary choice model producing 0 and 1, indicating accept and reject for a given alternative, the acceptance rate of the given speed limit information can be modeled for each individual driver. It is also possible to apply the sensitivity analysis approach for the simulation of traveler's behavior.

The quality of wireless communication would affect the performance of the SPD-HARM application because collecting real-time traffic data and disseminating warning messages rely on the Connected Vehicles. The project team proposes the use of a radio propagation model, such as free-space, two-ray ground, and/or Nakagami fading models (Rappaport, 2001) to reflect the quality of wireless communications in the activity-based modeling tool under a large-scale network. The radio propagation model estimates the strength of radio signals based on the distance between transceivers and probability distributions, resulting in communications performances (success or failure).

Obtaining the optimal speed limit can be calculated by using aggregated link-based performance measures. For example, Lu et al. (2011) tested the performance of VSL by using macroscopic traffic flow relationships. Since the activity-based model is able to produce the macroscopic measures, generating the optimal speed limits from the activity-based model is possible.

<u>Multi-Scale Modeling Approach</u>

The microscopic modeling approach focusing on the impact of the SPD-HARM application on a freeway or corridor section enables an estimate of the benefits of SPD-HARM, such as travel time savings, throughput improvements, and delay time reductions. Under the microscopic modeling approach proposed by the project team, such benefits can be examined with multiple external factors such as various congestion conditions,

driver compliance rates, and market penetrations rates. The benefits of the external factor cases can be identified using a statistical modeling approach such as parametric or nonparametric methods for estimating the performance of the SPD-HARM application for a large scale network using a mesoscopic modeling tool. As noted earlier, the mesoscopic modeling tool is considered to be more suitable for the multi-scale modeling approach tool than the activity-based modeling tool. This is because the mesoscopic modeling tool can ensure faster implementation for a large-scale network when it is incorporated with the microscopic modeling tool.
To evaluate SPD-HARM for a large-scale network, the benefit model can be applied by adjusting the speed-density functions for links where the application is implemented. For instance, assuming a freeway section where high congestion occurs recurrently due to a lane drop, SPD-HARM would improve the throughputs of the freeway section by adjusting the speed limits of upstream links to mitigate congestion at the lane drop section. These improvements can be used for the adjustment of the speed-density functions of the same links in the mesoscopic modeling tool. The adjusted speed-density function is fed into the mesoscopic modeling tool covering a large-scale network to implement a DTA with initial modal OD demands. Once the DTA is complete, one can obtain OD travel times and link travel times, which are used for updating OD tables and routes for each OD pair. It is possible to adjust the initial OD demands using mode choice models, which take OD travel time, cost and transfer time as independent variables for their utility functions, if these mode choice models are given by a regional travel demand model. Likewise, with the link travel times obtained from the DTA, the best route for each modal OD pair can be updated. With the updated OD demands and routes, the DTA in the mesoscopic modeling approach is repeated until the network converges. Once the convergence is achieved, performance measures (e.g., travel time, throughput) will be calculated to examine the large scale performance of the SPD-HARM application.

6.2.3. Cooperative Adaptive Cruise Control (CACC)

6.2.3.1. Review of modeling research efforts

Su et al. (2011) developed an AIMSUN-based simulation test-bed for the evaluation of Adaptive Cruise Control (ACC) and Cooperative Adaptive Cruise Control (CACC) technologies. The test-bed handles an individual, equipped vehicle's driving maneuvers, such as acceleration and deceleration, based on the given gap time to maintain safe distance between the subject car and lead and following cars. To this end, the research team developed an API module to control both equipped vehicles as well as the simulation environment such as market penetration rate, compliance rate, and vehicle compositions.

6.2.3.2.Modeling approach

This section presents two modeling approaches for the CACC application based on mesoscopic and microscopic modeling tools to address the following core modeling components:

- Capturing instantaneous vehicular information
- Modeling the impact of wireless communications performance among CACC vehicles
- Modeling driver behavior reacting to the provided speed from CACC

Microscopic Tool-Based Modeling Approach
The microscopic modeling tool enables precise modeling of the CACC application, as demonstrated by an existing study (Su et al., 2011). However, it is important to note that the off-the-shelf capability of the microscopic tool is not able to handle all the required modeling elements. Thus, it will be necessary to develop external modules by using APIs to handle the following key components:

- *Adjusting real-time speed for each equipped vehicle to maintain the headway*

- *Handling driver behaviors in response to the headway*
- *Emulating the wireless communications performances*

There currently exists an API that can adequately deal with the CACC application within the framework of a microscopic modeling tool (Su et al., 2011). The CACC API, developed on the AIMSUN-based simulation test-bed, divides the vehicles into four groups based on market penetration rate scenarios, covering CACC, Adaptive Cruise Control (ACC), Vehicle Awareness Devices (VADs), and unequipped vehicles. Assuming all the vehicles are passenger vehicles, in the simulation model, when two CACCs are consecutive on the same lane, the API handles the maneuver of both vehicles to maintain the predefined gap. In a case where an unequipped vehicle and CACC vehicle run in a row on the same lane, the CACC vehicle drives like an ACC vehicle.

Since the existing CACC API is designed to maintain pre-defined time gaps between two CACC vehicles, it must be enhanced to estimate the optimal speeds for CACC vehicles under the various traffic conditions covering both recurrent and non-recurrent traffic conditions.

In contrast to some of the other applications, identifying the quality of wireless communications (e.g., communication latencies and potential drops) would be a crucial element for the modeling of CACC, as the safety of CACC vehicles would be significantly affected by wireless communications performance. In order to take into consideration the wireless communications within the modeling framework, there are two possible approaches: one is to incorporate a wireless communication simulator into the traffic simulation tool (Park et al., 2010), and the other is to employ a hybrid V2V/V2I communications model proposed by Assenmacher et al. (2011). While using the wireless communications network simulator would require additional simulation running time, the hybrid radio propagation model can dramatically reduce the time required for simulations. The VISSIM program supports the V2V/V2I model as an external API module.

In summary, the following is the list of APIs required for the microscopic modeling approach for the CACC application.

Existing API:

- *CACC API proposed by California PATH (Su et al., 2011).*

New API:

- *Real-time vehicle manipulation based on the given gap (e.g., acceleration/deceleration adjustment and speed change)*
- *Capturing real-time vehicular information (e.g., position, speed, travel time, and route)*

New API supported by external models:

- *Hybrid V2V/V2I wireless communication performance estimation model (e.g., Assenmacher et al. (2011))*
- *Traffic simulator-integrated wireless communications network simulator (Park et al., 2010)*

Non-API type external module:

- *Performance measure generation (e.g., safety (SSAM), emission and energy (VT-Micro model))*

<u>Multi-Scale Modeling Approach</u>

The direct effects of CACC are to (a) decrease vehicle following distance, (b) smooth reactions to disturbance in traffic flow, and (c) decrease the likelihood of a collision when a traffic flow disturbance occurs. The first two of these will change the speed-flow relationships that are used to model traffic flow on roadways. For example, freeway capacity will increase (because of smaller vehicle headways), stable traffic flow may persist at higher volumes relative to the freeway capacity (because of reduced likelihood for a disturbance in traffic flow to magnify), and incident rates will drop (because CACC will reduce the likelihood of a rear-end collision if a vehicle slows suddenly). However, CACC could introduce challenges in lane changing and entrance ramp merging operations: with smaller vehicle headways, drivers may be less able to adjust their headway to make room for entering vehicles.

The best tool to investigate how CACC will impact freeway traffic flow is a microscopic model, in which the usual vehicle-following models could be replaced with a CACC vehicle following model and observe the impact on traffic flow through a series of simulation runs that vary factors such as overall demand, CACC market penetration, and the impact on entering traffic.

One result of these microscopic simulations could be new speed-density relationships that apply to freeways where CACC is available. These speed-density relationships could then be used in higher level models to explore how the impacts of CACC on freeways might impact the regional transportation system. For example, the adjusted speed-density function is fed into the mesoscopic modeling tool covering a large-scale network to implement a DTA with initial modal OD demands. Once the DTA is complete, one can obtain OD travel times and link travel times, which are used for updating OD tables and routes for each OD pair. It is possible to adjust the initial OD demands using mode choice models, which take OD travel time, cost and transfer time as independent variables for their utility functions, if these mode choice models are given by a regional travel demand model. Likewise, with the link travel times obtained from the DTA, the best route for each modal OD pair can be updated. With the updated OD demands and routes, the DTA in the mesoscopic modeling approach is repeated until the network converges. Once convergence is achieved, performance measures (e.g., travel time, throughput) will be calculated to examine the large-scale performance of the CACC application.

6.3. M-ISIG Bundle

This section presents a modeling approach for the M-ISIG bundle to provide researchers with proper directions on how to model each bundle application:

1) Intelligent Traffic Signal System (ISIG)
2) Transit Signal Priority (TSP)
3) Mobile Accessible Pedestrian Signal System (PED-SIG)
4) Emergency Vehicle Preemption (PREEMPT)
5) Freight Signal Priority (FSP)

Figure 6-4 shows a high-level data flow diagram for the M-ISIG bundle in which the red dotted line indicates the data flow of the I-SIG application while the black solid line indicates the data commonly used for each application. It is possible to collect real-time data under a Connected Vehicle environment, such as individual vehicular data, transit vehicle information, emergency vehicle arrival, pedestrian call, and freight vehicle information. The collected data will be fed into either a traffic management center (i.e., centralized system) or a corresponding traffic controller (i.e., decentralized system) through adjacent RSE. With the collected data, the optimal traffic signal operational strategies including the priority signals for transit and freight vehicles, pedestrians, and emergency vehicles will be generated by using proper algorithms dealing with each control strategy.

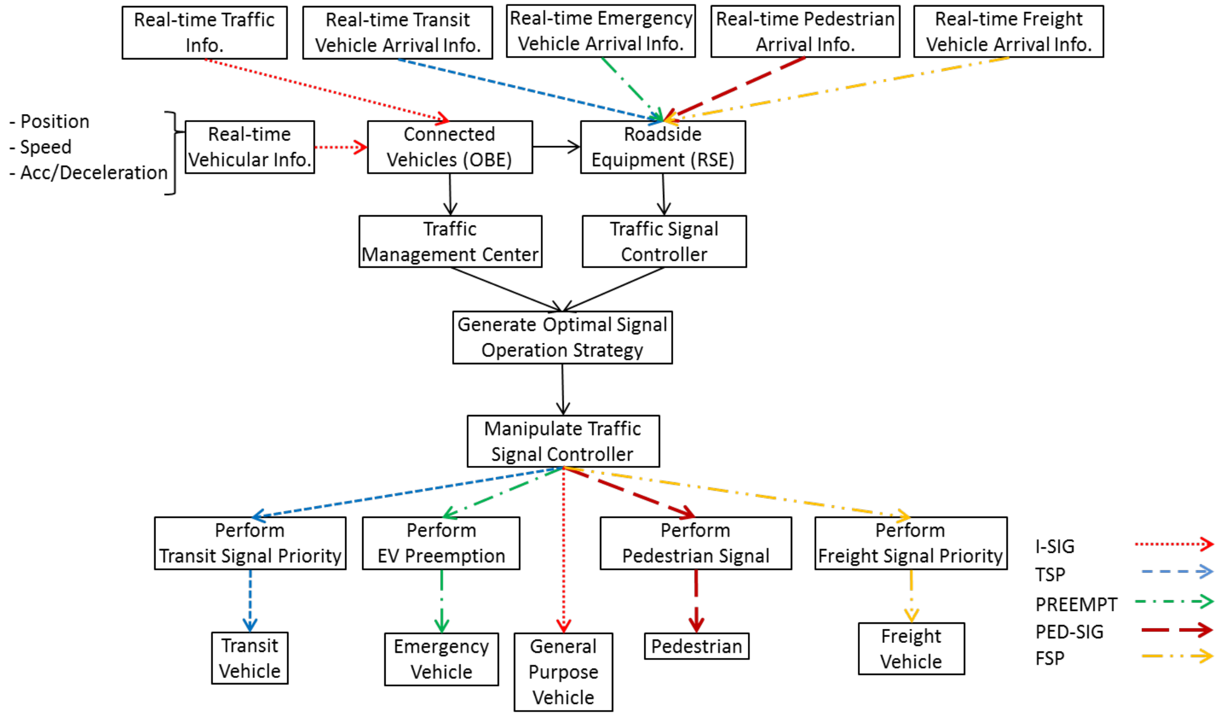

Figure 6-4. M-ISIG Data Flow Diagram.

<u>Proposed Modeling Tools</u>

With respect to the selection of proper modeling tools to successfully accommodate modeling needs, the microscopic simulator was selected as the primary modeling tool while an activity-based modeling tool was chosen for handling a large-scale network. The microscopic tool would be suitable for a small-scale network, such as a few corridors or a small region, and would also enable both the individual capture of vehicular information as well as the manipulation of traffic signals in real-time. Thus it enables the precise simulation of each M-ISIG bundle application as described in its concept of operations. However, as identified in Section 5, there are numerous modeling elements that are beyond the off-the-shelf modeling capability provided by the microscopic modeling tool, such as real-time route change and user-defined signal adjustment. For those elements, this research proposes proper API-type external modules and describes how to design the API modules.

While the mesoscopic and hybrid modeling tools might be suitable for dealing with larger areas, one critical challenge of using such tools is modeling individual vehicle-related features, such as instantaneous driving information from equipped vehicles, drivers' traveling behaviors (e.g., lane changing and accelerating or decelerating), and the impact of wireless communications performance for the equipped vehicles. It is important to note that the hybrid model would also be unable to handle individual vehicles for the entire network because its microscopic modeling capability is designed to cover a small-scale sub-network.

Collecting instantaneous vehicular data, such as position, speed, acceleration, or deceleration, is crucial for the implementation of the M-ISIG bundle applications; however, it is impossible to collect such data using the mesoscopic modeling tools.

In that sense, an activity-based modeling approach would be a uniquely appropriate option to properly evaluate the M-ISIG bundle for a large-scale network. For the activity-based model, the project team proposes the TRANSIMS model, an open-source program and one of the most notable activity-based models, as it appears to be appropriate for handling large-scale networks while allowing the capture of each individual vehicle's instantaneous information—a crucial element for realizing Connected Vehicle-based applications. However, it must be noted that the TRANSIMS model does not support any user interfaces (e.g., API or COM) that enable individual vehicles handling during the simulation. Thus, the modeling approach proposed for each M-ISIG application is based on the assumption that the TRANSIMS model can be customized in the near future. The project team proposes TRANSIMS-based modeling approach for the I-SIG application to examine its impact on a large-scale network. It is expected that the I-SIG application would produce notable benefits under the large-scale network. This is because the I-SIG application covers general purpose vehicles while the other applications, such as TSP, PED-SIG, PREEMPT, and FSP, focus on the special treatments (e.g., priority signal and preemption) of specific modes such as transit, freight, and emergency vehicles and pedestrians.

6.3.1. Intelligent Traffic Signal System (ISIG)

6.3.1.1.Review of existing modeling efforts

He (2010) proposed two Connected Vehicle-based traffic signal control methods: 1) platoon-based arterial multimodal signal control with online data (PAMSCOD) (He et al., 2012) and 2) robust actuated priority signal control with V2I communications (He and Larry, 2011). While the former focuses on priority signal systems such as transit signal priority (TSP), emergency vehicle preemption, or freight vehicle signal priority (FSP), PAMSCOD deals with real-time optimization of arterial coordination based on platoons observed by both Connected Vehicles and loop detectors. By applying mixed integer linear programming (MILP) for PAMSCOD, the author formulated an optimization problem to find the optimal traffic signal control for an arterial. To evaluate the effectiveness of PAMSCOD, a VISSIM-based microscopic simulation model was developed with new APIs to handle traffic signal control features that are unsupported within the off-the-shelf capability in VISSIM.

Dresner and Stone (2008) focused on exploring the potential benefits of an autonomous vehicle-based intersection control under a Connected Vehicle environment. With a multi-agent based simulation approach utilizing an intersection reservation system, they developed an intersection management algorithm for autonomous vehicles. Allowing an intersection manager program to coordinate the reservation requests of temporal/spatial cell occupancies from every autonomous vehicle (AV) enables the manager program to grant the right-of-way, ensuring safe crossing for each AV. A simple system recovery algorithm was also proposed to manage unexpected dangerous events such as vehicle malfunctions and crashes. Assuming 100 percent autonomous vehicles, the performance of the proposed algorithm was evaluated by a custom traffic simulator developed by the authors. With a hypothetical four-way isolated intersection having three lanes at each approach, the performances of the proposed algorithm were evaluated using a delay time measure under varying traffic conditions in which the maximum volume was 750 vph for each approach (note that no scenarios over 750 vph were performed in their research). Compared to the delay times resulting from four-way stop sign control for the same intersection, the proposed algorithm showed about 92-94 percent of delay time savings.

Lee and Park (2012) proposed an algorithm for a Cooperative Vehicle Intersection Control (CVIC) environment and assessed its potential benefits on a hypothetical isolated intersection. The proposed algorithm examined the predictive trajectories of vehicles that would be at risk for coming into conflict with one another at an intersection area. When multiple vehicles on conflicting approaches are projected to cross the intersection area at the same time with a safe gap constraint between two consecutive vehicles, the algorithm optimizes their trajectories in search of optimal speeds and accelerations that will prevent the occurrence of trajectory overlaps. Comprehensive microscopic traffic simulation-based experiments covering various traffic congestion conditions were performed on a hypothetical isolated intersection. Statistically significant benefits were observed in this experiment for mobility (a 99 percent improvement); stop delays and travel time (a 33 percent improvement); and both CO_2 emissions and fuel savings (about 34 percent each).

Agbolosu-Amison et al. (2012) quantified the potential benefits of a dynamic gap-out feature for an actuated signal control within the Connected Vehicle technology. Knowing the arrival time of each vehicle approaching an intersection, the gap-out was dynamically implemented based on the arrival time of each vehicle. This resulted in efficiency improvements at the actuated control intersections. Assuming a 100 percent market penetration rate of Connected Vehicle technology deployment, the authors examined the performance of the dynamic gap-out feature on a hypothetical intersection using a simulation-based test-bed and demonstrated approximately 5 percent to 20 percent of benefits can be obtained even for congested conditions.

6.3.1.2.Modeling approach

This section deals with the modeling approaches of the I-SIG application for both the microscopic and activity-based modeling tools by addressing how each modeling tool handles the core modeling components listed below:

- *Capturing real-time traffic congestion (e.g., speed, density, etc.)*
- *Modeling various modes (auto, transit, pedestrian, freight)*
- *Generating optimal traffic signal timing strategy by incorporating proper optimization algorithms*
- *Real-time signal control based on the optimal signal timing strategy*
- *Disseminating the optimal signal timing to equipped travelers through the Connected Vehicle environment(e.g., SPaT and ASM messages)*
- *Modeling traveler behaviors (route diversion, speed change) in response to optimal traffic signal controls*

To incorporate the above modeling elements, the I-SIG application can be modeled by microscopic and activity-based modeling tools. This section describes the modeling approach and discusses potential research needs for each modeling approach.

<u>Microscopic Tool-Based Modeling Approach</u>
The microscopic modeling tool is selected for modeling the ISIG application as its API capability can cover all the functional requirements for the application. The APIs developed by He and Larry (2011) can be expanded to deal with:

i. *Capturing the real-time traveling information of each OBE vehicle*
ii. *Generating the optimal signal control logic*
iii. *Manipulating traffic signal controllers to reflect the optimal control logic*

The API dealing with the traveler information will gather the real-time information of each OBE vehicle, such as position, speed, route, and origin and destination. The gathered information will be used for the estimation of the current traffic condition, including the number of vehicles, the length of queues, the arrival time of upstream vehicles, and the size of the platoon. A new API will use such estimated traffic conditions for creating the optimal signal control logic. Since the core architecture of the I-SIG application can vary as long as it utilizes the Connected Vehicle environment, obtaining optimal signal timing strategies can be obtained by either existing algorithms, such as He and Larry (2011), Lee (2010), and Agbolosu-Amison et al. (2012), or new methodologies that can generate the best traffic signal timing strategies. Thus, the most suitable control algorithm must be identified prior to implementing the I-SIG application. Once the optimal control logic is ready, the API manipulating the signal controller in the modeling tool implements required actions, such as green time changes and phase sequence adjustment, to reflect the optimal control logic in real-time.
The quality of wireless communication might affect the performance of the I-SIG application as real-time traffic information is collected in a Connected Vehicle environment. However, it should be noted that the impact of imperfect wireless communications performance such as packet drops and/or long communications lags would be insignificant for the safety aspect of the I-SIG application. Thus, it would be unnecessary to precisely model the wireless communications for the application. Instead, the project team suggests a hybrid V2V/V2I communications model proposed by Assenmacher et al. (2011). The VISSIM program supports the hybrid V2V/V2I communications model as an external API module.

The information provided by the I-SIG application would affect a driver's route choice behavior, assuming they are aware of downstream signal changes in advance through advisories from the Connected Vehicle environment. The project team, again, proposes two options to deal with such route choice behaviors: one is choice model-based approaches proposed by several researchers (Ben-Akiva and Lerman, 1985; Cascetta et al., 1996; Koppelman and Wen, 1998; Ramming, 2002; Bovy et al., 2008) and the other one is scenario-based sensitivity analysis.

The choice model approach, based on either the Logit or the Probit model, estimates the probability of a traveler's decision in selecting one out of all other competing alternatives by using a utility function developed for each alternative. For example, assuming an existing Logit-based model can estimate the utility of selecting a downstream route out of multiple route alternatives, it would be possible to calculate the probability of selecting a certain path. By generating a random number, it is possible to model how the driver selects the downstream path. However, it should be noted that it is typically quite expensive to collect proper data. (FHWA, 2010; NHSTA, 2011) Highway driving simulators and the products from exploratory advanced research (EAR) projects led by FHWA can be used to overcome this challenge. With the driving simulator, it might be possible to capture how drivers react to guidance information in a Connected Vehicle environment. Such captured driver reaction data can be useful for building the utility functions of the choice model.

The other option to handle the traveler behavior in the simulation model is to use the sensitivity analysis by using a range of plausible compliance rates (e.g., from 10 percent to 90 percent by 10 percent increments). For example, assuming a driver's compliance rates for selecting the first, second, and third shortest time paths are 50 percent, 30 percent, and 20 percent, respectively, the behavior of the driver's path selection can be determined by generating a random number at every moment in which the driver needs to make a decision. Compliance rates can be obtained by experimental design approaches such as full factorial method and Latin Hypercube Sampling to create unbiased compliance rate scenarios.

In summary, the following is the list of APIs required for the microscopic modeling approach for the I-SIG application.

Existing API:

- *Connected Vehicle-based intersection control API developed by He and Larry (2011)*

New API:

- *Real-time vehicular information capture (e.g., position, speed, travel time, and route)*
- *Real-time signal timing manipulation (e.g., phase sequence change and green time adjustment)*
- *Real-time traffic condition estimation (e.g., queue length, delay time, and upstream traffic volumes)*

New APIs to be supported by external models:

- *Optimal signal timing strategy generation by using either existing research efforts (e.g., Lee, 2010; He and Larry, 2011; Agbolosu-Amison et al., 2012) or new algorithms*
- *Choice model-based traveler behavior model (e.g., decision on route selection, speed change, lane change, and traveler compliance in response to the given information)*
- *Sensitivity analysis for travel behavior*
- *Hybrid V2V/V2I wireless communication performance estimation model (e.g., Assenmacher et al. (2011))*

Non-API type external module:

- *Performance measure generation (e.g., safety (SSAM), emission and energy (VT-Micro model))*

Activity-Based Modeling Approach

Because the macro- and mesoscopic modeling tools are incapable of handling not only individual vehicles, but also traffic signal controls in real-time, the activity-based modeling tool would be the most suitable option to examine the impact of the I-SIG application on a large-scale network. However, without source code modification, the activity modeling tools are incapable of both handling real-time traffic signal control and modeling individual vehicle-related features, such as real-time traffic information and the impact of wireless communications performance for equipped vehicles. Thus, the project team proposes that the TRANSIMS model, which is able to be customized by users, be used as the major activity modeling tool.

The real-time traffic information from equipped vehicles within the TRANSIMS framework can be obtained by customizing the program source code to incorporate the market penetration rate of Connected Vehicle technology. Thus, the variable speed limit information can be generated from individual vehicular information. Customizing the program's source code is also necessary to handle the response of drivers reacting to the provided speed limit information.

With respect to modeling traveler's decision making in response to the speed limit information, it is possible to incorporate choice model approaches. For example, assuming a multinomial Logit model covering possible alternate routes, the probability of selecting a certain route can be obtained. It is also available to apply the sensitivity analysis approach for the simulation of traveler behavior.

The quality of wireless communication would affect the performance of the I-SIG application, as collecting real-time traffic data and disseminating traffic signal information rely on the Connected Vehicles. To reflect the quality of the wireless communications in the activity-based modeling tool, the project team proposes the use of a radio propagation model, such as free-space, two-ray ground, and/or Nakagami fading models (Rappaport, 2001). The radio propagation model estimates the strength of radio signals based on the distance between transceivers and probability distributions to evaluate the performances of communications.

Since the core architecture of the I-SIG application can vary as long as it uses the Connected Vehicle environment, obtaining optimal signal timing strategies can be realized by either existing algorithms, as found by He and Larry(2011), Lee (2010), and Agbolosu-Amison et al. (2012), or new methodologies that can best generate the traffic signal timing strategies. Thus, the most suitable control algorithm must be determined prior to implementation of the I-SIG application.

Multi-Scale Modeling Approach

Through the microscopic modeling approach, which focuses on the impact of ISIG on an isolated intersection or multiple intersections along a corridor, it is possible to measure the improvements of those intersections produced by the ISIG application, such as delay time reduction, throughput increase, and travel time savings. By comparing with performance measures from non-ISIG intersection cases, a model can be built to identify the relationships between the intersection improvements (e.g., delay time saving s or throughput increase) that directly result from the ISIG application and other various external factors including market penetration rates, congestion conditions, and wireless communications quality levels.

The intersection improvement model can be used to evaluate the ISIG application performance for a large-scale network by implementing a multi-scale approach that employs a mesoscopic modeling tool. For example, using the intersection improvements model that reveals the delay time savings at a certain market penetration rate and congestion level, the delay time saving can be estimated where the ISIG application is implemented without performing the microscopic modeling approach. The speed-density functions of all the links connected to ISIG intersections can then be adjusted to reflect the impact of the application on those intersections.

To properly reflect the intersection improvements on the speed-density functions, the study team recommends that the speed-density relationship obtained from the microscopic modeling approach under the ISIG application case be determined and the optimal parameter coefficient set such as jam density, speed intercept, maximum flow rate, and model shape parameters (e.g., α and β) identified. Once the speed-density functions are adjusted, they can be fed into the mesoscopic modeling tool covering a large scale network to implement a dynamic traffic assignment (DTA) with initial modal OD demands. Once the DTA is complete, one can obtain OD travel times and link travel times which are used for updating OD tables and routes for each OD pair. It is possible to adjust the initial OD demands using mode choice models, which take OD travel time, cost and transfer time as independent variables for their utility functions, if these mode choice models are given by a regional travel demand model. Likewise, with the link travel times obtained from the DTA, the best route for each modal OD pair can be updated. With the updated OD demands and routes, the DTA in the mesoscopic modeling approach is repeated until the network converges. Once convergence is achieved, performance measures (e.g., travel time, throughput) will be calculated to examine the large-scale performance of the I-SIG application.

It should be noted that the mesoscopic modeling tool is considered to be more suitable for the multi-scale modeling approach tool than the activity-based modeling tool. This is because the mesoscopic modeling tool can ensure faster implementation for a large scale network when it is incorporated with the microscopic modeling tool.

6.3.2. Transit Signal Priority (TSP)

6.3.2.1. Review of modeling research efforts

Lee et al. (2005) proposed a high-performance online microscopic simulation model for predicting transit travel time for an advanced Transit Signal Priority (TSP) control method. The research team concluded that the microscopic simulation model is the most suitable to evaluate the performance of TSP scenario. The PARAMICS program supported by API, dealing with customized transit signal logic, was chosen for the evaluation.

Liao and Davis (2008) evaluated a Transit Signal Priority (TSP) logic based on the AVL, GPS, and wireless communications technologies. To this end, the authors developed an AIMSUN-based simulation test-bed with proper API supports designed to handle wireless communications and the proposed transit signal priority control that is not supported by the off-the-shelf AIMSUN functionality.

He and Head (2011) proposed a robust actuated priority signal control with V2I communications. Under a Connected Vehicles environment, the authors proposed two methods to solve optimal signal control strategies for the proposed priority signal control: one is a mixed linear integer program-based approach and the other is a heuristic approach to enable the implementation of the proposed priority control in real-time. The performance of the heuristic approach was evaluated by a VISSIM-based simulation test-bed employing VISSIM COM interface and an ASC/3-based software-in-the-loop (SILS) program.

6.3.2.2. Modeling approach

This section deals with the modeling approaches of the TSP application for the microscopic modeling tool by addressing how the modeling tool handles the core modeling components listed below:

- Capturing real-time traffic congestion (e.g., speed, density, etc.)
- Capturing real-time transit vehicle information (e.g., instantaneous position, speed, passenger load)
- Generating optimal transit signal priority strategy by incorporating proper optimization algorithms
- Manipulating signal timing control in real-time

It should be noted that the project team proposes a microscopic modeling approach for the TSP application, as it can be covered by the microscopic modeling tool. Also, knowing that the TSP application focuses on the improvement of intersections on major corridors, the impact of TSP on a large-scale network would be unlikely to make sizable benefits. Thus, the modeling approach for the TSP application deals with the microscopic modeling-based approach.

Microscopic Tool-Based Modeling Approach

There are a few existing off-the-shelf TSP plug-ins provided by the vendors of the microscopic modeling tools (PTV, 2011; TSS, 2011; Quadstone, 2006). While the existing TSP plug-ins are considered useful for modeling the current state-of-the-practice of the transit priority signal, they are insufficient to deal with the Connected Vehicle environment as the current technology in the TSP plugins is based on existing communications technologies such as video detection, infrared (IR), or DSRC, which make it challenging to cover detailed transit vehicle information such as the number of passengers. Thus, it is necessary to develop a new API linking the Connected Vehicle environment and the implementation of TSP logic.

The new API will gather real-time information from transit vehicles, such as position, speed, schedule, the number of passengers, and passengers' stop requests, which are unobtainable through legacy loop or video-based detection systems. The collected information will be fed into a new API designed to generate the optimal transit signal priority strategy, such as green time insertion or truncation and phase sequence adjustment, taking into consideration the collected information as the crucial elements for determining the strategy. A new API, handling the operation of intersection signal control, will apply the obtained transit priority strategies to the signal controller. For the proper transit signal priority logic, either existing research efforts (e.g., Lee, 2005; Lao and Davis, 2008; He and Larry, 2011) or newly developed logic can be applied.

For the TSP application, modeling traveler behavior appears unnecessary as all drivers are assumed to obey the traffic signal.

The impact of the number of transit vehicles enabling V2I communications can be determined by sensitivity analysis based on predefined market penetration scenarios. The quality of wireless communications might affect the performance of the TSP application as real-time transit information is collected in a Connected Vehicle environment. Furthermore, knowing that the TSP application adjusts the signal phase sequences based on the priority call from equipped transit vehicles, it would significantly affect the safety of intersection. Consequently, wireless communication must be precisely modeled to adequately assess these impacts. To this end, the project team proposes two optional approaches: one is to incorporate a wireless communication simulator into the traffic simulation tool (Park et al., 2010) and the other is to employ a hybrid V2V/V2I communications model proposed by Assenmacher et al. (2011). While using the wireless communications network simulator would require additional simulation running time, the hybrid radio propagation model can dramatically reduce the time required for simulations. The VISSIM program supports the V2V/V2I model as an external API module.

In summary, the following is the list of APIs required for the microscopic modeling approach for the TSP application.

Existing API:

- *Connected Vehicle-based TSP logic API developed by He and Larry (2011)*

New API:

- *Real-time transit vehicle information capture (e.g., position, speed, travel time, and route)*
- *Real-time signal timing manipulation (e.g., phase sequence change and green time adjustment)*
- *Real-time traffic condition estimation (e.g., queue length, delay time, and upstream traffic volumes)*

New API to be supported by external models:

- *Optimal TSP strategy by using either existing research efforts (e.g., Lee, 2005; Lao and Davis, 2008; He and Larry, 2011)*

- *Hybrid V2V/V2I wireless communication performance estimation model (e.g., Assenmacher et al., 2011)*
- *Traffic simulator-integrated wireless communications network simulator (Park et al., 2010)*

Non-API type external module:

- *Performance measure generation (e.g., safety (SSAM), emission and energy (VT-Micro model))*

<u>Multi-Scale Modeling Approach</u>

The impact of TSP on a large-scale network can be examined by using a multi-scale modeling approach integrating the microscopic modeling approach and the activity based modeling tool. Knowing that the microscopic modeling approach for TSP will cover a single transit route, it is possible to produce the estimations of the gains or losses for 1) transit routes (e.g., transit travelers travel time savings and passenger throughputs and 2) general purpose vehicles (e.g., delay time increase and throughput decrease). It is also possible to measure the range of such gains or losses based on external factors such as the level of traffic congestion near the transit route, the number of passengers boarding and/or alighting at the stations, the number of equipped vehicles.

Under the multi-scale modeling approach, the examined performances from the microscopic model based on various external factor cases are used for adjusting the traffic flow model of activity-based modeling tool (e.g., TRANSIMS). By investigating the relationships between the obtained gains and/or losses and the external factors such as the headway, waiting time, and transfer time of a certain transit route, it is possible to develop a proper performance model by using either a parametric (e.g., regression model) or a nonparametric (e.g., artificial neural network) approach. For example, the performance of a transit route obtained from the microscopic approach can be extended to other transit routes by applying the performance model and adjusting some parameters in the traffic flow model that handle transit movement within the activity-based model. It should also be noted that it is possible to create experimental scenarios dealing with the combination of external conditions to examine the impacts of the TSP application for a large-scale network.

6.3.3. Mobile Accessible Pedestrian Signal System (PED-SIG)

6.3.3.1. Review of modeling research efforts

Lu et al. (2011) proposed signal control logic to provide pedestrians with dynamic clearance time in order to improve multimodal safety and operations under the wireless communications environment. The rationale of the logic is to combine the concept of a dynamic pedestrian clearance interval with the Fuzzy Logic Control (FLC) and thus realize the full protection of the pedestrian green while intelligently serving the needs of vehicles. This rationale is simulated and evaluated in the VISSIM environment with the support of VISSIM COM interface. The result of the simulation showed significant benefits from the new signal control logic over the conventional National Electrical Manufacturers Association (NEMA) control.

DeVoe et al. (2009) explored how internet technology can be used for communication between smart devices and the traffic control. The goal is to use the internet as the replacement for the conventional methods used for traffic control, in which signals and sensors are connected by dedicated wire. No evaluation is performed on the system that the paper introduces. Instead, an explanation is provided as to how the system could be assembled technically and provides the rationale behind it.

6.3.3.2.Modeling approach

This section deals with the modeling approaches of the PED-SIG application for the microscopic modeling tool by addressing how the modeling tool handles the core modeling components listed below:

- *Capturing real-time traffic information*
- *Modeling pedestrian (e.g., pedestrian call, normal pedestrian, and visually impaired pedestrian)*
- *Manipulating signal timing control in real-time*

It is necessary to note clearly that the PED-SIG application focuses on improving pedestrian crossing at intersections; the impact on a large-scale network would be unlikely to make sizable benefits. Therefore, the project team proposes, as a modeling approach, only the microscopic modeling tool for the PED-SIG application. In addition, the quality of wireless communications would not affect the performance of the PED-SIG application and therefore the project team does not consider the wireless communications for the modeling approach.

<u>Microscopic Tool-Based Modeling Approach</u>

It is possible to model the request of a visually impaired pedestrian for his/her safe intersection crossing by using a new API within the microscopic simulation modeling tool. Once the API handling the pedestrian call disseminates a request signal, a new API designed to operate the intersection signal controller will be able to capture the pedestrian call if the call is within communication range. Once the call is received, the API will estimate the arrival time of the pedestrian by continuously monitoring their position and speed. If the pedestrian is identified to be located near the crosswalk of the current signal controller, the signal controller API manipulates the controller to let the pedestrian safely cross the street by turning the signal to green.

In summary, the following is the list of APIs required for the microscopic modeling approach for the PED-SIG application.

New API:

- *Real-time pedestrian calls modeling including visually impaired pedestrians*
- *Real-time signal timing manipulation in response to the pedestrian call (e.g., phase sequence adjustment and green time change)*

<u>Multi-Scale Modeling Approach</u>

With the microscopic modeling approach, it is possible to estimate the impact of PED-SIG on an intersection where the PED-SIG application will be implemented, such as travel time savings of pedestrians and the delay time increase of general purpose traffics. Moreover, such impacts can be easily estimated based on various external factors such as traffic congestion levels, the number of pedestrians equipped with communications devices for the PED-SIG. Such impacts can be modeled using either a parametric (e.g., regression model) or a nonparametric (e.g., artificial neural network) to explain the relationship between the impact and the external factors

The unit impacts can be used as input for activity modeling tools for the large scale evaluation of the PED-SIG application. Assuming there are a certain number of PED-SIG intersections in a large scale network covering multiple cities or a state, the traffic flow model for the links connected to such intersection can be adjusted to reflect the impact of the application: e.g., pedestrian travel time reduction and motorist delay time increase. By building experiment scenarios that deal with various ranges of external factors, such as Connected Vehicle market penetration rates and congestion levels, it is possible to assess the impact of the PED-SIG application for a regional scale transportation network.

6.3.4. Emergency Vehicle Preemption (PREEMPT)

6.3.4.1. Review of modeling research efforts

Obenberger and Collura (2007) assessed the performance of several transition strategies that are proposed to help the transition from preemption control to regular timing plans. To better evaluate which transition strategy best minimizes the negative effect of the preemption, the research team proposed a CORSIM microscopic traffic simulation model interfaced with the Siemens NextPhase Suitcase Tester (Obenberger and Collura, 2007) traffic signal controller software. To this end, the research team enhanced the CORSIM model by using a run-time extension (RTE) program to enable real-time interaction between CORSIM and NextPhase.

6.3.4.2. Modeling Approach

This section deals with the modeling approaches of the PREEMPT application for the microscopic modeling tool by addressing how the modeling tool handles the core modeling components below:

- *Modeling emergency vehicles*
- *Capturing real-time traffic information including emergency vehicle information (e.g., position, speed, route)*
- *Generating optimal preemption control strategy by incorporating proper optimization algorithms*
- *Real-time signal timing control including the preemption call*

Microscopic Tool-Based Modeling Approach

The project team proposes a microscopic modeling approach for the PREEMPT application because it primarily focuses on intersection improvement and likely will not have significant impacts when applied to a large-scale network.

In a Connected Vehicle environment, the preemption request of an OBE-equipped emergency vehicle (EV) is modeled by a microscopic tool with the support of a new API, handling the behavior of EV, such as real-time preemption call dissemination, aggressive lane changing, and red- light running at intersections which are not covered by off-the-shelf microscopic modeling capability. Once a preemption call is disseminated from an EV, a new API designed to handle the implementation of a traffic signal controller equipped with a RSE captures the preemption signal.

An intersection controller API estimates the arrival time of EV by using its real-time information, such as position, speed, and route, sent from the EV along with its preemption call signal. With such EV information, the API will generate an optimal signal timing plan that can minimize the impact of the EV by using green time extension, phase sequence adjustment, and optimal transition operation and then manipulating the traffic signal controller to reflect the timing plan.

The quality of wireless communication will be crucial for the safety aspect of the PREEMPT application; the application adjusts the signal phase sequences based on the priority call from equipped EVs. To take this into consideration, it is important to model the wireless communications precisely. To this end, the project team proposes two optional approaches: one is to incorporate a wireless communication simulator into the traffic simulation tool (Park et al., 2010) and the other is to employ a hybrid V2V/V2I communications model proposed by Assenmacher et al. (2011). While using the wireless communications network simulator would require additional simulation running time, the hybrid radio propagation model can dramatically reduce the time required for simulations. The VISSIM program supports the V2V/V2I model as an external API module.

In summary, the following is the list of APIs required for the microscopic modeling approach for the PREEMPT application.

New API:

- *Real-time emergency vehicle information capture (e.g., position, speed, travel time, and route)*
- *Real-time emergency vehicle manipulation (e.g., real-time preemption call dissemination, aggressive lane changing, and red- light running)*

- *Real-time signal timing manipulation in response to approaching EVs (e.g., phase sequence change, optimal transition operation, and green time adjustment)*

New API to be supported by external models:

- *Hybrid V2V/V2I wireless communication performance estimation model (e.g., Assenmacher et al., 2011).*
- *Traffic simulator-integrated wireless communications network simulator (e.g., Park et al., 2010)*

Non-API type external module:

- *Performance measure generation: e.g., safety (SSAM), emission and energy (VT-Micro model)*

<u>Multi-Scale Modeling Approach</u>

The microscopic modeling approach enables examination of the performance of PREEMPT under various conditions: e.g., emergency vehicle (EV) travel time saving and intersection delay time increase caused by the progression disruption for EV signals. Such impacts captured by the microscopic modeling approach covering multiple corridors and intersections can be expanded within the proposed multi-scale approach. For example, the ratios of EV travel times and the total intersection delay time measured with and without the PREEMPT application can be easily estimated. With the mesoscopic modeling tool, those ratios are applied to adjust the speed-density functions to reflect the large-scale impact of PREEMPT on both EVs and general purpose vehicles.

6.3.5. Freight Signal Priority (FSP)

6.3.5.1. Review of modeling research efforts

No relevant research efforts dealing with the freight vehicle signal priority logic were undertaken, but studies for the TSP and PREEMPT application can be expanded for the FSP application.

6.3.5.2. Modeling Approach

This section deals with the modeling approaches of the FSP application for the microscopic modeling tool by addressing how the modeling tool handles the core modeling components listed below:

- *Capturing real-time traffic congestion (e.g., speed, density, etc.)*
- *Capturing real-time freight vehicle information (e.g., instantaneous position, speed, route)*
- *Generating optimal freight signal priority strategy by incorporating proper optimization algorithms*
- *Manipulating signal timing control in real-time*

It should be noted that the modeling approach proposed by the project team deals with the microscopic modeling tool. This is because the FSP application primarily focuses on the improvement of intersections where the application is installed, likely resulting in insignificant improvements when it is applied to a large-scale network.

<u>Microscopic Tool-Based Modeling Approach</u>

The FSP application has a similar process as the TSP application in terms of its modeling approach. A new API in a microscopic modeling tool can model the dissemination of priority calls. It is also necessary to develop a new API dealing with the traffic signal controller. The API for traffic signal controller captures a priority call from a freight vehicle as long as the call is identified to be within the Connected Vehicle communications range. Since it is possible for the priority call message to convey the real-time information of the driving status of the freight vehicle, such as position, speed, and route, the signal controller, the API will be able to estimate the arrival time of the freight vehicle and generate optimal signal control logic to minimize the impact of the freight vehicle preemption. The API will manipulate the traffic signal controller to reflect the optimal control logic.

The impact of the number of freight vehicles enabling V2I communications would affect the operation of the intersections where the FSP application is deployed as real-time freight vehicle information is collected in a Connected Vehicle environment. Furthermore, since the FSP application would adjust the signal phase sequences based on the priority call from equipped freight vehicles, it would significantly affect the safety of the intersection. Thus, it is important to precisely model wireless communication to accurately assess their impact. To this end, the project team proposes two optional approaches: one is to incorporate a wireless communication simulator into the traffic simulation tool (Park et al., 2010) and the other is to employ a hybrid V2V/V2I communications model proposed by Assenmacher et al. (2011). While using the wireless communications network simulator would require additional simulation running time, the hybrid radio propagation model can dramatically reduce the time required for simulations. The VISSIM program supports the V2V/V2I model as an external API module.

In summary, the following is the list of APIs required for the microscopic modeling approach for the FSP application.

New API:

- *Real-time freight vehicle information capture (e.g., position, speed, travel time, and route)*
- *Real-time signal timing manipulation (e.g., phase sequence change, optimal transition operation, and green time adjustment)*
- *Real-time traffic condition estimation (e.g., queue length, delay time, and upstream traffic volumes)*

New APIs to be supported by external models:

- *Optimal FSP strategy generation by using either existing research efforts converted from TSP (e.g., Lee, 2005; Lao and Davis, 2008; He and Larry, 2011) or new one*
- *Hybrid V2V/V2I wireless communication performance estimation model (e.g., Assenmacher et al., 2011).*
- *Traffic simulator-integrated wireless communications network simulator (e.g., Park et al., 2010)*

Non-API type external module:

- *Performance measure generation [e.g., safety (SSAM), emission and energy (VT-Micro model)].*

<u>Multi-Scale Modeling Approach</u>

Knowing that the microscopic modeling approach for FSP will cover a corridor that includes a few intersections, it is possible to estimate the impacts of 1) freight vehicles (FVs) (e.g., freight vehicle travel time savings) and 2) general purpose vehicles (GPVs) (e.g., delay time increase and throughput decrease). Such captured impacts can be used to adjust the speed-density functions of a mesoscopic modeling tool employed within a multi-scale model. By investigating the relationships between the examined impacts and external factors such as the number of FVs, traffic congestion conditions, and market penetration rates, it is possible to build a performance model that uses either a parametric (e.g., regression model) or a nonparametric modeling (artificial neural network) approach. With the performance model, the speed-density functions can be adjusted to reflect the impact of FSP on the network. To this end, the project team recommends examining the speed-density relationship obtained from the microscopic modeling approach for the combination of external factors under the FSP application case and finding the optimal parameter coefficient set such as jam density, speed intercept, maximum flow rate, and model shape parameters (e.g., α and β). With the adjusted speed-density functions, the mesoscopic modeling tool covering a large scale network implement a dynamic traffic assignment (DTA) with initial modal OD demands. Once the DTA is complete, one can obtain OD travel times and link travel times which are used for updating OD tables and routes for each OD pair. It is possible to adjust the initial OD demands using mode choice models, which take OD travel time, cost and transfer time as independent variables for their utility functions, if these mode choice models are given by a regional travel demand model. Likewise, with the link travel times obtained from the DTA, the best route for each modal OD pair can be updated. With the updated OD demands and routes, the DTA in the mesoscopic modeling approach is repeated until the network converges. Once convergence is achieved, performance measures (e.g., travel time, throughput) will be calculated to examine the large-scale performance of the FSP application.

6.4. IDTO Bundle

This section presents modeling approaches for the IDTO bundle applications: Connection Protection (T-CONNECT), Dynamic Transit Operations (T-DISP), and Dynamic Ridesharing (D-RIDE).
Figure 6-5 shows a high-level data flow diagram for the IDTO bundle. In the diagram, each arrow indicates the data flow for each corresponding IDTO application: e.g., the red dotted arrow line indicates the data flow of the T-CONNECT application while the blue dashed arrow line indicates the T-DISP data flow. In a Connected Vehicle technology environment, the data covering real-time traffic information, transit vehicle information, and requesting calls from passengers or pedestrians can be collected by not only a traffic management center but also communications device-equipped vehicles. The collected data will be used for estimating:

1. Transit vehicle performance (e.g., passenger travel time and throughputs),
2. Real-time traffic congestion, and
3. Anticipated travel time for ridesharing vehicles to determine whether or not each application can be implemented.

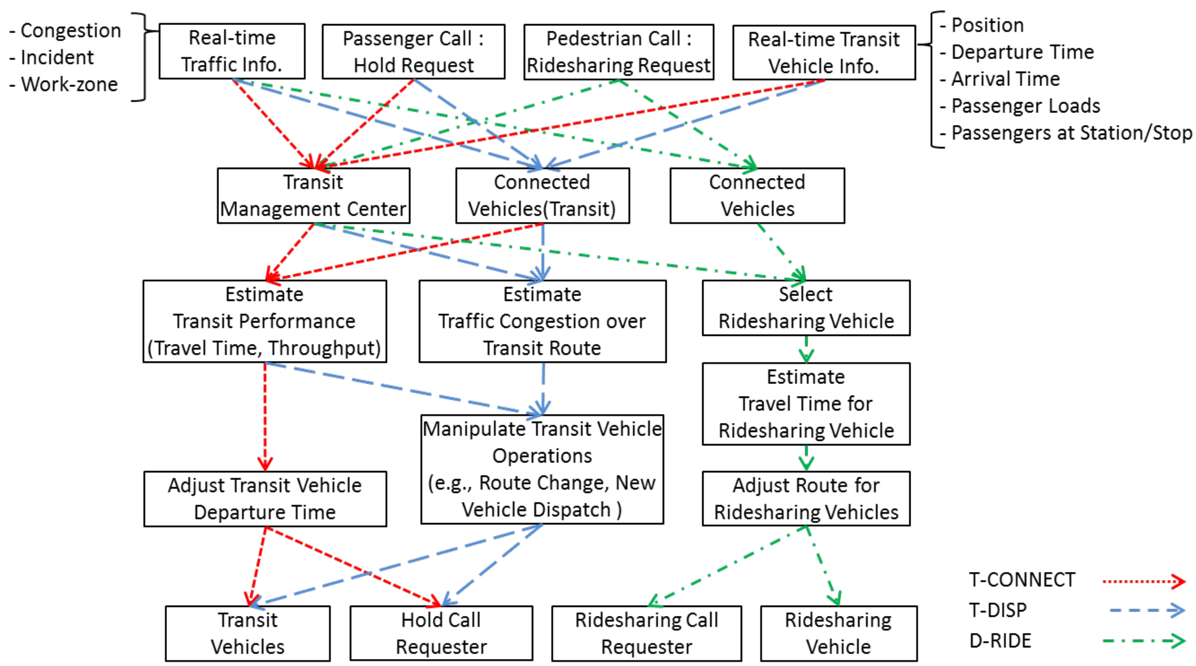

Figure 6-5. IDTO Data Flow Diagram.

In developing a modeling approach, it appears that the most critical challenge is to manipulate transit vehicles (e.g., departure time change, route change, dispatching a new vehicle in response to requests) in real-time, as no existing modeling tool allows handling of transit mode on the fly except for the microscopic tool that is supported by API.

<u>Proposed Modeling Tools</u>

This section describes two different types of modeling approaches for the microscopic tool, allowing precise analysis but limited to a small-scale network and the activity-based modeling tool, enabling the assessment of large scale impacts. In the case of the microscopic modeling approach, there are numerous modeling elements that are beyond the capability of off-the-shelf microscopic modeling tools, such as real-time route change. For those elements, this research suggests development of API-type external modules and describes how to design the API modules. It should be noted that the activity-based modeling tool is incapable of handling individual transit vehicles in real-time, which is a crucial element for the IDTO bundle, unless the program source code is customized.

It is necessary to clearly address the limitations of the mesoscopic and hybrid modeling tools, that might be suitable for dealing with the larger area, but one critical challenge of using such tools for the IDTO bundle is to handle individual transit vehicles (e.g., route manipulation, late departure, etc.) as well as to obtain the instantaneous information from the transit vehicles on the fly; this information includes position, passenger loads, and arrival and departure time. It is also important to note that the hybrid model would also be unable to accommodate such requirements for the entire network because its microscopic modeling capability is designed to cover a small-scale network. To overcome such challenges, the project team proposes the TRANSIMS model as an appropriate activity-based modeling tool for a large scale network.

With respect to the quality of wireless communications, it is unlikely that there would be any critical impacts of wireless communications on the IDTO bundle as long as IDTO service requesters are located in the communication range, which is very likely, assuming that passengers would use any commercial network (e.g., 3G or 4G LTE) and transit vehicles remain connected. For that reason, the project team does not provide a modeling approach dealing with the wireless communications in the following sections. However, a large-scale radio propagation model (e.g., as free-space and two-ray ground models; Rappaport, 2001) can be applied to estimate the performance of wireless communications based on the fact that the signal strength would be gradually weakened as the distance between transmitters and receivers becomes longer.

6.4.1. Connection Protection (T-CONNECT)

6.4.1.1. Review of existing modeling efforts

Hadas and Ceder (2008a) proposed a hybrid simulation model for flexible bus passenger transfer by incorporating a Dynamic Programming (DP) based optimization model and a discrete event simulation model. The DP model determines whether the bus needs to wait for transferring passengers when they are expected to arrive late. The discrete event simulation model deals with the arrival and departure times of transit vehicles at the stops in a stochastic manner.

6.4.1.2. Modeling approach

Based on the findings in Section 5, the following core modeling elements are identified.

- *Modeling a hold request from a pedestrian*
- *Capturing real-time transit vehicle information (e.g., positions, departure/arrival time, and passenger loads)*

- *Assessing the feasibility of a holding request based on minimizing the total passenger delay*
- *Manipulating transit vehicles in real-time (e.g., late departure) based on pedestrian calls*

Under the current modeling practice, a microscopic modeling tool is possibly the best one to accommodate transit and pedestrian modes. For example, no existing modeling tools, except the microscopic tool, allow adjustment of either the route of a transit vehicle or its schedule in real-time. Thus, the project team proposes a modeling approach based on the microscopic simulator as a primary modeling tool for the T-CONNECT application. However, as mentioned in the previous sections, since the microscopic modeling tool is unsuitable for covering a large-scale network, the project team proposes a modeling approach for the TRANSIMS model, an activity-based modeling tool, enabling the assessment of the impact of T-CONNECT on a large area.

Microscopic Tool-Based Modeling Approach

To properly handle the departure time of transit vehicles and the traveler's call requesting a hold for his/her next transit vehicle, the T-CONNECT application must be modeled by API-supported microscopic modeling tools. The API monitors the operation of transit vehicles in real-time and estimates the arrival time of each transit vehicle to the next stop, or station, based on the instant position, speed, and traffic congestion condition. Once the API detects that there are transit vehicles that are likely to arrive late at the next stop, it selects travelers in the late transit vehicles who might disseminate a holding message for the next transit vehicles at the transferring stops or stations. These travelers can be either randomly selected or modeled by external scenarios defining the number and the frequency of the holding messages.

The API collects the requesting calls and determines whether each of the requests is accepted or not by estimating the impact of the delay time at the stop or station on the performance of the subject transit route. For example, if the delay time due to late departure is estimated to exceed a threshold value, then the requesting calls would be rejected. The departure time of transit vehicles, corresponding to the accepted requests, are controlled by the API to serve the requesters.

It is also noted that the impact of wireless communications quality on the performance of the T-CONNECT application would be insignificant as long as passengers requesting holds and transit vehicles are located within communications range.

In summary, the following is the list of APIs required for the microscopic modeling approach for the T-CONNECT application.

New API:

- *Modeling real-time passenger call (e.g., location, transit information)*
- *Capturing real-time transit vehicle information (e.g., position, speed, departure time, passenger loads)*
- *Manipulating transit vehicles in real-time (e.g., departure time adjustment)*

New API supported by external models:

- *Estimation of the feasibility of the pedestrian call by employing an optimization method.*

Activity-Based Modeling Approach

In cases when it is necessary to estimate the impact of the T-CONNECT application for a large area (e.g., covering a city or a region) where numerous transit vehicles comprise a major transportation mode, the microscopic modeling tool would be insufficient. To this end, the activity-based modeling tool would be the most suitable option; however, without source code modification, the activity modeling tool is incapable of modeling the operation of individual transit vehicles in real-time. Thus, the project team proposes the TRANSIMS model, which can be customized by advanced users, for the major activity modeling tool.

While TRANSIMS is capable of modeling transit vehicles, it is still necessary to customize the program source code to manipulate each transit vehicle in real-time. To this end, it might be necessary to modify the trip planner and microscopic simulator modules in the TRANSIMS model. Customizing the program source codes is also necessary to not only model a hold request call from transit passengers but also to capture traffic information in the network. To this end, we recommend adding a new module for handling the passenger call that can be modeled by either a Monte Carlo simulation-based random selection approach or an external scenario-based approach.

Once customized TRANSIMS detects passenger calls and estimates the gain or loss when the calls are accepted by measuring the performance measures for both the subject transit route and the requester, such as throughputs, travel time, and delay time. If the impact of passenger call appears insignificant, the departure time of the subject transit vehicle is adjusted to accommodate the requester's call.

Multi-Scale Modeling Approach

Once the microscopic modeling tool-based approach is ready for implementation, it would be possible to assess the gains or losses of a specific transit route under the various plausible conditions of using the T-CONNECT application. With the individual gains or losses (e.g., passenger throughput increase or travel time increase), the performance of several transit routes can be adjusted in the activity-based modeling tool.

For example, assuming the microscopic modeling tool reveals that, for a certain holding request case, the T-CONNECT application obtains 5 percent of pedestrian throughput improvement while it increases the travel time by 3 percent for a certain transit route, it is possible to estimate the travel times and throughputs of multiple transit routes by adjusting the line-haul time of each transit route based on the gain and loss obtained from the microscopic modeling approach. The updated line-haul time would affect the behavior of transit passengers on the entire network, which enables us to assess the T-CONNECT impacts on a large scale network. Once the line-haul time is adjusted, it can be fed into the activity-based modeling tool to reflect the improvement of transit travel time for the implementation of a DTA with initial modal OD demands. Once the DTA is complete, one can obtain OD travel times and transit route travel times, which are used for updating OD tables and transit route selections for each OD pair. It is possible to adjust the initial OD demands using mode choice models, which take OD travel time, cost and transfer time as independent variables for their utility functions, if these mode choice models are given by a regional travel demand model. Likewise, with the link travel times obtained from the DTA, the best route for each OD pair can be updated. With the updated OD demands and routes, this is repeated until the network converges. Once convergence is achieved, performance measures (e.g., travel time, throughput) will be calculated to examine the large-scale performance of the T-CONNECT application.

A performance model can be developed by identifying the relationships between external factors, such as the number of requests, traffic congestion conditions, and the number equipped pedestrians, and the gains/losses estimated by the microscopic modeling approach. By employing a statistical method covering either parametric (e.g., regression model) or nonparametric (e.g., artificial neural network) approaches, the performance model can be used for estimating the performance of T-CONNECT under any combination of external factors.

6.4.2. Dynamic Transit Operations (T-DISP)

6.4.2.1. Review of modeling research efforts

Hadas and Ceder (2008b) proposed a Dynamic Programming (DP) based approach to improve transit operation by minimizing unnecessary transfer waiting time. The DP model was employed to intelligently decide whether a bus should be held to accommodate a transfer from a late bus. A stochastic discrete event simulation model was constructed to evaluate the proposed optimization model.

Cortes et al. (2005) developed a methodology to simulate a transit system in the available commercial simulation environment. In order to prove the validity of this methodology, two different transit systems were simulated: one was a bus rapid transit system based on high-speed fixed routes and the other was a flexible transit system. The research team developed a hybrid simulation approach by integrating PARAMICS and

ABSNET (Jayakrishnan, 1995)**,** a routing and behavior response simulator. In this research, the authors used PARAMICS as the microscopic simulator and ABSNET on top of the PARAMICS as the route decisionmaker.

6.4.2.2.Modeling approach

Based on the findings in Section 4, the following core modeling elements are identified.

- *Capturing real-time transit vehicle information (e.g., positions, departure/arrival time, and passenger loads)*
- *Manipulating transit vehicles in real-time (e.g., route change, new vehicle dispatch) based on traffic conditions*
- *Generating optimal paths for transit vehicles*

To incorporate the above modeling elements, the T-DISP application can be modeled by the microscopic and activity-based modeling tools. This section describes the modeling approach and discusses potential research needs for each modeling approach.

<u>Microscopic Tool-Based Modeling Approach</u>
The most suitable modeling tool for the T-DISP application is the microscopic modeling tool, as it is capable of handling transit vehicles on the fly by the support of the API capability.
A new API in the microscopic modeling tool can model a transit control center dealing with the operation of transit vehicles. The control center API collects not only the real-time information of transit vehicles covering the position (e.g., number of passengers, arrival and departure times, and number of passengers waiting at the stops or stations) by emulating the use of mobile hands-on devices such as smart phone, but also traffic condition information such as congestion, incidents, and work zones. The route of transit vehicles can be dynamically adjusted by the API as long as the adjustments can improve the performance of transit vehicle operations. For example, if the API detects serious congestion due to an incident or a work zone on a certain street that is a part of a transit vehicle route and finds no passengers who are willing to board or alight at the corresponding stops along the street, the route of the transit vehicle can be adjusted to avoid the congestion by the API. In a case when passengers are waiting at the stops but there are no available transit vehicles to serve them, the API will dispatch a para-transit vehicle to the stops.
The API also gathers dynamic demand calls from transit travelers who request the dispatch of new transit vehicles or para-transit vehicles. The travelers' demand call, incidents, and work-zone can be modeled by either a random probability model or predefined scenario.
In summary, the following is a list of APIs required for the microscopic modeling approach for the T-DISP application.
New API:

- *Capturing real-time transit vehicle information (e.g., position, speed, departure time, passenger loads, passengers boarding/alighting at the stops or stations)*
- *Manipulating transit vehicles in real-time (e.g., departure time adjustment, route change, and new transit vehicle dispatching)*
- *Capturing real-time traffic information (e.g., congestion, incident, and/or work-zone)*

New API supported by external models:

- *Optimal route guidance for transit vehicles reflecting concurrent traffic conditions based on a shortest path algorithm*

<u>Activity-Based Modeling Approach</u>
The project team proposes the TRANSIMS model, one of the activity-based modeling tools, as a suitable modeling tool for the evaluation of T-DISP application in a large-scale network. It should be noted that the

TRANSIMS model does not handle individual transit vehicles in real-time. However, because its program source code is open to the public, it can be customized to accommodate such handling (e.g., route change, stop skip, or late departure).

By customizing the program source code, the TRANSIMS model can both capture real-time traffic information as well as adjust the routes of transit vehicles in real-time to reflect the traffic information. For example, if severe congestion is detected on a roadway section that is a part of a bus's route, and where a corresponding stop for the bus is located, the route of the bus can be adjusted if there are no boarding and alighting passengers for the stop. The optimal paths for transit vehicles can be generated by using path-finding algorithms embedded in the TRANSIMS model.

If a station detects passengers waiting, but there are no available transit vehicles to serve them, a para-transit vehicle can be dispatched to the stops by customizing the program source code. For the modeling dynamic demand calls from transit travelers who request the dispatch of new transit vehicles or para-transit vehicles, it is possible to employ either a random probability model or predefined scenarios.

Multi-Scale Modeling Approach

The impact of T-DISP on a large-scale network can be examined by using a multi-scale modeling approach that integrates the microscopic modeling approach and the activity-based modeling tool. Knowing that the microscopic modeling approach for T-DISP will cover a single transit route, it is possible to evaluate the gains or losses of the route such as transit travelers travel time savings, total number passengers (i.e., throughput), and waiting time increase or decrease at a station or a stop. It is also possible to measure the spectrum of such gains or losses based on external factors likely affecting the performances of the T-DISP application, such as the level of traffic congestion near the transit route, the number of passengers boarding and/or alighting at the stations, the number of equipped passengers who can easily access the real-time information of transit route.

Under the multi-scale modeling approach, the examined performances revealed by the microscopic modeling approach under various external factor cases are used to adjusting the transit performance of the activity-based modeling tool. By investigating the relationships between the obtained gains and/or losses and external factors such as headway, waiting time, and transfer time, a proper performance model can be developed based on various external conditions. To this end, two statistical modeling approaches can be employed: one is a parametric approach (e.g., regression model) and the other is a nonparametric approach (e.g., artificial neural network). Using the relationships between the performances (i.e., outputs) and the external factors (i.e., inputs), a model can be built that relates the performance of T-DISP and the external factors. Obviously, it is possible to build experimental scenarios dealing with the combination of external conditions to examine the impacts of the T-DIPS application for a large-scale network.

For instance, with improved passenger throughputs for a certain transit route from the microscopic modeling tool, one can adjust transit model parameters in the activity-based modeling tool, such as capacity and headway. The updated capacity and headway for a T-DISP transit route would affect the behaviors of transit passengers. Once the headway and capacities are adjusted to reflect the improvement of transit travel time, the activity-based modeling tool implements a dynamic traffic assignment (DTA) with initial modal OD demands. Once the DTA is complete, one can obtain OD travel times and transit route travel times which are used for updating OD tables and transit route selections for each OD pair. It is possible to adjust the initial OD demands using mode choice models, which take OD travel time, cost and transfer time as independent variables for their utility functions, if these mode choice models are given by a regional travel demand model. Likewise, with the link travel times obtained from the DTA, the best route for each OD pair can be updated. With the updated OD demands and routes, this is repeated until the network converges. Once the convergence is achieved, performance measures (e.g., travel time, throughput) will be calculated to examine the large scale performance of the T-DISP application.

6.4.3. Dynamic Ridesharing (D-RIDE)

6.4.3.1. Review of modeling research efforts

No relevant modeling efforts with respect to dynamic ridesharing are identified. However, knowing that the core of the modeling approach for dynamic ridesharing is to adjust the path of ride sharing providers in real-time, the modeling approach used for ATIS can be applied for the modeling of the D-RIDE application.

6.4.3.2.Modeling approach

To develop viable modeling approaches for the D-RIDE application, the following modeling elements must be addressed:

- *Modeling real-time ridesharing requests from pedestrians*
- *Manipulating ridesharing vehicles in real-time (e.g., selecting ridesharing vehicles and route change)*
- *Modeling ridesharing driver behavior (e.g., compliance to the ridesharing request)*
- *Generating the best ridesharing option incorporating the information of transit schedule, availability, location, and real-time traffic condition*

To incorporate the above modeling elements, the D-RIDE application can be modeled using microscopic and activity-based modeling tools. It should be noted that the activity-based modeling tool is challenged by the requirement to handle pedestrians, which are necessary for modeling ridesharing requests. It also faces the challenge of manipulating individual vehicles to adjust their paths in response to the ridesharing request. To overcome such challenges, a modeling approach based on the microscopic simulator was proposed as a primary modeling approach for the D-RIDE application. However, the activity-based modeling approach is also proposed based on the same approach as described in T-CONNECT and T-DISP applications to assess the impact of D-RIDE on a large area.

<u>Microscopic Tool-Based Modeling Approach</u>

Handling an individual carpool requester and a willing driver are the most crucial elements needed to properly model the D-RIDE application. While the microscopic modeling tool is one of the tools capable of handling individual subjects by the support of APIs, it is worth noting that an event-based discrete simulation would be available for this application. The pedestrian's rideshare request can be modeled by either a probability model or a predefined scenario. The D-RIDE application can be implemented through either a centralized system or a decentralized system.

In a centralized system, once the API, mimicking a control center for the ridesharing system, captures a ridesharing call, including the requester's information such as his/her position, final destination, and other personal information, it searches for the most suitable driver committed to provide the ridesharing and asks whether that driver will accept the request or not. If the driver refuses the request, the API looks for other ridesharing drivers. In a decentralized system, each of the ridesharing drivers captures the request call at the same moment, but the time in which they respond to the requester might vary based on the driver's behavior. The compliance of the ridesharing drivers can be modeled by either 1) a choice model-based analytical approach or 2) a scenario-based sensitivity analysis. The choice model-based approach would be the most promising method in that it can precisely reflect drivers' acceptance behaviors in response to the ridesharing request as long as properly calibrated utility functions are available. With the utility functions, the probability of whether a ridesharing driver accepts the request or not can be calculated by using either the Logit or the Probit model. On the other hand, sensitivity analysis on driver's compliance behavior can be implemented by simulating a range of plausible compliance rates (e.g., from 10 percent to 90 percent by 10 percent increments) in response to the ridesharing request.

In summary, the following is the list of APIs required for the microscopic modeling approach for the D-RIDE application.

New API:

- *Real-time pedestrian call modeling (e.g., position, final destination, and other personal information)*
- *Capturing real-time pedestrian calls requesting ridesharing*
- *Manipulating ridesharing vehicles in real-time (e.g., route adjustment)*
- *Capturing real-time traffic information (e.g., congestion, incident, and/or work-zone)*

New API supported by external models:

- *Optimal route guidance for ridesharing drivers to the requester reflecting concurrent traffic conditions based on a shortest path algorithm*
- *Choice model-based behavior model for ridesharing driver (e.g., decision on the request and compliance in response to the ridesharing request)*
- *Sensitivity analysis for the behavior of ridesharing driver*

<u>Activity-Based Modeling Approach</u>

One critical challenge of the activity-based tool is capturing real-time information of individual vehicles and pedestrians, which is crucial for modeling ridesharing. The ridesharing requests would not necessarily be modeled precisely in the activity-based modeling tool unless its program source code was properly customized. The ridesharing vehicles can be modeled by adding an additional demand representing the ridesharing vehicles. By customizing the program source code of the activity-based modeling tool, it is possible to handle their en-route route change in response to ridesharing requests as described in the modeling approach sections for ATIS and WX-INFO.

The compliance of the ridesharing drivers can be modeled by either a binary choice model-based approach or a sensitivity analysis as described in the microscopic modeling tool approach. Once the driver appears to accept a ridesharing request, the driver's route will be adjusted in real-time to pass over the link where the ridesharing request is supposed to be by using the minimum path algorithm embedded in the activity-based model. Driver's path selection is determined by a path selection model included in the activity-based modeling tool.

<u>Multi-Scale Modeling Approach</u>

The D-RIDE application is expected to reduce travel time for passengers who would use transit modes when no ridesharing is available. In parallel, the total travel times of ridesharing providers would rise due to the increase of travel distances to pick up ridesharing requesters. The microscopic modeling approach for D-RIDE would capture the number of passengers who switched to the ridesharing from their original transportation modes based on external factors such as the market penetration rates, compliance rate of ridesharing drivers, and the number of ridesharing requesters.

Such impacts captured by the microscopic modeling approach covering multiple corridors and intersections can be used for the proposed multi-scale approach by expanding the identified impacts. For example, the ratio of the travel time of ridesharing passengers over non-ridesharing passengers under various market penetration rates, compliance rates, mode shift rates, and traffic congestion conditions can be easily estimated using the microscopic modeling approach. This ratio can be then applied to the estimation of the travel time of ridesharing class for the activity-based modeling tool. In the same manner, the travel time ratio of ridesharing providers over the non-ridesharing drivers can be estimated. Moreover, under a specific market penetration and driver compliance rate, the number of passengers who used the ridesharing service identified by the microscopic modeling tool can be used for the ratio of mode shifts from the original to ridesharing. With the estimated travel time for ridesharing passengers and drivers, and the number of ridesharing users, one can adjust OD tables and transit route selections for each OD pair by using dynamic traffic assignment. It is possible to adjust the initial OD demands using mode choice models, which take OD travel time, cost and transfer time as independent variables for their utility functions, if these mode choice models are given by a regional travel demand model. Likewise, with the link travel times obtained from the DTA, the best route for each OD pair can be updated. With the updated OD demands and routes, it is repeated until the network converges. Once the convergence is achieved, performance measures (e.g., travel time, throughput) will be calculated to examine the large scale performance of the D-RIDE application.

6.5. FRATIS Bundle

This section presents a modeling approach for the FRATIS bundle to provide researchers and stakeholders with proper directions on how to model each application within the state-of-the-art and the state-of-the-practice of current modeling tools.

Figure 6-6 shows a high-level data flow diagram for the FRATIS bundle. For example, the red dotted arrow lines indicate the data flow of both the F-ATIS and F-DRG applications while the black solid arrow lines depict the data commonly used for each application. In a Connected Vehicle environment, the data covering traffic information, incidents, weather conditions, and parking facility availability can be collected by not only a traffic management center but also by communications device-equipped vehicles. The collected data will be used for generating both real-time and predicted guidance information to provide travelers with the route alternatives and the expected travel time of the routes. To this end, real-time OD estimation model and path finding algorithms are required. The guidance information will be disseminated to freight vehicle operators through Connected Vehicles, variable message signs (VMS), broadcasting, and personal mobile devices.

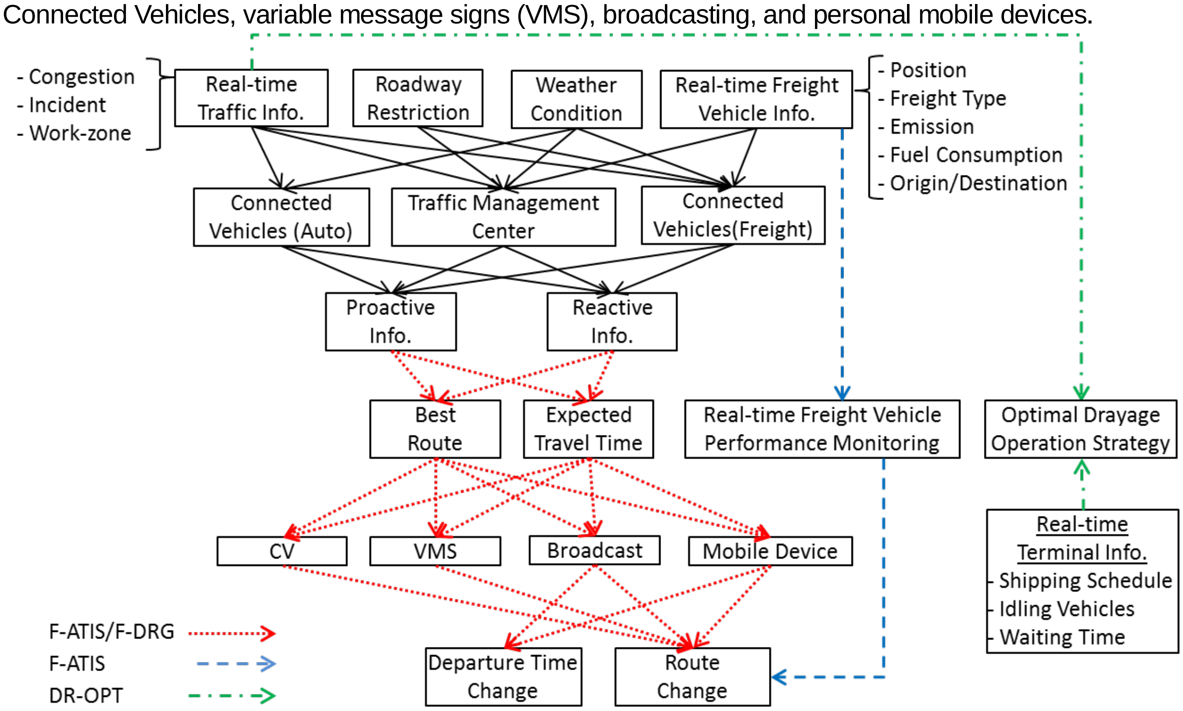

Figure 6-6. FRATIS Data Flow Diagram.

<u>Proposed Modeling Tools</u>

With respect to the selection of proper modeling tools to successfully accommodate proposed modeling approaches, all of the applications dealt with in this section are prepared for both microscopic and activity-based modeling tools. Despite the fact that the microscopic modeling tool is insufficient to cover a large-scale network, the project team proposes it as a primary modeling tool due to its capability to handle individual vehicles in real-time and extendibility, enabling API type external modules. While the mesoscopic and hybrid modeling tool would be suitable for dealing with the larger area, the modeling approach for a large-scale network proposed for the FRATIS bundle applications in this section focuses on the activity-based modeling tool. However, both tools would be insufficient to capture individual vehicles' instantaneous information which is a crucial element for the F-ATIS and F-DRG applications, as it is unable to handle individual freight vehicles. The hybrid model would also be unable to handle individual vehicles for the entire network because they are only considered for a narrowed area of the network. Thus, it is challenging to model individual vehicle-related features such as obtaining real-time traffic information from equipped vehicles, and truckers' traveling behaviors (e.g., lane changing, car following, and route selection in response to the F-ATIS/F-DRG information). To overcome this challenge, the project team proposes the TRANSIMS model as a proper tool for the FRATIS bundle. It must be noted that the current activity-based modeling tool does not provide any interfaces (e.g., API or COM) to enable the handling of individual vehicles during the simulation. However, because the source codes for TRANSIMS are open, the program can be customized to accommodate any required modeling elements for FRATIS. Thus, the modeling approach proposed for each FRATIS application is based on the assumption that the TRANSIMS model can be customized in the near future.

A microscopic modeling tool would be suitable for a small-scale network, such as multiple corridors or a small region, because it can capture vehicular information instantaneously and, consequently, it can precisely simulate each application as described in its concept of operations. However, as identified in Section 5, there are numerous modeling elements exceeding the off-the-shelf modeling capability given by the microscopic modeling tool, such as real-time route adjustment for freight vehicles. For those elements, this research proposes proper API-type external modules and describes how to design the API modules.

While developing a modeling approach, it was determined that the most challenging component for the FRATIS bundle is to model freight vehicles and their behaviors in response to the provided information properly. This research proposes two options to deal with truckers' behavior: one is choice model-based approach proposed by several researchers (Ben-Akiva and Lerman, 1985; Cascetta et al., 1996; Koppelman and Wen, 1998; Ramming, 2002; Bovy et al., 2008) and the other one is scenario-based sensitivity analysis. The choice model approach, based on either the Logit or the Probit model, estimates the probability of a driver's selecting one out of all the competing alternatives by using a utility function developed for each alternative. It is then crucial to use proper utility functions, but obtaining and calibrating such functions are challenging. While this approach may sufficiently explain the behavior of travelers, it is typically quite expensive and often not reliable when stated preference (SP) data instead of revealed preference (RP) data is used. The sensitivity analysis assumes the compliance of a traveler in selecting one alternative among other competing alternatives by simulating a range of plausible compliance rates (e.g., from 10 percent to 90 percent by 10 percent intervals). For example, assuming a traveler's compliance rates in choosing the alternative routes are 60 percent, 30 percent, and 10 percent for the best, second, and third shortest paths, respectively, the behavior of traveler's path selection can be simulated based on a Monte Carlo simulation approach. It should be noted that the compliance rates can be obtained by experimental design approaches such as full factorial method (Winer et al., 1991) and Latin Hypercube Design (McKay et al., 2000) to create unbiased compliance rate scenarios. While the sensitivity analysis may seem insufficient to precisely capture the behavior of travelers and requires numerous simulation replications to cover the diversity of choice behaviors, this approach enables a dramatic reduction in the cost and efforts to build behavior models.

Highway driving simulators (FHWA, 2010; NHSTA, 2011) would be a viable option to support the modeling of driver behavior. For example, as one of the exploratory advanced research (EAR) projects, FHWA has led in innovative research applying the highway driving simulator for the examination of driver behaviors (e.g., lane changing and car following) in response to external stimuli such as aggressive driving and sudden stop. With the driving simulator, it might be possible to capture how drivers react to guidance information in a Connected

Vehicle environment. Such captured driver reaction data can be useful for building the utility functions of the choice model.

6.5.1. Freight Real-Time Traveler Information with Performance Monitoring (F-ATIS)

6.5.1.1. Review of existing modeling efforts

Previous modeling efforts (e.g., Ben-Akiva et al., 1997; Wunderlich, 1998; Bottom et al., 1999; Farver, 2005) for route guidance systems can be applied for a freight vehicle route guidance system. The route guidance model proposed by Lee and Park (2008) can be easily expanded to cover freight vehicles.

6.5.1.2. Modeling approach

Based on the findings in Section 5, the following core modeling elements are identified.

- *Modeling freight vehicles (e.g., departure time, desired speed, origin-destination)*
- *Collecting real-time traffic information (e.g., congestion, incident)*
- *Modeling freight operators' traveling behavior in response to the F-ATIS information*
- *Modeling freight operator's driving behaviors (compliance, route diversion, and speed changes) based on traffic Information.*
- *Using the dynamic k-shortest path algorithm*
- *Using the dynamic origin/destination matrix estimation*

To incorporate the above modeling elements, the F-ATIS application can be modeled by activity-based and microscopic modeling tools. This section describes the modeling approach and discusses the pros and cons of each modeling approach.

<u>Microscopic Tool-Based Modeling Approach</u>

The APIs developed for the ATIS application in the EATIS bundle can be expanded for modeling the F-ATIS application by incorporating freight vehicle (FV) specific information into the APIs. The FV-specific information would include terminal status, congestion at shipyards, and restricted routes or areas depending on the size, weight, and hazmat risk of freight vehicles. To properly deal with such FV-specific information in the modeling of this application, the most suitable approach would be to use scenario-based experiments covering various conditions with respect to the information.

The real-time vehicle status information is captured and provided to the FV drivers by an API. In addition to the typical traffic information, both the vehicle status information and the FV information will be used to provide FV drivers with the best route guidance accommodating their diverse objectives (e.g., minimizing travel time, fuel consumption, or travel cost) by the API.

Modeling the compliance of FV drivers to the given guidance information is challenging. Since the FV drivers have diverse objectives affecting the determination of their route, the behavior of their route choice would be more sophisticated than that of auto drivers as they have additional constraints in determining the best route, such as roadway restrictions, hazmat risk, and driving costs. There are two possible options to model the compliance of FV drivers: one is the choice model-based statistical approach and the other is the scenario-based sensitivity analysis approach. Developing proper choice models requires a tremendous amount of data and modeling effort, while the sensitivity analysis approach is simple to implement but requires numerous simulation runs to cover various drivers' route choice behaviors.

In summary, the following is the list of APIs required for the microscopic modeling approach for the F-ATIS application.

New API:

- *Controlling freight operators in real-time (e.g., en-route path change and departure time adjustment)*
- *Capturing real-time vehicular information (e.g., position, speed, travel time, and route)*

New API supported by external models:

- *Choice model-based traveler behavior model (e.g., decision on route selection, departure time change, and traveler compliance in response to the given information)*
- *Sensitivity analysis for travel behavior*
- *Optimal path generation based on a k-shortest path algorithm*

Non-API type external module:

- *Performance measure generation (e.g., safety (SSAM), emission and energy (VT-Micro model)).*

Activity-Based Modeling Approach

It is possible to collect real-time traffic information (e.g., delay, travel time, or incident information) from equipped vehicles within the TRANSIMS simulation framework as long as it is properly customized. Thus, instantaneous vehicular information can be obtained for individual freight vehicles, such as position, origin and destination, and speed.

The TRANSIMS model provides both pre-trip and en-route route selection models that are based on choice model approach. Both models are suitable for simulating the traveling behaviors of freight vehicle operators in response to the F-ATIS information. For example, the utility functions given in the route selection model consist of travel times of each competing route; thus, as long as it is possible to capture the travel time of each route at every update interval, the behavior of route selection can be modeled. However, to apply those route selection models in real-time, it is necessary to customize the program source code.

One of the crucial elements in the F-ATIS application is finding the shortest path for freight vehicles based on collected traffic information at every update interval. The TRANSIMS model has a proper algorithm to build multiple paths (a.k.a., k-shortest paths), but it must be enhanced to consider specific information for freight vehicles, such as roadway restriction information for weight or hazmat. Furthermore, a dynamic OD table for each mode might be the most critical input data for the evaluation of any ATIS-type application, including F-ATIS. There exist a few relevant research efforts to obtain the dynamic OD tables; the most notable approaches can be found in Van Aerde et al.(2003), Ashok and Ben-Akiva (2002), and Bierlaire and Crittin (2004). These approaches can be incorporated as an external module for the activity-based modeling tool for estimating dynamic ODs.

Multi-Scale Modeling Approach

The proposed microscopic approach is challenging for modeling a large-scale network, so, in addition to the activity based modeling approach, the project team proposes a hybrid, multi-scale modeling approach to incorporate the revealed performances discovered by microscopic modeling approach and a mesoscopic modeling tool for high level impact assessment for the F-ATIS application on a large scale network. It should be noted that the mesoscopic modeling tool is considered to be more suitable for the multi-scale modeling approach tool than the activity-based modeling tool. This is because the mesoscopic modeling tool can ensure faster implementation for a large scale network when it is incorporated with the microscopic modeling tool.

For the largest network that microscopic modeling tools can handle, the performance of F-ATIS can be evaluated using the microscopic modeling approach based on the various external factors such as Connected Vehicles market penetration rates, traffic congestion conditions, compliance rates, and freight vehicle demand levels. By using an experimental design approach, it is possible to create numerous experimental scenarios covering the variety of relevant external factors to examine the benefits of the F-ATIS application, such as travel time savings among operators that use F-ATIS compared to those that do not.

These travel time savings can be applied to adjust the speed-density functions of mesoscopic modeling tools that can efficiently handle a large-scale network. For example, a dynamic traffic assignment (DTA) can be performed for each scenario by properly modifying the coefficient of the speed-density functions to reflect the travel time savings of the F- ATIS users.

To properly reflect the impact of F-ATIS on links in the speed-density functions, it is recommended to examine the speed-density relationship obtained from the microscopic modeling approach under the F-ATIS application case and find the optimal parameter coefficient set such as jam density, speed intercept, maximum flow rate, and model shape parameters (e.g., α and β). The adjusted speed-density function is fed into the mesoscopic modeling tool covering a large-scale network to implement a dynamic traffic assignment (DTA) with initial modal OD demands. Once the DTA is complete, one can obtain OD travel times and link travel times which are used for updating OD tables and routes for each OD pair. It is possible to adjust the initial OD demands using mode choice models, which take OD travel time, cost and transfer time as independent variables for their utility functions, if these mode choice models are given by a regional travel demand model. Likewise, with the link travel times obtained from the DTA, the best route for each modal OD pair can be updated. With the updated OD demands and routes, the DTA in the mesoscopic modeling approach is repeated until the network converges. Once the convergence is achieved, performance measures (e.g., travel time, throughput) will be calculated to examine the large scale performance of the F-ATIS application.

6.5.2. Drayage Optimization (DR-OPT)

6.5.2.1.Review of modeling research efforts

Ioannou et al. (2007) developed an integrated simulation test-bed incorporating both macroscopic and microscopic models, namely TermSim (Ioannou, 2005) and TrafficSim (Ioannou, 2007), respectively, for evaluating strategies for freight vehicle operations at terminals or on corridors. The TermSim model, a flow-based terminal simulation model, deals with the movement of freight vehicles at terminals and interacts with TrafficSim, a VISSIM-based roadway network simulator. The TrafficSim model provides TermSim with the realistic movements of freight vehicles resulting from the traffic congestion conditions outside of the terminal. With the simulation test-bed, the research team evaluated the performances of a few terminal operation strategies, such as 1) empty container re-use and 2) inland port and truck-dedicated lane, to assess the impacts of both terminal and corridor.

Huynh and Zumerchik (2010) proposed a discrete event simulation model to evaluate the performance of drayage operations at terminal or port by using the Arena simulation program (Arena, 2012). Assuming the instant information of all the freight vehicles, such as position and waiting time, is known, the research team can assess the impact of drayage operations by demonstrating not only mobility measures but also emission measures by using the SmartWay DrayFLEET program (EPA, 2007).

6.5.2.2.Modeling approach

Based on the findings in Section 5, the following core modeling elements are identified.

- *Modeling drayage vehicles (e.g., freight arrival time, loading/unloading time)*
- *Generating optimal drayage operation strategy*

To incorporate the above modeling elements, the DR-OPT application can be modeled by the microscopic modeling tool. It should be noted that it is not necessary to evaluate the DR-OPT application for a large-scale network.

<u>Microscopic Tool-Based Modeling Approach</u>

Real-time line-haul information of freight vehicles, such as position, route, and freight type and amount, can be obtained by a microscopic simulation modeling tool with the support of a new API, as demonstrated by previous research (Ioannou et al., 2007). The information collected through the API will be used for the optimization of trans-shipment schedules in real-time. Since the microscopic tool is unable to perform this optimization task with off-the-shelf capabilities, it will be necessary to develop a new API enabling it to interact with an external program to obtain the optimal trans-shipment schedule.

Based on the optimal trans-shipment schedule, individual freight vehicles can be controlled by a new API, handling their behaviors, such as waiting, trans-shipping, and moving, at terminals or ports in response to the schedule.

In summary, the following is the list of APIs required for the microscopic modeling approach for the DR-OPT application.

Existing API:

- *Capturing real-time freight vehicles' line-haul information as developed by Ioannou et al. (2007)*

New API:

- *Controlling freight operators in real-time (e.g., en-route path change and departure time adjustment)*
- *Capturing real-time vehicular information (e.g., position, speed, travel time, and route)*

New API supported by external models:

- *Optimizing real-time trans-shipment scheduling by incorporating an external algorithm program (e.g., SmartWay and DrayFLEET)*

Large-Scale Modeling Approach

The microscopic modeling approach proposed for the DR-OPT application enables an assessment of the benefits of DR-OPT such as trans-shipment time savings and freight vehicle idling time reductions at a port or a terminal. Using an experimental design method, those benefits can be evaluated based on various external factors such as the market penetration rate of freight vehicles, traffic congestion conditions of the freight vehicle route, and trans-shipment demands at the port or terminal. By employing each of those benefits as the unit benefit per port or terminal for each case, the benefits can be used to examine the high-level impact of the application on a large-scale network, including multiple ports or terminals. Thus, for the large-scale impact assessment for DR-OPT, it is necessary to create multiple scenarios covering the number of ports or terminals in addition to the external factors mentioned above.

6.5.3. Freight Dynamic Route Guidance (F-DRG)

6.5.3.1. Review of modeling research efforts

Ioannou et al. (2000) evaluated the impact of dynamic route guidance for trucks by developing a new microscopic simulation model based on the dynamic traffic assignment (DTA) technique. In the simulation model, the research team developed a car following model for truck driving behaviors while the behavior of the passenger car was simulated by Pipes model. Assuming that all the trucks in a hypothetical network have access to the guidance information (100 percent market penetration) and accept the provided information (i.e., 100 percent compliance), the research team evaluated the impact of a route guidance system by demonstrating mobility measures compared to non-guidance and static guidance information cases.

6.5.3.2. Modeling approach

Based on the findings in Section 5, the following core modeling elements are identified.

- *Modeling freight vehicles (e.g., departure time, desired speed, origin-destination)*

- *Collecting real-time traffic information (e.g., congestion, incident)*
- *Modeling freight operators' traveling behavior in response to the F-ATIS information*
- *Modeling freight operator's driving behaviors (compliance, route diversion, and speed changes) based on traffic Information.*
- *Using the dynamic k-shortest path algorithm*
- *Using the dynamic origin/destination matrix estimation*

To incorporate the above modeling elements, the F-DRG application can be modeled by activity-based and microscopic modeling tools. This section describes the modeling approach and discusses the pros and the cons of each modeling approach.

Microscopic Tool-Based Modeling Approach

APIs discussed in the ATIS application can be easily expanded to model the F-DRG application by customizing those APIs to integrate additional guidance objectives related to freight vehicles, such as fuel and emission minimization, hazmat risk removal, and weather-related safety improvement.

The API will gather real-time congestion, incident, weather-condition and work-zone information from the microscopic simulation modeling tool. A new API can model the incident condition and work-zone information. The weather conditions likely affecting the capacity and desired speed of a roadway can be imported from existing studies (Mahmassani, 2009; Rakha, 2009). With the collected information, the API will find the best path, while accommodating the truck drivers' diverse objectives.

The behaviors of freight vehicle operators in response to the guidance information, which are crucial elements supporting route-guidance simulation, can be modeled by an analytical approach based on a traveler's choice model (e.g., Logit or Probit) or a scenario-based sensitivity analysis. The choice model-based approach would be the most promising method in that it can precisely reflect drivers' route choice behavior. For the choice model approach, the utility functions given in the route choice model consist of travel times for each alternative path competing with the others; thus, as long as it is possible to obtain the travel time of each path at every update interval, the real-time route shift can be modeled. Note that the choice model approach requires significant amounts of data and data collection effort to calibrate the model properly, while the scenario-based compliance rate approach is easy to implement, although its theoretical background is challenging.

On the other hand, the sensitivity analysis would be easy to implement to assess driver compliance behavior by simulating a range of plausible compliance rates (e.g., from 10 percent to 90 percent by 10 percent increments) in response to the given route information, but this approach requires a relatively large number of simulated scenarios.

In summary, the following is the list of APIs required for the microscopic modeling approach for the F-DRG application.

New API:

- *Controlling freight operators in real-time (e.g., en-route path change and departure time adjustment)*
- *Capturing real-time vehicular information (e.g., position, speed, travel time, and route)*

New API supported by external models:

- *Choice model-based traveler behavior model (e.g., decision on route selection, departure time change, and traveler compliance in response to the given information)*
- *Sensitivity analysis for travel behavior*
- *Optimal path generation based on a k-shortest path algorithm*
- *Traveler behavior model based on weather impact (e.g., Mahmassani et al.(2009) and Rakha et al. (2009))*

Non-API type external module:

- *Performance measure generation (e.g., safety (SSAM), emission and energy (VT-Micro model))*

Activity-Based Modeling Approach

The activity-based model is selected for evaluatng the F-DRG application on a large-scale network. With TRANSIMS, one of the most notable activity-based models, in which the program source codes are open, it is possible to collect real-time traffic information (e.g., delay, travel time, or incident information) from equipped vehicles as long as the software is properly customized. Thus, instantaneous vehicular information can be obtained for individual freight vehicles, such as position, origin and destination, and speed.

The TRANSIMS model provides both pre-trip and en-route route selection models that are based on choice model approach. Both models are suitable for simulating the traveling behaviors of freight vehicle operators in response to the route guidance information. For example, the utility functions given in the route selection model consist of the travel times of each competing route; thus, as long as it is possible to capture travel time for each route at every update interval, the behavior of route selection can be modeled. However, to apply those route selection models in real-time, it is necessary to customize the program source code.

One of the crucial elements in the F-DRG application is to find the shortest path for freight vehicles based on collected traffic information at every update interval. The TRANSIMS model has a proper algorithm to build multiple paths (a.k.a., k-shortest paths), but it must be enhanced to consider specific information for freight vehicles, such as roadway restriction information for weight or hazmat. Furthermore, a dynamic OD table for each mode might be the most critical input data for the evaluation of any ATIS-type applications, including F-ATIS. A few relevant research efforts to obtain the dynamic OD tables exist; the most notable approaches can be found in Van Aerde et al. (2003), Ashok and Ben-Akiva (2002), and Bierlaire and Crittin (2004). These can be incorporated as an external module for the TRANSIMS model for estimating dynamic ODs.

Multi-Scale Modeling Approach

The high level performance evaluation for the F-DRG application can be obtained by the same approach proposed for the F-ATIS application incorporating the microscopic and mesoscopic modeling tools. It should be noted that the mesoscopic modeling tool is considered to be more suitable for the multi-scale modeling approach tool than the activity-based modeling tool. This is because the mesoscopic modeling tool can ensure faster implementation for a large scale network when it is incorporated with the microscopic modeling tool.

It is possible to assess the benefits of freight vehicle operators who utilize the freight-specific route guidance information covering fuel and emission minimization, hazmat risk removal, and weather-related safety improvement in addition to other conventional information for route guidance such as congestion and incident. Consequently, it is necessary to build more specific experiment scenarios dealing with the additional factors such as the number of restriction zones, heavy weather conditions, and the risks of hazmat that likely affect the optimal paths for freight operators. With these additional experimental factors, a performance model explaining the relationship between the benefits of F-ATIS and external factors can be built. To this end, parametric or nonparametric modeling approaches (such as regression models and artificial neural networks, respectively) can be applied based on external factors including the market penetration rates, traffic congestion conditions, inclement weather condition, and compliance rates.

Assuming the performance model deals with travel time savings of F-DRG users for each experiment scenario, the speed-density functions of mesoscopic modeling tools can be adjusted to reflect the travel-time savings to the links in the network. Applying the modified speed-density functions, one can then assess the high-level performance for the F-DRG application with the mesoscopic modeling tool. That is, the adjusted speed-density function is fed into the mesoscopic modeling tool covering a large scale network to implement a DTA with initial modal OD demands. Once the DTA is complete, one can obtain OD travel times and link travel times which are used for updating OD tables and routes for each OD pair. It is possible to adjust the initial OD demands using mode choice models, which take OD travel time, cost and transfer time as independent variables for their utility functions, if these mode choice models are given by a regional travel demand model. Likewise, with the link travel times obtained from the DTA, the best route for each modal OD pair can be updated. With the updated OD demands and routes, the DTA in the mesoscopic modeling approach is repeated until the network converges. Once convergence is achieved, performance measures (e.g., travel time, throughput) will be calculated to examine the large-scale performance of the F-DRG application.

6.6. Response, Emergency Staging, Communications, Uniform Management and Evacuation (R.E.S.C.U.M.E.) Bundle

This section presents modeling approaches for the R.E.S.C.U.M.E. bundle. Based on the findings from Section 5, the sub-applications of the bundle are not necessarily modeled for a large network except for the Emergency Communications and Evacuation (EVAC) application, which is suitable for the activity-based modeling tool. Thus, this section primarily focuses on a microscopic tool-based modeling approach for the applications of 1) Incident Scene Pre-Arrival Staging Guidance for Emergency Responders (RESP-SIG), 2) Incident Scene Work Zone Alerts for Drivers and Workers (INC-ZONE), and 3) Mayday Relay (Mayday). Figure 6-7 shows a high-level data flow diagram for the R.E.S.C.U.M.E. bundle. The Connected Vehicle environment enables capturing real-time information, such as traffic congestion, incident, work-zone, and crash information. With other additional off-line information, such as undrivable evacuees and evacuation shelter locations, the collected traffic congestion information is used for generating not only optimal evacuation routes for evacuees with their own transportation but also new transit vehicle dispatching plans for captive evacuees. The incident and work-zone information collected through Connected Vehicles in the network is fed into the traffic management center to produce guidance information for emergency responders dealing with the incident and for drivers or workers around the work-zone or the incident area. The real-time vehicle crash information is captured by Connected Vehicles and disseminated to other Connected Vehicles to relay the crash information.

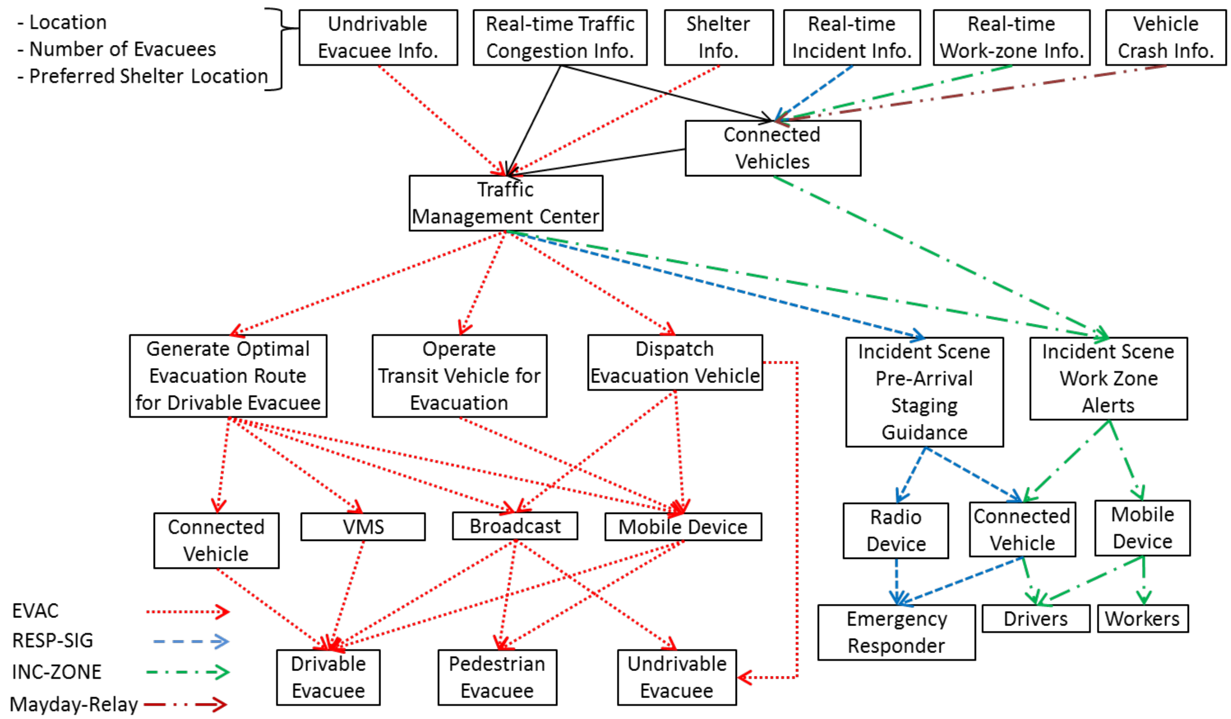

Figure 6-7. R.E.S.C.U.M.E. Data Flow Diagram.

<u>Proposed Modeling Tools</u>

The microscopic modeling tool would be suitable for small-scale networks, such as multiple corridors or a small region, as it allows capturing vehicular information on the fly. Thus it can precisely simulate each application as described in its concept of operations. However as identified in Section 5, there are numerous modeling elements exceeding the off-the-shelf modeling capability given by the microscopic modeling tool, such as real-time route change and user-defined signal adjustment. For those elements, this research proposes proper API-type external modules and describes how to design the API modules.

6.6.1. Emergency Communications and Evacuation (EVAC)

6.6.1.1. Review of existing modeling efforts

There are numerous research efforts dealing with the modeling of evacuations. Hardy et al. (2009) and Pel et al. (2011) clearly summarized the previous modeling efforts. While almost all evacuation modeling efforts performed by either DTA-based mesoscopic or microscopic simulation approaches mainly focus on passenger vehicles, a few relevant studies address the modeling of transit-based evacuation (Elmitiny et al., 2007) and the evacuation modeling for individuals with disabilities (Manley et al., 2011).

Elimitiny et al. (2007) proposed a VISSIM-based simulation model to evaluate the multiple evacuation scenarios for pedestrians involving the use of buses in an urban area. The authors employed the VISSIM program explicitly to model bus and pedestrian-related operational strategies such as priority signals for buses and pedestrians at intersections and temporary bus-dedicated lanes under the evacuation condition.

Manley et al. (2011) estimated the total evacuation time of individuals with disabilities at an airport under a hypothetical emergency case by using an agent-based simulation model, namely BUMMPEE (Manley, 2010). The authors divided the evacuees into 6 categories based on a defined set of disabilities (or lack therof), including visually impaired, motorized wheelchair, non-motorized wheelchair, low stamina, non-hearing, and non-disabled. The behaviors of each evacuee group were modeled by a social force model with a different parameter set.

6.6.1.2.Modeling approach

Activity-Based Modeling Approach

The EVAC application would best be modeled with an activity-based model such as TRANSIMS because the size of the roadway network that this application covers must be relatively large, and that might be challenging using either the microscopic or hybrid modeling tools. It must be noted that the current activity-based modeling tool does not provide any interfaces (e.g., API or COM) enabling the handling of individual vehicles during the simulation. However, because the source codes are open in TRANSIMS, in which the source codes are open, it is possible to customize its program to accommodate any required modeling elements for the EVAC application. Thus, the proposed modeling approach is based on the assumption that the TRANSIMS model can be customized in the near future.

TRANSIMS can generate the best routes, accommodating evacuees' diverse objectives for path finding. Trip planner, a trip chain generator for TRANSIMS, can model both drivable evacuees as well as captive riders in need of transportation modes. Evacuees who are drivable and equipped with communication devices such as DSRC, 3G or 4G networks can adjust their en-route path by customizing the program source codes of TRANSIMS to be able to control individual vehicles in real-time. Customizing the program is also necessary to deal with those who own no transportation modes and to handle special vehicles having specific origin and destination to serve such evacuees.

To properly handle evacuee behavior in response to the evacuation information, such as route choice and mode choice, the project team proposes two options: one is choice model-based approaches proposed by several researchers (Ben-Akiva and Lerman, 1985; Cascetta et al., 1996; Koppelman and Wen, 1998; Ramming, 2002; Bovy et al., 2008) and the other one is scenario-based sensitivity analysis.

The choice model approach, based on either the Logit or the Probit model, estimates the probability of a traveler's decision in selecting one competing alternative by using a utility function developed for each alternative. It is then crucial to use proper utility functions, but obtaining and calibrating such models are challenging. While this approach may sufficiently explain the behavior of travelers, it must be noted that it is typically quite expensive and often not reliable when stated preference (SP) data instead of revealed preference (RP) data is used. It is also noted that only SP data can be obtained at this point as each dynamic mobility application is based on the Connected Vehicle, which is not available yet.

The sensitivity analysis assumes the compliance of a traveler for selecting one alternative among other competing alternatives by simulating a range of plausible compliance rates (e.g., from 10 percent to 90 percent by 10 percent increments). For example, assuming a traveler's compliance rates for choosing the alternative routes are 60 percent, 30 percent, and 10 percent for the best, second, and third shortest paths, respectively, the behavior of traveler's path selection can be simulated based on a Monte Carlo simulation-based approach. The compliance rates can be obtained using an experimental design approach, such as full factorial method and Latin Hypercube Sampling, to create unbiased compliance rate scenarios. While the sensitivity analysis may be insufficient to precisely capture the behavior of travelers and requires numerous simulation replications to cover the diversity of choice behaviors, this approach enables a dramatic reduction in the cost and effort to build behavior models.

Multi-Scale Modeling Approach

This application does not require multi-scale evaluation because the activity-based modeling tool covers large scale networks.

6.6.2. Incident Scene Pre-Arrival Staging Guidance for Emergency Responders (RESP-SIG)

6.6.2.1. Review of modeling research efforts

Jordan et al. (2012) developed a VISSIM-based simulation model to evaluate the performance of wireless communications for emergency vehicles to improve the response time to incidents by using Component Object Model (COM)-based VISSIM API. In the model, COM handles most crucial elements required for the modeling, such as emergency vehicles' driving behavior, passenger vehicles' lane changing, and incident occurrence and duration. With traffic congestion scenarios covering various traffic volumes, the authors measured the response time to the incident location by using a simplified hypothetical simulation corridor.

6.6.2.2. Modeling approach

Based on the findings in Section 5, the following core modeling elements are identified.

- Modeling and manipulating emergency responder vehicles (e.g., route, departure time)
- Modeling Incidents (e.g., location, occurrence time, duration, severity)
- Developing optimal route guidance for emergency responders

<u>Microscopic Tool-Based Modeling Approach</u>

To incorporate the above modeling elements, the RESP-SIG application can be modeled by the microscopic modeling tool. It should be noted that this application is not necessary to be evaluated for a large-scale network.

A virtual crash case can be modeled in a microscopic modeling tool with the support of a new API, dealing with its location, occurrence time, duration, and severity (e.g., capacity reduction) by employing a Monte Carlo simulation-based approach. Given a crash event, the traffic condition information around the crash site will be collected by OBE-equipped vehicles controlled by a new API dealing with the monitoring of individual vehicles. The collected data will be broadcasted to other OBE-vehicles and RSEs located within the DSRC communications range, which can be modeled by existing DSRC communications performance studies (Lee and Park, 2010; Park et al., 2011; Assenmacher et al., 2011).

Once the collected crash information is received at a local TMC, the API creates a new vehicle as an emergency responder and dispatches it to the crash site by providing it with new destination and path obtained from a proper shortest path algorithm.

In summary, the following is the list of APIs required for the microscopic modeling approach for the RESP-SIG.

New API:

- Modeling virtual incidents based on a Monte Carlo simulation-based approach (e.g., location, occurrence time, duration, and severity (e.g., capacity reduction))
- Collecting real-time incident information through Connected Vehicles (e.g., queue length, delay time, and capacity reduction)
- Manipulating emergency responder vehicles in real-time (e.g., dispatching and route control)

New API supported by external models:

- Optimal path generation for the emergency responder.

Microscopic Tool-Based Modeling Approach

The most suitable modeling tool for the T-DISP application is the microscopic modeling tool, which is capable of handling transit vehicles in real-time with the support of the API capability.

A new API in the microscopic modeling tool can model a transit control center dealing with the operation of transit vehicles. The control center API collects both real-time information of transit vehicles covering the position (e.g., number of passengers, arrival and departure times, and number of passengers waiting at the stops or stations) by emulating the use of mobile hands-on devices such as smart phone, as well as traffic condition information such as congestion, incident, and work-zone. The route of transit vehicles can be dynamically adjusted by the API to improve the performance of transit vehicle operations. For example, if the API detects serious congestion due to an incident or a work zone on a certain street that is a part of a transit vehicle route and finds no passengers who are willing to board or alight at the corresponding stops along the street, the route of the transit vehicle can be adjusted to avoid the congestion by the API. In a case when passengers are waiting at the stops but there are no available transit vehicles to serve them, the API will dispatch a para-transit vehicle to the stops.

The API also gathers dynamic demand calls from transit travelers who request the dispatch of new transit vehicles or para-transit vehicles. The travelers' demand call, incidents, and work-zone can be modeled by either a random probability model or predefined scenarios.

In summary, the following is a list of APIs required for the microscopic modeling approach for the T-DISP application.

New API:

- Capturing real-time transit vehicle information (e.g., position, speed, departure time, passenger loads, passengers boarding/alighting at the stops or stations)
- Manipulating transit vehicles in real-time (e.g., departure time adjustment, route change, and new transit vehicle dispatching)
- Capturing real-time traffic information (e.g., congestion, incident, and/or work-zone)

New API supported by external models:

- Optimal route guidance for transit vehicles reflecting concurrent traffic conditions based on a shortest path algorithm

Multi-Scale Modeling Approach

To examine the impact of RESP-SIG on a large scale network using the multi-scale modeling approach, it is necessary to clearly identify the expected benefits of the application. One crucial expected benefit is the travel time reduction of emergency responders (ER). The microscopic modeling approach for RESP-SIG enables capture of the ERs performance to the incident scene under various external conditions such as the market penetration rates and traffic congestion conditions.

Such performances captured by the microscopic modeling approach can then be modeled using either a parametric (e.g., regression model) or a nonparametric (e.g., artificial neural network) approach. By examining the relationships between the performances (i.e., outputs) and the external factors (i.e., inputs), a regression model or an artificial neural network model can be built to estimate the performance of RESP-SIG without implementing the microscopic modeling approach

For example, once the nonparametric performance model is built, both the travel time saving of ERs and delay time increase of general purpose vehicles (GPVs) can be estimated for a certain corridor under various market penetration rates, compliance rates, and traffic congestion conditions. These estimated performances can be fed into the speed-density function of a mesoscopic modeling tool to reflect the impact of the RESP-SIG application on the links in the network. Knowing that the mesoscopic model efficiently handles the large-scale network, this enables evaluation of the range of the performances of the RESP-SIG application under various conditions for a large scale network.

6.6.3. Incident Scene Work Zone Alerts for Drivers and Workers (INC-ZONE)

6.6.3.1. Review of modeling research efforts

Kamyab et al. (1999) developed a microscopic traffic simulation model to evaluate the performance of smart work zone technologies. The research team pointed out that macroscopic models are insufficient to deal with the lane changing behaviors of individual drivers. The research team also concluded that the CORSIM model, a commercial microscopic simulator, has difficulty incorporating an external lane changing model, which needs to reflect the realistic lane changing behavior in the vicinity of an incident-based work zone.

Fullerton et al. (2010) evaluated the performance of V2V communications technology under an accident case by using a hybrid simulation model incorporating VISSIM for traffic simulation and an event-driven mathematical model for wireless communications performance. To this end, the authors developed an API module to enable data exchange between VISSIM and the communications model. Assuming a 100 percent market penetration rate and a 100 percent compliance rate, the simulation model adjusts the approaching speeds of individual vehicles and lets drivers change lanes if necessary to avoid congestion in the vicinity of the accident area.

6.6.3.2.Modeling approach

Based on the findings in Section 5, the following core modeling elements are identified.

- Modeling Incident scene (e.g., location, occurrence time, and severity)
- Capturing real-time traffic congestion
- Generating safe speed for the vehicles near the incident scene
- Modeling traveler behavior model in response to the speed advisory information

To incorporate the above modeling elements, the INC-ZONE application can be modeled by the microscopic modeling tool as this application is not necessary to be evaluated for a large-scale network.

Microscopic Tool-Based Modeling Approach

Assuming that the location of a work-zone site is based on an external scenario dealing with the number of lanes closed and the length of the work-zone, it is possible to set up a work-zone site. With the API capturing OBE vehicles' movements, it is possible to estimate the safety risk of the approaching vehicles to the work-zone. With respect to estimating the safety risk, the Surrogate Safety Assessment Model (FHWA, 2010) can be applied by customizing it as an external module to capture real-time crash events in the simulation model. Once the API detects vehicles that would cause serious safety risk, it provides the drivers of such vehicles with advisory messages to reduce their speeds or to change lanes.

Driver compliance with the advisory messages can be modeled by either a choice model approach utilizing Logit or Probit models or a sensitivity analysis-based approach. For the vehicles assumed to have an opt-in automatic braking system, the API controls the approaching speed.

In summary, the following is the list of APIs required for the microscopic modeling approach for the INC-ZONE.

New API:

- Collecting real-time traffic information through Connected Vehicles (e.g., congestion, incident, or work-zone)

New API supported by external models:

- SSAM-based work-zone safety risk estimation
- Optimal safe speed generation for drivers passing by the work-zone site by using an external algorithm (e.g.., Speed Harmonization)
- Choice model-based traveler behavior model (e.g., decision on route selection, lane change, and traveler compliance in response to the given information)
- Sensitivity analysis for driver behavior

Multi-Scale Modeling Approach

Although the project team proposed that the INC-ZONE application does not necessarily require a large-scale evaluation, the following approach could be used. With the microscopic modeling approach, it is possible to capture the change of vehicular speeds of links where dangerous traffic safety conditions were detected. This change of speed would impact the speed-density relationship of roadways, requiring a similar adjustment of the speed-density function in the mesoscopic modeling tool. The adjusted speed-density functions would affect the behavior of traveler's route selection and then it is possible to evaluate the performance of the INC-ZONE application for a large scale network. It should be noted that the impact of the emergency vehicles on other general purpose vehicles and transit vehicles in the entire network would be insignificant. Thus, this application would not affect the change of OD demands and route selects for general purpose vehicles.

6.6.4. Mayday Relay

6.6.4.1. Review of modeling research efforts

There are no relevant research efforts that model the Mayday Relay application. However the modeling approach introduced in Fullerton et al. (2010) can be directly applied for the application, as it is based on the dissemination of messages from equipped vehicles under V2V and V2I wireless communications environment.

6.6.4.2.Modeling approach

It is possible to create a run-off road crash by using a new API and external crash scenarios in a microscopic simulation modeling tool.

7. Collective Impact Assessment Approach

7.1. Collective Assessment Approach for the E-ATIS Bundle

This bundle has ATIS, S-Park, T-Map and WX-Info as illustrated in Figure 7-1. Collective impact will be assessed by not only various performance measures covering mobility, safety, energy and emissions but also synergy effect. Capturing the synergy effect can be examined by tracking the flow of data and identifying algorithms commonly used for each application.

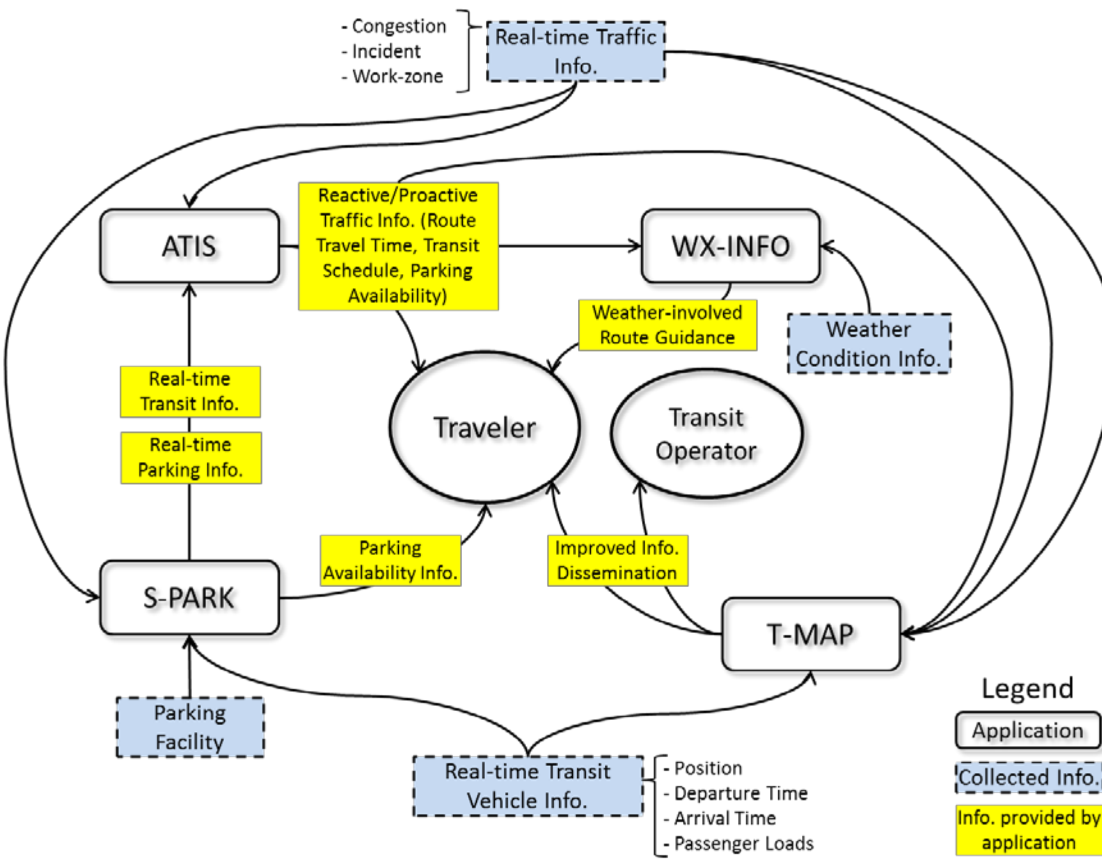

Figure 7-1. High-level Inter-application Data Flow for E-ATIS.

The real-time network information can be used for all four applications. These include link travel time information, work-zone or incident information, and real-time travel demand for each mode. S-PARK would need to have parking lot information. Transit information such as departure time, arrival time, and the number of passengers might be necessary for both S-Park and T-MAP. Weather-specific information, such as roadway speed reduction and visibility, would be useful for the WX-Info application to generate the proper guidance information.

The real-time transit and parking facility information obtained from the S-PARK application will be used for the ATIS application to generate both reactive and proactive traffic information covering not only roadway information but also transit and parking lot information. Traffic information generated from the ATIS application, such as roadway congestion, transit schedule, and parking lot availability, will be used for the WX-INFO to develop optimal route guidance strategies by incorporating weather information. Thus, the algorithm used for the generation of the reactive and proactive traffic information can be easily adopted for the WX-INFO application as the generation of guidance information must be the estimation of traffic information. The T-MAP application will incorporate not only real-time transit information but also the traffic information generated by the ATIS application to provide travelers and transit operators with enhanced information dissemination methods.

Multi-scale Modeling Approach

The project team proposes a multi-scale modeling approach incorporating a microscopic modeling approach and a mesoscopic modeling tool (e.g., Dynus-T, DynaSMART) to assess the impact of the E-ATIS bundle.

Similar to the multi-scale modeling approach for the ATIS application, it is possible to evaluate the performance of each bundle application by capturing the performance changes obtained from each modeling approach, such as travel time savings, travel time accuracy improvement, and transit line-haul and transfer time saving. Based on experimental design approach covering various external factors such as Connected Vehicles market penetration rates, traffic congestion levels, and traveler’s compliance rate to the provided guidance information, one can build numerous experimental scenarios to examine the relationships between a variety of the external factors and the benefit of each bundle application.

It should be noted that the E-ATIS performances captured by the microscopic modeling approach for each application can be modeled by either a parametric (e.g., regression model) or nonparametric (e.g., artificial neural network) approach. By examining the relationships between the performances of E-ATIS (i.e., output) and the external factors (i.e., inputs), a model relating the performance of E-ATIS and the external factors (e.g., vehicles market penetration rates, traffic congestion levels, and compliance rates) can be built.

For example, the speed-density functions can be adjusted to reflect the impact of ATIS and WX-INFO on the network. Transit route travel time and transfer time savings also can be obtained by T-MAP and S-PARK to be used for updating transit route performance functions. Such adjusted functions (e.g., the speed-density functions) obtained from the microscopic modeling approach are fed into the mesoscopic modeling tool to implement a DTA with initial modal OD demands. Once the DTA is complete, one can obtain OD travel times for each different mode and link and transit route travel times which are used for updating OD tables and routes for each OD pair. It is possible to adjust the initial OD demands using mode choice models, which take OD travel time, cost and transfer time as independent variables for their utility functions, if these mode choice models are given by a regional travel demand model. Likewise, with the link travel times obtained from the DTA, the best route for each modal OD pair can be updated. In particular, the travelers who are equipped with communication devices and accessible to variable message signs can perform en-route route selection while the pre-trip route is assigned to the travelers who have no access to the information. With the updated OD demands and routes, the DTA in the mesoscopic modeling approach is repeated until the network converges. Once convergence is achieved, performance measures (e.g., travel time, throughput) will be calculated to examine the collective assessment of the E-ATIS bundle.

7.2. Collective Assessment Approach for the INFLO Bundle

The INFLO bundle consists of three applications: Q-WARN, CACC, and SPD-HARM. For the collective assessment of the INFLO bundle, it is necessary to examine how each application interacts when it exchanges data and shares algorithms. Figure 7-2 shows a high-level inter-application data flow for the INFLO bundle.

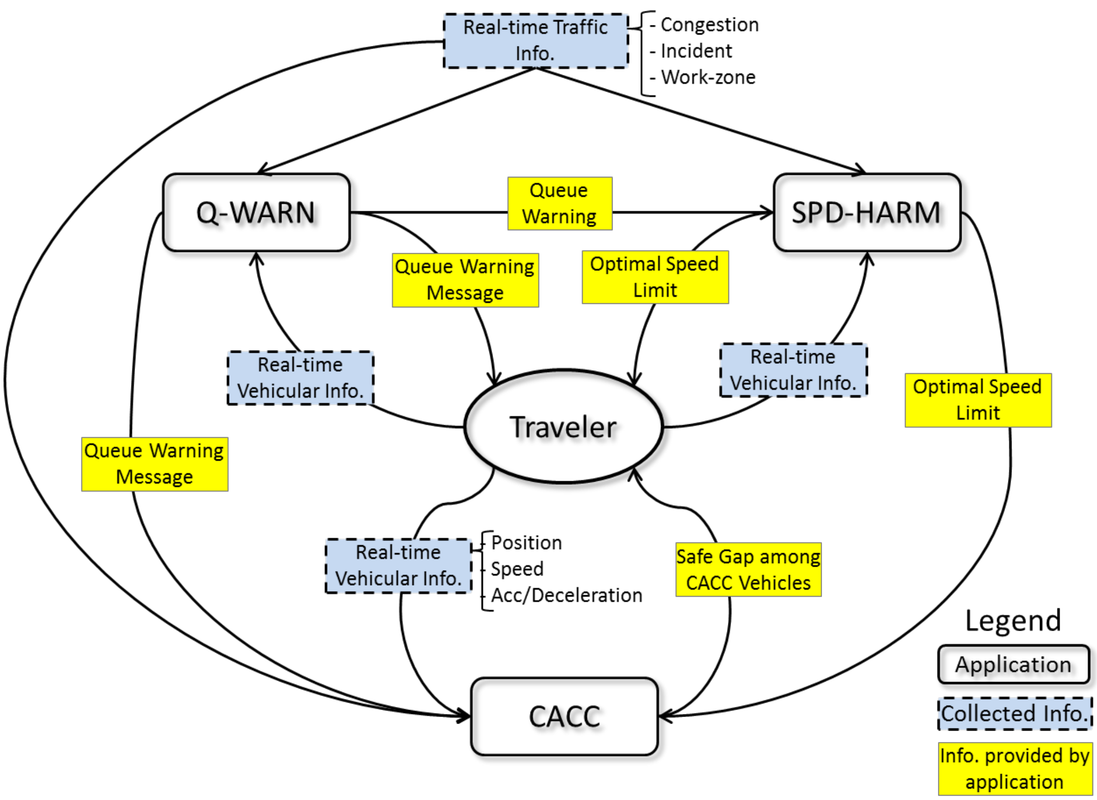

Figure 7-2. High-level Inter-application Data Flow for INFLO.

Real-time traffic conditions covering queue, delay, traffic congestions, and incident or work-zone are used for all the applications. Instantaneous vehicular information, such as real-time position, speed, and acceleration or deceleration, is also crucial information that is required for all three applications. With the real-time traffic information and vehicular information, the Q-WARN application detects queues occurring either recurrently or non-recurrently and generates proper queue warning messages. The detected queue information will be shared by the SPD-HARM application to generate variable speed limits based on real-time traffic conditions by incorporating the collected real-time traffic information. Both the queue warning and the variable speed limit information will be captured by the CACC application so that it can generate the optimal gap for the CACC vehicles, satisfying both mobility and safety needs by reflecting the real-time traffic conditions.

In a case when all three applications are simultaneously deployed into a network, the queue warning messages, variable speed limit guidance, and optimal gap for CACC vehicles will be disseminated to travelers at the same moment through Connected Vehicles, and they are expected to improve the network performance better than when each application is applied independently. Thus, the collective impact can be assessed based on performance measures reflecting mobility, safety, energy and emissions, and synergy effect (common data and algorithm use).

<u>Multi-scale Modeling Approach</u>

The project team proposes a multi-scale modeling approach incorporating a microscopic modeling approach and a mesoscopic modeling tool to assess the collective impact of the INFLO bundle.

With the microscopic modeling approach for each INFLO application in Section 6, it is possible to evaluate the performance of each bundle application by capturing the changes of performances obtained from each application modeling approach, such as travel time savings, throughput improvement, and delay time savings. Based on an experimental design approach covering various external factors such as Connected Vehicle market penetration rates, traffic congestion levels, and traveler compliance rates to the provided guidance information, one can build numerous experimental scenarios to examine the relationships between the benefit of each bundle application and the external factors.

For instance, the speed-density functions can be adjusted to reflect the impact of CACC, Q-WARN, and SPD-HARM. The adjusted speed-density functions are fed into the mesoscopic modeling tool to implement a dynamic traffic assignment (DTA) with initial modal OD demands. Once the DTA is complete, one can obtain OD travel times and link travel times which are used for updating OD tables and routes for each OD pair. It is possible to adjust the initial OD demands using mode choice models, which take OD travel time, cost and transfer time as independent variables for their utility functions, if these mode choice models are given by a regional travel demand model. Likewise, with the link travel times obtained from the DTA, the best route for each modal OD pair can be updated. In particular, the travelers who are equipped with communication devices and accessible to variable message signs can perform en-route route selection while the pre-trip route is assigned to the travelers who have no access to the information. With the updated OD demands and routes, the DTA in the mesoscopic modeling approach is repeated until the network converges. Once convergence is achieved, performance measures (e.g., travel time, throughput) will be calculated to examine the collective assessment of the INFLO bundle.

7.3. Collective Assessment Approach for the M-ISIG Bundle

This bundle includes the applications of I-SIG, TSP, PED-SIG, PREEMPT, and FSP. For the collective assessment of the M-ISIG bundle, it is necessary to examine how each bundle application interacts with each other by sharing data and algorithms to cooperatively implement each application. Figure 7-3 shows a high-level inter-application data flow for the M-ISIG bundle.

Real-time intersection information such as signal phases, queue lengths, delay time, and upstream traffic volume is used for all the applications. The real-time pedestrian call, captured by and used for the PED-SIG application, will affect the implementation of I-SIG, TSP, and FSP. The real-time emergency vehicle (EV) information, as the EV approaches the intersection, is captured by the PREEMPT application to trigger the preemption signal, and it will be shared by the other applications for use in adjusting their signal implementations to reflect the approach of the EV. Transit and freight vehicle information is collected by the TSP and FSP applications, respectively. Based on the information collected, each application implements its proper priority signal logic to serve such vehicles. In a case where no pedestrians, EV, transit, or freight vehicles are present, the intersection is controlled by the I-SIG application.

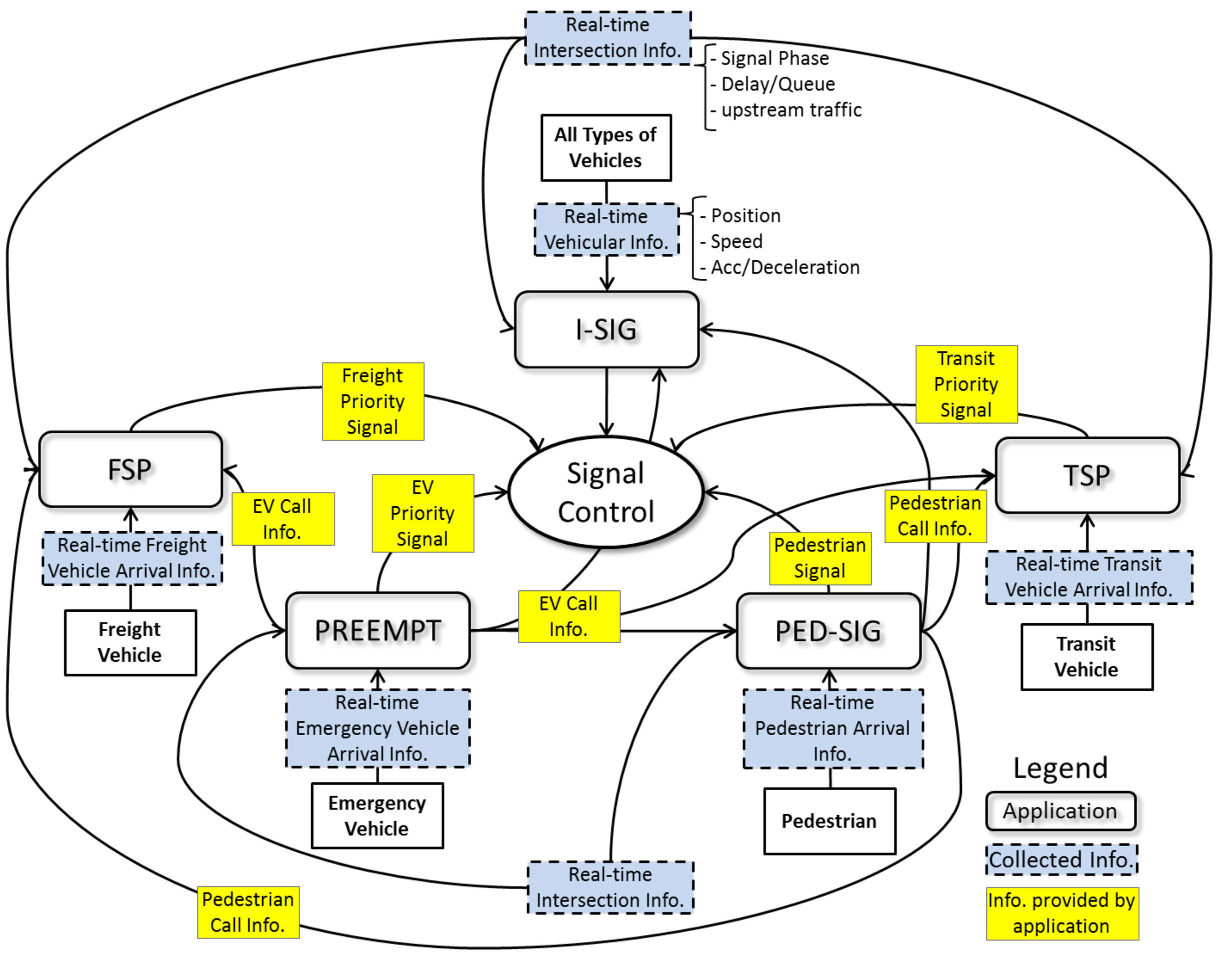

Figure 7-3. High-level Inter-application Data Flow for M-ISIG.

<u>Multi-scale Modeling Approach</u>

Assuming that the I-SIG application is a baseline for the evaluation of the M-ISIG bundle, each application handling pedestrian, EV, transit and freight vehicles can be used as external modules. Thus, the collective impact can be assessed by measuring multiple performance measures reflecting mobility, safety, energy and emissions under the various application deployment scenarios. For example, one can design multiple experiments defining the deployment of each application (e.g., I-SIG + TSP+ PED-SIG, or I-SIG + FSP+PREEMPT). By examining the performance measures under such a combination of scenarios, it would be possible to assess the collective benefits of using the M-ISIG bundle.

The project team proposes a multi-scale modeling approach incorporating a microscopic modeling approach and a mesoscopic modeling tool to assess the collective impact of the M-ISIG bundle. With the microscopic modeling approach proposed for each the bundle application, one can evaluate the performance of each bundle application by capturing the changes of performances such as delay time savings, travel time saving, transit travel time improvements, and throughput increase. Such captured performances can be used for updating the property of links in the mesoscopic modeling tool. For instance, the speed-density functions can be adjusted to reflect the impact of I-SIG, TSP, or FSP. The adjusted speed-density functions are fed into the mesoscopic modeling tool to implement a dynamic traffic assignment (DTA) with initial modal OD demands. Once the DTA is complete, one can obtain OD travel times and link travel times which are used for updating OD tables and routes for each OD pair. It is possible to adjust the initial OD demands using mode choice models, which take OD travel time, cost and transfer time as independent variables for their utility functions, if these mode choice models are given by a regional travel demand model.. Likewise, with the link travel times obtained from the DTA, the best route for each modal OD pair can be updated. In particular, the travelers who are equipped with communication devices and accessible to variable message signs can perform en-route route selection while the pre-trip route is assigned to the travelers who have no access to the information. With the updated OD demands and routes, the DTA in the mesoscopic modeling approach is repeated until the network converges. Once the convergence is achieved, performance measures (e.g., travel time, throughput) will be calculated to examine the collective assessment of the M-ISIG bundle.

7.4. Collective Assessment Approach for the IDTO Bundle

The IDTO bundle deals with transit-related dynamic mobility applications such as T-CONNECT, D-RIDE, and T-DISP. In order to assess the collective performance of the IDTO bundle, it is crucial to investigate how each bundle application interacts with each other by sharing data and algorithms to be cooperatively implemented. Figure 7-4 shows a high-level inter-application data flow for the IDTO bundle.

The real-time transit information will be collected by both the T-CONNECT and T-DISP application. Given a passenger call to request a hold for a transit vehicle to which the requester is willing to transfer, the T-CONNECT application estimates the acceptance of the request. If the request is acceptable, the corresponding transit vehicle's departure time will be adjusted to catch the requester and the adjusted departure time information is shared by the T-DISP and D-RIDE applications. With the real-time traffic information covering congestion and incident or work-zone and transit information, such as passenger loads, the number of passengers boarding/alighting at the stops or station, including the adjusted departure times of transit vehicles, the T-DISP application generates the optimal routes for transit vehicles. The adjustment of departure time and routes would affect the pedestrians' ridesharing requests in real-time. For example, if a pedestrian misses a bus due to the change of routes, the pedestrian would likely request the ridesharing call. Alternatively, a new transit vehicle or a paratransit vehicle can be dispatched to the pedestrian by the T-DISP application.

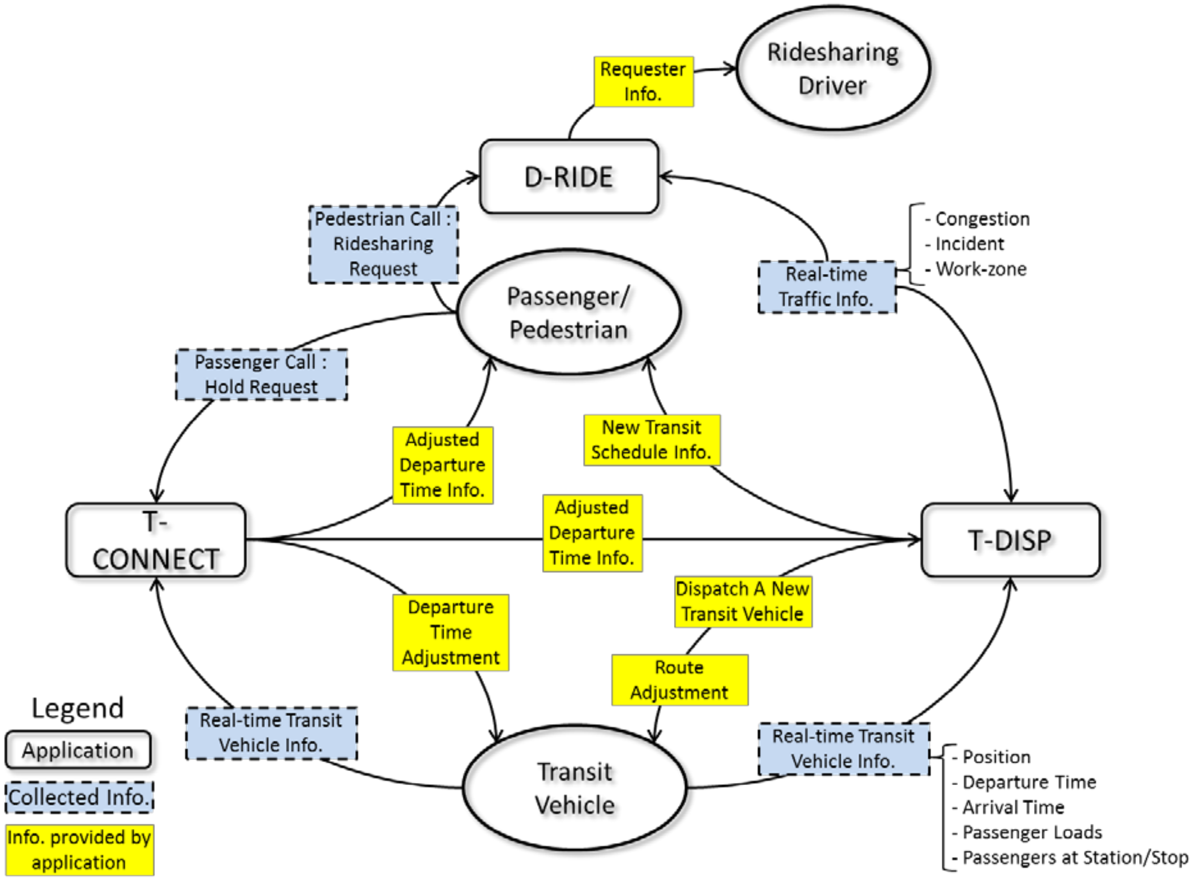

Figure 7-4. Collective Assessment Approach for the IDTO Bundle.

<u>Multi-scale Modeling Approach</u>

In a case when all three applications are simultaneously deployed into a network, the changes of departure times and routes of transit vehicles would be occurring at the same moment, which is expected to improve the travel performances of passengers and transit operators. In addition, the dynamic ridesharing would likely improve not only the pedestrian travel time but also emission and fuel consumption. Thus, the collective impact can be assessed by measuring multiple performance measures reflecting mobility, safety, energy and emissions under the various application deployment scenarios. To this end, the project team proposes a multi-scale modeling approach incorporating a microscopic modeling approach and a mesoscopic modeling tool to assess the collective impact of the IDTO bundle.

With the microscopic modeling approach proposed for each the bundle application, one can evaluate the performance of each bundle application by capturing the changes of performances such as transit line-haul time saving, transfer time saving, and passenger throughput improvement. Such captured performances can be used for updating the property of links in the mesoscopic modeling tool. For instance, the link performance function (e.g., speed-density function) dealing with transit vehicle movement can be adjusted to reflect the impact of IDTO bundle. The adjusted link performance functions are fed into the mesoscopic modeling tool to implement a DTA with initial modal OD demands. Once the DTA is complete, one can obtain OD travel times and link travel times which are used for updating OD tables and routes for each OD pair. It is possible to adjust the initial OD demands using mode choice models, which take OD travel time, cost and transfer time as independent variables for their utility functions, if these mode choice models are given by a regional travel demand model. Likewise, with the link travel times obtained from the DTA, the best route for each modal OD pair can be updated. In particular, the travelers who are equipped with communication devices can perform en-route route selection while the pre-trip route is assigned to the travelers who have no access to the information. With the updated OD demands and routes, the DTA in the mesoscopic modeling approach is repeated until the network converges. Once convergence is achieved, performance measures (e.g., travel time, throughput) will be calculated to examine the collective assessment of the M-ISIG bundle.

7.5. Collective Assessment Approach for the FRATIS Bundle

This bundle has F-ATIS, DR-OPT, and F-DRG. It should be noted that the F-ATIS and F-DRG applications can be modeled by using the same modeling approaches used for the ATIS application of the E-ATIS bundle because F-ATIS and F-DRG adjust their routes based on real-time time traffic information. However, it should be noted that, in addition to the traffic information, both the F-ATIS and F-DRG applications are necessary to take into consideration freight-specific constraints such as route restrictions and delivery schedules. To assess the collective impacts of the FRATIS bundle, it is necessary to examine how each bundle application interacts with each other by sharing data and algorithms to be cooperatively implemented. Figure 7-5 illustrates a high-level inter-application data flow for the FRATIS bundle.

The real-time network information can be commonly used for all three applications. These include link travel time information, work-zone or incident information, and roadway restrictions. The real-time freight vehicle information will be used for both the F-ATIS and F-DRG applications. With collected freight vehicle information covering position, route, emission and fuel consumption, and real-time traffic information, the F-ATIS application generates both reactive and proactive traffic information for freight vehicles, covering not only roadway information but also terminal information. Such traffic information generated from the ATIS application will be used for the F-DRG application to develop optimal route guidance strategies by incorporating both weather conditions (e.g., visibility, precipitation, pavement status) and freight vehicle performances (e.g., fuel consumption and emission). Thus, the algorithm used for the generation of the reactive and proactive traffic information can be easily adapted for the F-DRG application, as the generation of guidance information must be the estimation of traffic information. The DR-OPT application would need both the terminal congestion information and the traffic information obtained from the F-ATIS application to generate optimal drayage operation strategies.

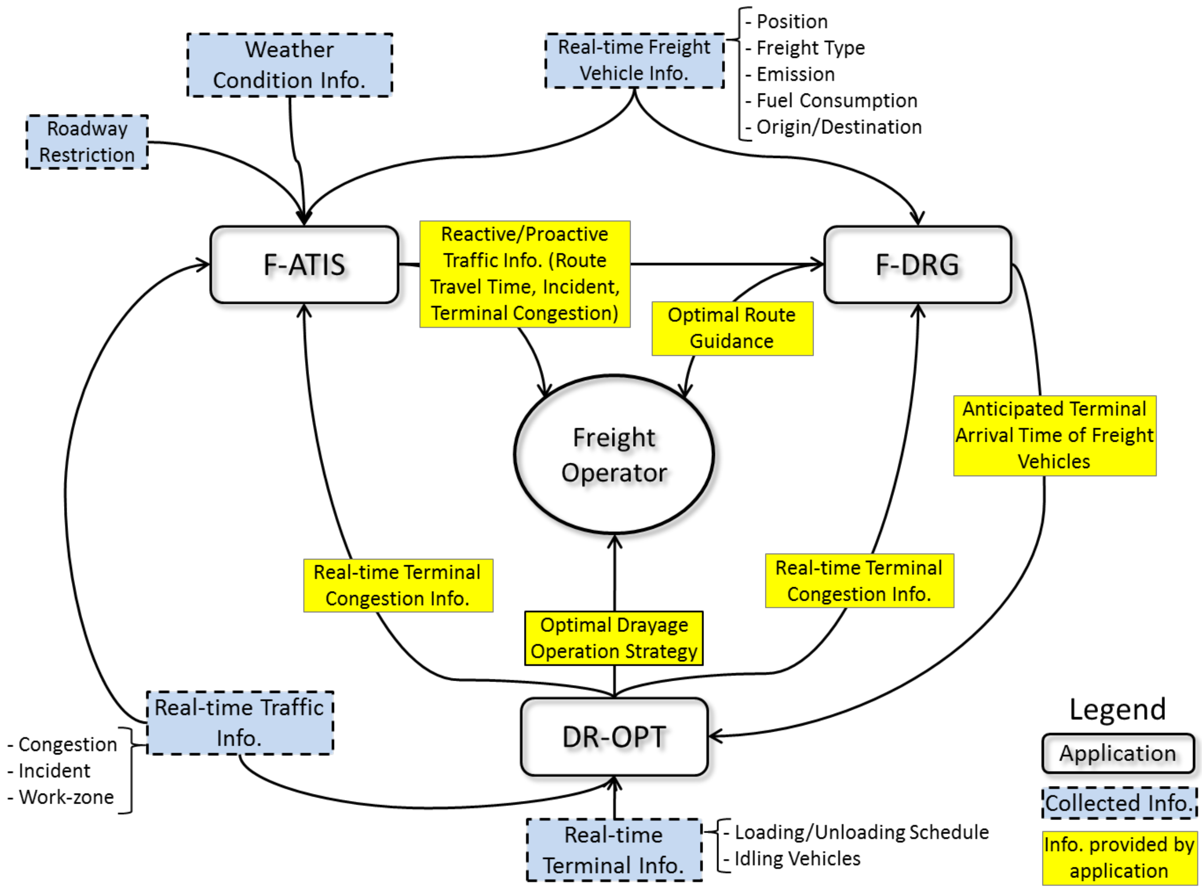

Figure 7-5. High-level Inter-application Data Flow for FRATIS.

Multi-scale Modeling Approach

In the case when all three applications are simultaneously deployed into a network for the collective assessment, the FRATIS bundle is expected to improve the performances of freight operators. Thus the collective impact can be assessed by measuring multiple performance measures reflecting mobility, safety, energy and emissions under the various application deployment scenarios. To this end, multi-scale modeling approach would be suitable as it incorporate both microscopic and mesoscopic modeling tools.

Based on multiple experiments of defining the deployment of each application (e.g., F-ATIS+DR-OPT or F-ATIS+F-DRG+DR-OPT), it is possible to assess the collective benefits by examining the performance of each bundle application and applying it to the mesoscopic modeling tool. For example, the speed-density functions can be adjusted to reflect the impact of F-ATIS and F-DRG on the network. The adjusted speed-density functions obtained from the microscopic modeling approach is fed into the mesoscopic modeling tool to implement a DTA with initial modal OD demands. Once the DTA is complete, one can obtain OD travel times for each different mode and link and transit route travel times which are used for updating OD tables and routes for each OD pair. It is possible to adjust the initial OD demands using mode choice models, which take OD travel time, cost and transfer time as independent variables for their utility functions, if these mode choice models are given by a regional travel demand model. Likewise, with the link travel times obtained from the DTA, the best route for each modal OD pair can be updated. In particular, the travelers who are equipped with communication devices and accessible to variable message signs can perform en-route route selection while the pre-trip route is assigned to the travelers who have no access to the information. With the updated OD demands and routes, the DTA in the mesoscopic modeling approach is repeated until the network converges. Once the convergence is achieved, performance measures (e.g., travel time, throughput) will be calculated to examine the collective assessment of the FR-ATIS bundle.

7.6. Collective Assessment Approach for the R.E.S.C.U.M.E. Bundle

The R.E.S.C.U.M.E. bundle includes four sub-applications that are difficult to model. The applications are EVAC, REP-SIG, INC-ZONE, and Mayday Relay. To assess the collective impact, it is necessary to examine how each bundle application interacts with each other by sharing data and algorithms to be cooperatively implemented. Figure 7-6 illustrates a high-level inter-application data flow for the RESCUME bundle. It should be noted that the EVAC application is not necessarily incorporated with the other applications as shown in Figure 12.

The real-time traffic congestion information will be used for the EVAC, REP-SIG, and INC-ZONE applications. The real-time incident information captured by Connected Vehicles will be used by the REP-SIG, INC-ZONE, and Mayday. With both the traffic congestion and incident information, the INC-ZONE application generates warning messages for incident zone workers about approaching vehicles while it gives the speed advisory information for those who pass by the incident zone to protect the workers. The Mayday application would enable faster propagation of the incident information to the emergency responders. Given the incident information reported, the REP-SIG application immediately dispatches an emergency responder by providing it with incident information, such as incident location, staging plans, and real-time weather information, which is not likely to be modeled.

It should be noted that each application in this bundle do not necessarily work together except for the Mayday and REP-SIG applications that are expected to have synergy effect by sharing the incident information. Thus, the performance measure used for assessing the impact of each application would be different: e.g., the total travel time of evacuees would be a proper measure for the EVAC application while the travel time of emergency responder to the incident zone is proper for the REP-SIG application. For that reason, the project team proposes the collective assessments of Mayday and REP-SIG applications by examining the performance measures of a scenario incorporating both of them.

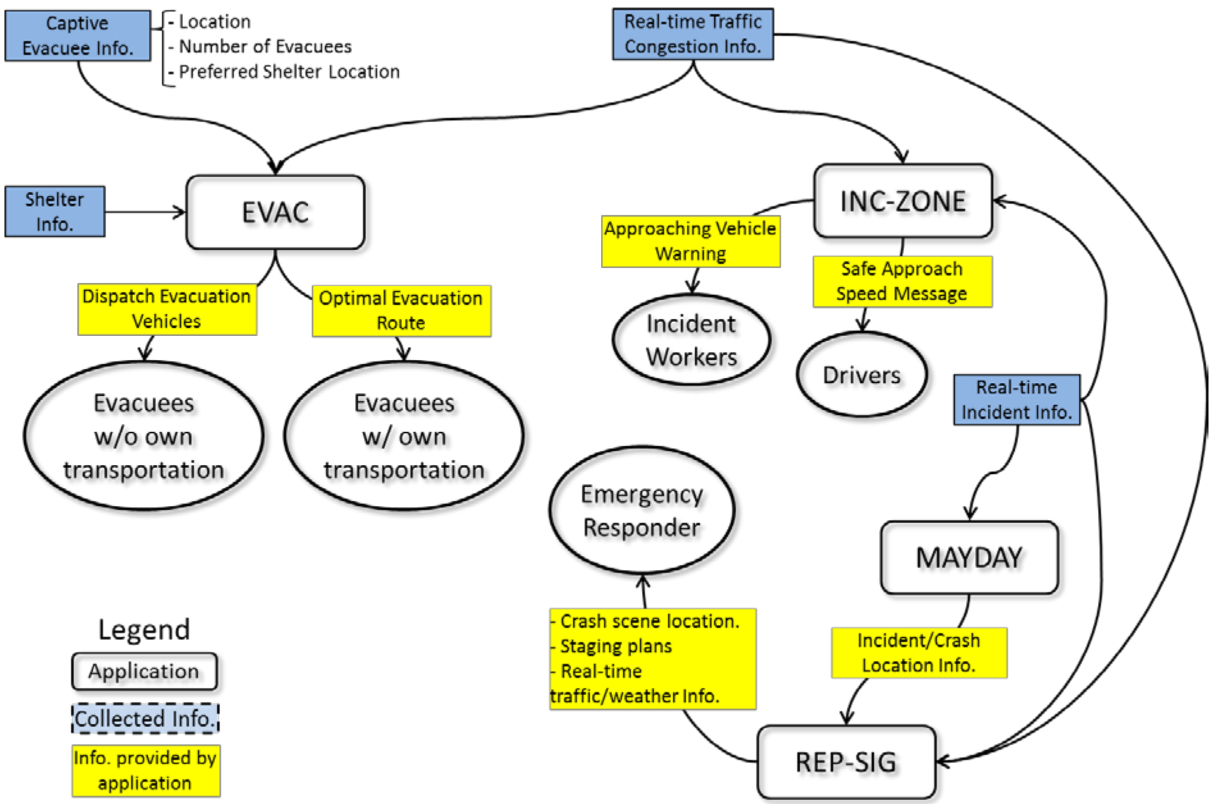

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Figure 7-6. High-level Inter-application Data Flow for R.E.S.C.U.M.E.

7.7. System-wide Collective Assessment Approach

There are 22 high priority dynamic mobility applications explored in this study. Each of the applications has unique characteristics in terms of its performance measures, key modes, and modeling approach. Thus it would be challenging to collectively examine the performances of all the applications together. The number of combinations for many parameters are enormous; moreover, many of the parameters are continuous values rather than discrete. So, in fact, it is not possible to examine all possible combinations of a parameter set. For instance, if there were 10 parameters that needed to be tested and each discrete parameter had 5 levels, then 9,765,625 combinations would need to be tried; this could take years. To overcome such a challenge, the project team proposes an experimental design-based collective evaluation approach to identify crucial factors and key applications that affect the system-wide multi-modal performances covering mobility, safety, and sustainability.

There are numerous experimental design methods (e.g., full factorial design method, random design method, space filling method, etc.). The project team suggests a Latin Hypercube Design (LHD) method (McKay et al., 2000). The LHD algorithm is used to reduce the number of combinations to a reasonable level, while still reasonably covering the entire parameter surface. It is part of a space-filling method which tries to maximally cover space. For example, assuming there are two experimental factors, x1 and x2, with five levels for each factor and five samples are needed, LHD generates five different samples as represented by dots in Figure 7-7.

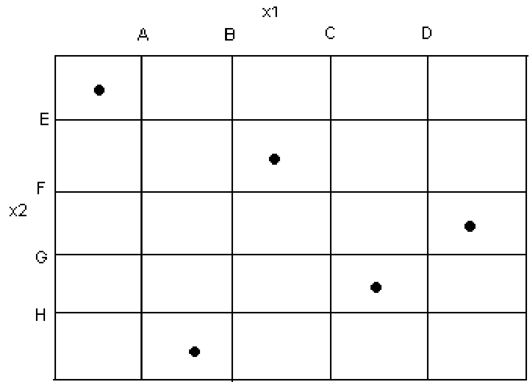

Figure 7-7. LHD Sampling Example.

With 22 high priority applications with their modeling approaches established, one can design the experiment by using multiple factors and levels as demonstrated in Table 7-1, to create optimal samples as an example shown in Table 7-2.

Table 7-1. Example of Factors and Levels for LHD-based Collective Assessment

Factor	Level
Total Number of DMAs for the Collective Assessment	2 – 16 (discrete)
Connected Vehicle Market Penetration Rate	0 – 1.0 (continuous)
Driver Compliance Rate if needed	0 – 1.0 (continuous)
Travel Demand Level	100 percent(Base case), 120 percent, 120 percent

Table 7-2. Example of Collective Assessment Sample.

Bundle		E-ATIS				INFLO			M-ISIG					IDTO			FRATIS			RESCUME			
App. ID		1	2	3	4	1	2	3	1	2	3	4	5	1	2	3	1	2	3	1	2	3	4
Travel Demand Level	100 percent		V			V				V				V				V				V	
	120 percent			V				V	V				V						V	V			
	140 percent	V					V				V					V							V

In addition, in order to quantify upper ceiling benefits of the dynamic mobility applications, one should implement system optimal solution. Unlike user optimal solution where every driver will travel his/her best route, system optimal solution will force drivers to travel sub-optimal routes so that the system can achieve the best performance. If understanding a system optimal condition is important, one can determine system optimal solution via either an analytical approach or a simulation-based approach. What is more likely to happen in the real world could be simulated on the basis of drivers' (or travelers') behavior model. When the travelers' behavior model is not readily available, one can deploy sensitivity analysis on potential behaviors.

8. Research Implementation Plan

The evaluation approaches of all the dynamic mobility applications dealt with in this project would require the gathering of non-conventional data sets (e.g., tracking of individual traveler movements across different modes of transportation) and developing new modeling approaches that track the movement of travelers separate from the movement of vehicles. This section deals with the preliminary research implementation plan for the evaluations of dynamic mobility applications based on the modeling approaches proposed in Sections 6 and 7. To this end, this section addresses the roles of government, modeling tool developers and vendors, and organizations conducting the research for the successful implementation of the DMA evaluation studies. This section also suggests a high-level management plan for the stakeholders of the evaluation research as a part of the implementation plan. In Section 6, the project team proposed an open source-based modeling approach for the activity modeling tool. Thus, this current section deals with the open source policy. The project team also addresses, in this section, outcomes expected from the evaluation research that are of interest to those who potentially conduct the evaluations of DMAs. Finally, we recommend the most suitable procurement option for the implementation of the research.

8.1. Recommended Role of Government

The evaluations of dynamic mobility applications require cutting edge modeling techniques, which are unsupported by the off-the-shelf capabilities of existing modeling tools. The most crucial unsupported modeling capabilities revealed by the project team include: 1) traveler behavior models; 2) integration of agent-based travel demand modeling with agent-based traffic modeling; 3) the separation of the traveler and vehicle in order to capture different in-vehicle capabilities; and 4) the integration of wireless communications with traffic modeling tools. Obviously, those unsupported modeling capabilities significantly affect the quality of modeling results, which in turn undermine the accuracy of the evaluation of each dynamic modeling application. However, in order for modeling tools to precisely handle those capabilities, comprehensive background studies must be performed in advance to provide modelers with proper data sets, which demand significant financial and administrative support from the government side. For example, modeling a route choice behavior dealing with each individual's route selection mechanism in response to provided information from the ATIS application would require the collection of the revealed preference of each traveler for multiple alternative routes, which is challenging to capture without proper authority and financial support from the government. Thus, it is necessary for the government to increase support for background studies to provide modelers with high-fidelity data sources for the successful evaluation research of DMA.

8.2. Necessary Developers/Vendors Cooperation

The project team suggests the customization of program source codes and the development of new APIs for modeling tools to successfully perform the evaluation of each dynamic mobility application. For example, assuming traveler mode choice model is available with the support of government, the modeling tools must be able to accommodate the mode choice model to examine the impacts travelers' choice behaviors properly. As revealed in the previous sections, no modeling tools perfectly support such modeling requirements within the context of off-the-shelf capabilities, thereby necessitating source code customization and the development of new APIs. To this end, the project team suggests modifying the program source for the activity-based modeling approach and developing a new API for the microscopic modeling approach. While developing new APIs is possible without the support of the program developers/vendors and occasionally developers/vendors distribute new APIs to the public as plug-in modules, customizing the program source codes would not be possible without the collaboration of the corresponding vendors. Thus, to successfully implement DMA evaluations, it would be crucial to acquire the cooperation of the program vendors.

8.3. Qualifications of Conducting Organizations

The organizations conducting the actual evaluation research for dynamic mobility applications need both in-depth knowledge of modeling tools and a keen insight into the subject application. Knowledge of the modeling tools would necessitate the understanding of sub models (e.g., mode choice and route selection models and wireless communications network models), the details of modeling capabilities provided by modeling tools, and the ability to handle external modules for the implementation of unsupported modeling capabilities such as API, post processing tools, and plug-ins (e.g., VT-Micro model, MOVES model, and Surrogate Safety Assessment Model). They must also have the ability to design multiple evaluation scenarios and analyze simulation outcomes for efficient implementation of evaluation research.

8.4. Stakeholder Management and Open Source Policy

The DMA project consists of six application bundles, each of which has three to six sub-applications. Moreover, in many cases, each of the applications is related to the others with respect to shareable elements, such as modeling approach, input data required for the modeling, and APIs or plug-ins. For example, the traveler's route choice model, which is crucial for the ATIS application, would be applied for determining the behaviors of ridesharing providers in the D-RIDE application. Thus, for anyone working on the D-RIDE application it would be unnecessary to develop the route choice model. This example indicates the importance of stakeholder management. Figure 8-1 shows a high-level example of stakeholder registry, defining the role and responsibility of each stakeholder. As demonstrated in Figure 1, with a well-organized stakeholder registry, it is certainly possible not only to reduce redundant efforts, but also to increase the efficiency of project implementation, thereby resulting in project cost savings and improved project quality.

Team Name: Team A DMA Bundle Application: ATIS in E-ATIS		
Task	Status	Note
Task 1 : Network Build	Completed	-
Task 2 : Develop route choice model API	in progress	-
Task 3: Develop ATIS Algorithm	in progress	-
.		-
.		-

Team Name: Team B DMA Bundle Application : D-RIDE in IDTO		
Task	Status	Note
Task 1 : Network Build	Completed	-
Task 2 : Develop route choice model API	in progress	From Team A
Task 3: Develop Pedestrian Call Behavior API	Not initiated	-
.		-
.		-

Figure 8-1. High-level Stakeholder Registry Example

The modeling approaches based on either mesoscopic or activity-based modeling tools were proposed with the intention of being customized to meet the modeling capabilities required for the evaluation of dynamic mobility applications. To this end, the project team suggested the use of open source programs for the mesoscopic and activity-based modeling tools. Since the source codes of the proposed modeling tools are open, their customized programs can also be open to the public. The open source policy can be applied to APIs suggested for microscopic tool-based modeling approaches. By using open source models for evaluation research on dynamic mobility applications, the software products developed can be improved in terms of program interoperability.

The DMA Open Source Application Development Portal (OSADP) Project was developed with this approach in mind. The secure portal supports the creation of new projects by stakeholders, new application submissions, core asset configuration management, stakeholder collaboration and contributor recognition. Through this portal, both federally funded and federally approved DMA projects will be included, and any advances in development will be available to other developers and stakeholders. For this reason, the project team recommends that all future DMA development efforts be tied into the portal.

8.5. Anticipated Research Outcomes

Once the modeling approaches proposed for the evaluation of a dynamic mobility application are successfully implemented, the potential impact of the selected application can be examined. The anticipated outcomes include:

- Assessment of potential benefits based on mobility, safety, and environment measures
- Impact investigation for the selected application under various external conditions, such as the quality of wireless communications, traveler compliances, and traffic congestion levels

- Collective impact assessment among applications within the bundle

It should be noted that the project team did not consider the following assessments:

- Extremely large scale impact assessment (e.g., inter-state and state level assessment)
- Further collective impact assessment

Procurement Options

As identified in the previous sections, the modeling approach for each dynamic mobility application has different characteristics based on the key mode (i.e., auto, transit, or pedestrian) and critical performance measures (i.e., vehicle-hours traveled for ATIS, passenger throughputs for T-DISP, or emergency response time for RESP-STG). Thus, the time required for the evaluation study and the outcomes from the modeling approaches would vary. This being the case, the most suitable procurement option would be Indefinite Delivery Indefinite Quality (IDIQ). By using an IDIQ contract vehicle, it is possible to manage the evaluation projects efficiently.

9. Summary

9.1. Conclusions

The project team proposed high-level modeling approaches for each dynamic mobility application in this project. To this end, the project team examined the analytical needs for each application and investigated analytic capabilities of modeling tools to support the analytical needs. The modeling tools dealt with in this project are: 1) sketch modeling tools, 2) macroscopic modeling tools, 3) mesoscopic modeling tools (e.g., DynaMIT, DYNASMART, Dynus-T), 4) microscopic modeling tools (e.g., VISSIM, AIMSUN, Paramics, CORSIM, INTEGRATION, TransModeler and SUMO), 5) activity-based modeling tools (e.g., TRANSIMS and MATSim), and 6) hybrid modeling tools (e.g., TransModeler).

With the revealed analytical needs and capabilities of each modeling tool, the project team built the traceability assessment matrix of every dynamic mobility application for each modeling tool. Based on the traceability matrix, the project team identified the gaps between the analytical needs for each application and the capability of modeling tools. The project team also addressed the challenges to be overcome for developing a modeling approach for each dynamic mobility application. The details of the gaps and challenges are summarized in Tables D-1 through D-44 in Appendix D. The most notable gaps and challenges identified are:

- Handling individual vehicles is the most crucial modeling element but no modeling tools, except for microscopic and activity-based modeling tools, are able to handle this.
- Separating the traveler from the vehicles. None of the existing modeling tools apart from TRANSIMS and MATSim have attempted to do that. These tools, however, lack the microscopic modeling fidelity. Consequently, there is a need to combine agent-based demand modeling tools (e.g. TRANSIMS) with microscopic traffic simulation software.
- Modeling traveler behavior (e.g., route selection, mode choice, and driver compliance) is one of the most critical modeling components required for the precise assessment of the impact of dynamic mobility applications, but existing modeling tools require further enhancement of traveler behavior models in their off-the-shelf capabilities. Thus, it is necessary to enhance the modeling tools to accommodate the traveler models.
- The performance of wireless communications must be incorporated to examine its impact on the quality of dynamic mobility applications. However, no modeling tools are able to precisely handle the wireless communications within the current context of modeling capabilities. It is necessary to develop an additional module to carry out the estimation of wireless communications performance in real-time.
- Microscopic modeling tools would be the most suitable tools for the precise evaluation of almost all dynamic mobility applications. However, it is also challenging for the microscopic tools to cover a large-scale network (e.g., a state, a region, and multiple cities). To overcome this challenge, the project team proposes the integration of agent-based traveler behavior tools with multi-level traffic modeling tools that can run simultaneously. TransModeler attempts to provide the concurrent multi-level modeling capabilities, however, it does not integrate these capabilities with activity based models. As such there is an urgent need to integrate activity based models with a multi-level vehicle modeling framework.

- There is a need to enhance the modeling of vehicle longitudinal and lateral movement behavior within microscopic traffic simulation tools. This will allow for the testing and capturing of unique vehicle capabilities and their interaction with in-vehicle systems.

Based on the findings in Sections 4 and 5, the project team proposed viable modeling approaches for the evaluation of each dynamic mobility application. Almost all applications are tied into two or three modeling approaches based on their analytic needs and modeling capabilities. The microscopic modeling tool-based approach was proposed for its capability of precisely handling the individual vehicles in real-time and its expandability, enabling it to easily incorporate external modules such as APIs or Plug-ins. However, it has difficulty covering a large-scale network. To overcome the scalability challenge of the microscopic modeling tools and assess the impacts of DMAs on large-scale networks, the activity modeling tool-based approaches were proposed. The activity modeling tool appeared insufficient to handle individual vehicle-based modeling elements such as wireless communications quality models, real-time traveler behavior models, and real-time transit vehicle controls. To the best of the project team's knowledge, there is an activity-based modeling tool in which the program source codes are open to public. Thus, assuming that the customization of the program is certainly available if needed, the project team suggested the activity-based modeling approach as an alternative method to examine the impact of DMAs on a large-scale network.

Finally, the project team also discussed a research implementation plan for the evaluations of DMAs in Section 8. For the successful evaluations of DMAs, the overarching leadership of government for both financial and administrative support must be ensured in addition to the cooperation among stakeholders, such as modeling tool developers/vendors, organizations conducting the evaluations, and government.

9.2. Recommendations

The project team identified that the leadership of government is the most crucial element for the successful implementation of the DMA evaluation research. For example, in order to precisely examine the impact of traveler behavior on a DMA, background studies on traveler behavior models need to be performed in advance to provide proper modeling capabilities on the traveler's decision making behavior on route choice, mode selection, and compliance in response to any given information from a DMA. In addition, given that all the DMAs are based on the Connected Vehicle environment, the impact of wireless communications quality would significantly affect the performance of DMAs. However, identifying the characteristics of the Connected Vehicle in terms of the wireless communications performances has not been fully examined because it requires tremendous investments for both infrastructure and vehicles. Thus, since collecting the traveler behavior data and wireless communications data requires both financial and administrative support from the government, it is recommended for the government to lead both background studies on traveler behavior and wireless communications performances prior to implementing the evaluations of DMAs.

With respect to the traveler behavior model, it is worth noting that cutting-edge highway driving simulators may be useful for the modeling of driver behavior. FHWA has led an innovative research initiative applying the highway driving simulator for the examination of driver behaviors (e.g., lane changing and car following) in response to external stimuli such as aggressive driving and sudden stops. With the driving simulator, one might be able to capture how drivers react to guidance information in a Connected Vehicle environment. Such captured drivers' reaction data can be useful for building the proper behavior models.

Finally, it is recommended that the developers/vendors of modeling tools provide organizations performing the evaluation and research with any technical supports for not only the customization of their software products but also the development of APIs or Plug-ins defined in the modeling approaches.

Microscopic Tool-Based Modeling Approach

The API associated with these scenarios will be able to deal with the occurrence time and the location of the run-off-road crash. By using a new API for OBE-equipped vehicles, it is possible to broadcast a mayday message from the OBE vehicles passing through the crash site. Once broadcast, the mayday message can be relayed to other OBE vehicles or RSEs within the DSRC communications range.

The quality of wireless communications would be the most crucial element affecting the relay of a mayday message, so it is necessary to model the dissemination of the mayday messages precisely. To this end, the project team proposes an integrated wireless communication simulator incorporating a microscopic simulator (e.g., VISSIM) and wireless communications network simulator (e.g., NCTUns) (Park et al., 2010). With the integrated simulation model, the API can detect the mayday message that is relayed by other Connected Vehicles. Based on the detected mayday message, the API creates a new vehicle representing an emergency responder and dispatches the vehicle to the crash site.

In summary, the following is the list of APIs required for the microscopic modeling approach for the Mayday.

New API:

- Real-time incident information collection through Connected Vehicles (e.g., location and severity)

New API supported by external models:

- Modeling Mayday message relay by using either a hybrid V2V/V2I wireless communication performance estimation model (Assenmacher et al., 2011) or a traffic simulator-integrated wireless communications network simulator (Park et al., 2010)

Non-API type external module:

- Modeling virtual crashes based on external scenario [e.g., location, occurrence time, duration, and severity (e.g., capacity reduction)].

<u>Multi-scale Modeling Approach</u>

Through the microscopic modeling approach, it is possible to identify the relationships between the crash reporting time and other external factors such as traffic congestion, the Connected Vehicle market penetration rates, and the number of vehicles near the crash site. These relationships can then be built into a model producing the crash reporting time based on the external factors. To this end, two statistical modeling approaches are available: one is a parametric approach (e.g., regression model) and the other is a nonparametric approach (e.g., artificial neural network), which both take the external factors and the crash reporting time as inputs and output, respectively.

Once the crash reporting time model is built, it can be applied to a larger scale network. For example, by using multiple simulation replications for a certain scenario covering a given market penetration rate and number of vehicles per hour on the crash site, the elapsed time taken by the crash reporting can be estimated. Similarly, it is then possible to estimate the crash reporting time of every scenario for a large scale network.

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Appendix A. Performance Measure Traceability Matrices

Table A-1. Performance Measure Traceability Matrix for EATIS Bundle

ATIS																			Summary		
	D.a	D.b	D.c	D.d	D.e	D.f	D.g	D.h	T.a	Q.a	Q.b	Q.c	S.a	S.c	S.d	F.a	E.a	C.a	I.a	O	X	N/A
SP	O	O	X	N/A	X	X	X	N/A	O	O	O	N/A	O	X	X	O	O	X	X	8	8	3
MA	O	O	X	N/A	O	X	O	N/A	O	O	O	N/A	O	X	X	O	O	X	X	10	6	3
ME	O	O	X	N/A	X	X	O	N/A	O	O	O	N/A	O	X	X	O	O	X	X	9	7	3
MI	O	O	O	N/A	O	O	O	N/A	O	O	O	N/A	O	O	X	O	O	X	X	13	3	3
HY	O	O	O	N/A	O	X	O	N/A	O	O	O	N/A	O	O	X	O	O	X	X	12	4	3
AC	O	O	X	N/A	O	O	O	N/A	O	O	O	N/A	O	O	X	O	O	X	X	12	4	3
WX-INFO																			Summary		
	D.a	D.b	D.c	D.d	D.e	D.f	D.g	D.h	T.a	Q.a	Q.b	Q.c	S.a	S.c	S.d	F.a	E.a	C.a	I.a	O	X	N/A
SP	O	O	X	N/A	X	N/A	X	X	O	O	O	X	O	X	X	N/A	N/A	N/A	X	6	8	5
MA	O	O	X	N/A	O	N/A	O	X	O	O	O	X	O	X	X	N/A	N/A	N/A	X	8	6	5
ME	O	O	X	N/A	X	N/A	O	X	O	O	O	X	O	X	X	N/A	N/A	N/A	X	7	7	5
MI	O	O	O	N/A	O	N/A	O	O	O	O	O	O	O	O	X	N/A	N/A	N/A	X	12	2	5
HY	O	O	O	N/A	O	N/A	O	X	O	O	O	O	O	O	X	N/A	N/A	N/A	X	11	3	5
AC	O	O	X	N/A	O	N/A	O	X	O	O	O	X	O	O	X	N/A	N/A	N/A	X	9	5	5
T-MAP																			Summary		
	D.a	D.b	D.c	D.d	D.e	D.f	D.g	D.h	T.a	Q.a	Q.b	Q.c	S.a	S.c	S.d	F.a	E.a	C.a	I.a	O	X	N/A
SP	N/A	N/A	N/A	N/A	X	N/A	X	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	X	0	3	16
MA	N/A	N/A	N/A	N/A	O	N/A	O	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	X	2	1	16
ME	N/A	N/A	N/A	N/A	X	N/A	O	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	X	1	2	16
MI	N/A	N/A	N/A	N/A	O	N/A	O	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	X	2	1	16
HY	N/A	N/A	N/A	N/A	O	N/A	O	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	X	2	1	16
AC	N/A	N/A	N/A	N/A	O	N/A	O	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	X	2	1	16

	S-PARK																			Summary		
	D.a	D.b	D.c	D.d	D.e	D.f	D.g	D.h	T.a	Q.a	Q.b	Q.c	S.a	S.c	S.d	F.a	E.a	C.a	I.a	O	X	N/A
SP	O	O	N/A	N/A	X	N/A	X	N/A	O	O	O	N/A	O	X	N/A	N/A	O	N/A	X	7	4	8
MA	O	O	N/A	N/A	O	N/A	O	N/A	O	O	O	N/A	O	X	N/A	N/A	O	N/A	X	9	2	8
ME	O	O	N/A	N/A	X	N/A	O	N/A	O	O	O	N/A	O	X	N/A	N/A	O	N/A	X	8	3	8
MI	O	O	N/A	N/A	O	N/A	O	N/A	O	O	O	N/A	O	O	N/A	N/A	O	N/A	X	10	1	8
HY	O	O	N/A	N/A	O	N/A	O	N/A	O	O	O	N/A	O	O	N/A	N/A	O	N/A	X	10	1	8
AC	O	O	N/A	N/A	O	N/A	O	N/A	O	O	O	N/A	O	O	N/A	N/A	O	N/A	X	10	1	8

Table A-2. Traceability Matrix for INFLO Bundle (Q-WARN,SPD-HARM)

Q-WARN																			Summary		
	D.a	D.b	D.c	D.d	D.e	D.f	D.g	D.h	T.a	Q.a	Q.b	Q.c	S.a	S.c	S.d	F.a	E.a	C.a	I.a	O	X	N/A
SP	O	O	X	N/A	X	N/A	X	X	O	O	O	N/A	O	N/A	X	O	O	X	X	8	7	4
MA	O	O	X	N/A	O	N/A	O	X	O	O	O	N/A	O	N/A	X	O	O	X	X	10	5	4
ME	O	O	X	N/A	X	N/A	O	X	O	O	O	N/A	O	N/A	X	O	O	X	X	9	6	4
MI	O	O	O	N/A	O	N/A	O	O	O	O	O	N/A	O	N/A	X	O	O	X	X	12	3	4
HY	O	O	O	N/A	O	N/A	O	X	O	O	O	N/A	O	N/A	X	O	O	X	X	11	4	4
AC	O	O	X	N/A	O	N/A	O	X	O	O	O	N/A	O	N/A	X	O	O	X	X	10	5	4
SPD-HARM																				Summary		
	D.a	D.b	D.c	D.d	D.e	D.f	D.g	D.h	T.a	Q.a	Q.b	Q.c	S.a	S.c	S.d	F.a	E.a	C.a	I.a	O	X	N/A
SP	O	O	X	N/A	X	N/A	X	X	O	O	O	N/A	O	N/A	X	O	O	X	X	8	7	4
MA	O	O	X	N/A	O	N/A	O	X	O	O	O	N/A	O	N/A	X	O	O	X	X	10	5	4
ME	O	O	X	N/A	X	N/A	O	X	O	O	O	N/A	O	N/A	X	O	O	X	X	9	6	4
MI	O	O	O	N/A	O	N/A	O	O	O	O	O	N/A	O	N/A	X	O	O	X	X	12	3	4
HY	O	O	O	N/A	O	N/A	O	X	O	O	O	N/A	O	N/A	X	O	O	X	X	11	4	4
AC	O	O	X	N/A	O	N/A	O	X	O	O	O	N/A	O	N/A	X	O	O	X	X	10	5	4
CACC																				Summary		
	D.a	D.b	D.c	D.d	D.e	D.f	D.g	D.h	T.a	Q.a	Q.b	Q.c	S.a	S.c	S.d	F.a	E.a	C.a	I.a	O	X	N/A
SP	O	O	X	N/A	X	N/A	X	X	O	O	O	N/A	O	N/A	X	O	O	X	X	8	9	4
MA	O	O	X	N/A	O	N/A	O	X	O	O	O	N/A	O	N/A	X	O	O	X	X	10	7	4
ME	O	O	X	N/A	X	N/A	O	X	O	O	O	N/A	O	N/A	X	O	O	X	X	9	8	4
MI	O	O	O	N/A	O	N/A	O	O	O	O	O	N/A	O	N/A	X	O	O	X	X	13	4	4
HY	O	O	O	N/A	O	N/A	O	X	O	O	O	N/A	O	N/A	X	O	O	X	X	12	5	4
AC	O	O	X	N/A	O	N/A	O	X	O	O	O	N/A	O	N/A	X	O	O	X	X	11	6	4

Table A-3. Traceability Matrix for MMITS Bundle (I-SIG,TSP,PED-SIG)

	ISIG																			Summary		
	D.a	D.b	D.c	D.d	D.e	D.f	D.g	D.h	T.a	Q.a	Q.b	Q.c	S.a	S.c	S.d	F.a	E.a	C.a	I.a	O	X	N/A
SP	O	O	X	N/A	X	X	X	N/A	O	O	O	X	N/A	X	X	O	O	X	X	7	9	3
MA	O	O	X	N/A	O	X	O	N/A	O	O	O	X	N/A	X	X	O	O	X	X	9	7	3
ME	O	O	X	N/A	X	X	O	N/A	O	O	O	X	N/A	X	X	O	O	X	X	8	8	3
MI	O	O	O	N/A	O	O	O	N/A	O	O	O	O	N/A	O	X	O	O	X	X	13	3	3
HY	O	O	O	N/A	O	X	O	N/A	O	O	O	O	N/A	O	X	O	O	X	X	12	4	3
AC	O	O	X	N/A	O	O	O	N/A	O	O	O	X	N/A	O	X	O	O	X	X	11	5	3
	TSP																			Summary		
	D.a	D.b	D.c	D.d	D.e	D.f	D.g	D.h	T.a	Q.a	Q.b	Q.c	S.a	S.c	S.d	F.a	E.a	C.a	I.a	O	X	N/A
SP	N/A	O	X	N/A	X	N/A	X	N/A	O	O	O	N/A	N/A	X	N/A	O	O	N/A	N/A	6	4	9
MA	N/A	O	X	N/A	O	N/A	O	N/A	O	O	O	N/A	N/A	X	N/A	O	O	N/A	N/A	8	2	9
ME	N/A	O	X	N/A	X	N/A	O	N/A	O	O	O	N/A	N/A	X	N/A	O	O	N/A	N/A	7	3	9
MI	N/A	O	O	N/A	O	N/A	O	N/A	O	O	O	N/A	N/A	O	N/A	O	O	N/A	N/A	10	0	9
HY	N/A	O	O	N/A	O	N/A	O	N/A	O	O	O	N/A	N/A	O	N/A	O	O	N/A	N/A	10	0	9
AC	N/A	O	X	N/A	O	N/A	O	N/A	O	O	O	N/A	N/A	O	N/A	O	O	N/A	N/A	9	1	9
	PED-SIG																			Summary		
	D.a	D.b	D.c	D.d	D.e	D.f	D.g	D.h	T.a	Q.a	Q.b	Q.c	S.a	S.c	S.d	F.a	E.a	C.a	I.a	O	X	N/A
SP	N/A	O	N/A	N/A	N/A	X	X	N/A	O	N/A	O	N/A	N/A	X	N/A	O	O	N/A	N/A	5	3	11
MA	N/A	O	N/A	N/A	N/A	X	O	N/A	O	N/A	O	N/A	N/A	X	N/A	O	O	N/A	N/A	6	3	11
ME	N/A	O	N/A	N/A	N/A	X	O	N/A	O	N/A	O	N/A	N/A	X	N/A	O	O	N/A	N/A	6	3	11
MI	N/A	O	N/A	N/A	N/A	O	O	N/A	O	N/A	O	N/A	N/A	O	N/A	O	O	N/A	N/A	8	0	11
HY	N/A	O	N/A	N/A	N/A	X	O	N/A	O	N/A	O	N/A	N/A	O	N/A	O	O	N/A	N/A	7	1	11
AC	N/A	O	N/A	N/A	N/A	O	O	N/A	O	N/A	O	N/A	N/A	O	N/A	O	O	N/A	N/A	8	0	11

Table A-4. Traceability Matrix for MMITS Bundle (PED-SIG,PREEMPT)

PREEMPT																				Summary		
	D.a	D.b	D.c	D.d	D.e	D.f	D.g	D.h	T.a	Q.a	Q.b	Q.c	S.a	S.c	S.d	F.a	E.a	C.a	I.a	O	X	N/A
SP	O	O	N/A	N/A	N/A	X	X	N/A	O	O	O	X	N/A	X	N/A	O	O	N/A	N/A	7	4	8
MA	O	O	N/A	N/A	N/A	X	O	N/A	O	O	O	X	N/A	X	N/A	O	O	N/A	N/A	8	3	8
ME	O	O	N/A	N/A	N/A	X	O	N/A	O	O	O	X	N/A	X	N/A	O	O	N/A	N/A	8	3	8
MI	O	O	N/A	N/A	N/A	O	O	N/A	O	O	O	O	N/A	O	N/A	O	O	N/A	N/A	11	0	8
HY	O	O	N/A	N/A	N/A	X	O	N/A	O	O	O	O	N/A	O	N/A	O	O	N/A	N/A	10	1	8
AC	O	O	N/A	N/A	N/A	O	O	N/A	O	O	O	X	N/A	O	N/A	O	O	N/A	N/A	10	1	8
FSP																				Summary		
	D.a	D.b	D.c	D.d	D.e	D.f	D.g	D.h	T.a	Q.a	Q.b	Q.c	S.a	S.c	S.d	F.a	E.a	C.a	I.a	O	X	N/A
SP	O	O	X	X	X	X	X	N/A	O	O	O	N/A	N/A	X	X	O	O	N/A	N/A	7	7	5
MA	O	O	X	X	O	X	O	N/A	O	O	O	N/A	N/A	X	X	O	O	N/A	N/A	9	5	5
ME	O	O	X	X	X	X	O	N/A	O	O	O	N/A	N/A	X	X	O	O	N/A	N/A	8	6	5
MI	O	O	O	X	O	O	O	N/A	O	O	O	N/A	N/A	O	X	O	O	N/A	N/A	12	2	5
HY	O	O	O	X	O	X	O	N/A	O	O	O	N/A	N/A	O	X	O	O	N/A	N/A	11	3	5
AC	O	O	X	X	O	O	O	N/A	O	O	O	N/A	N/A	O	X	O	O	N/A	N/A	11	3	5

Table A-5. Traceability Matrix for IDTO Bundle

T-CONNECT																				Summary	
	D.a	D.b	D.c	D.d	D.e	D.f	D.g	D.h	T.a	Q.a	Q.b	Q.c	S.a	S.c	S.d	F.a	E.a	C.a	I.a	O	X	N/A
SP	N/A	N/A	N/A	N/A	X	N/A	X	N/A	N/A	O	O	N/A	N/A	N/A	N/A	N/A	N/A	N/A	X	2	3	14
MA	N/A	N/A	N/A	N/A	O	N/A	O	N/A	N/A	O	O	N/A	N/A	N/A	N/A	N/A	N/A	N/A	X	4	1	14
ME	N/A	N/A	N/A	N/A	X	N/A	O	N/A	N/A	O	O	N/A	N/A	N/A	N/A	N/A	N/A	N/A	X	3	2	14
MI	N/A	N/A	N/A	N/A	O	N/A	O	N/A	N/A	O	O	N/A	N/A	N/A	N/A	N/A	N/A	N/A	X	4	1	14
HY	N/A	N/A	N/A	N/A	O	N/A	O	N/A	N/A	O	O	N/A	N/A	N/A	N/A	N/A	N/A	N/A	X	4	1	14
AC	N/A	N/A	N/A	N/A	O	N/A	O	N/A	N/A	O	O	N/A	N/A	N/A	N/A	N/A	N/A	N/A	X	4	1	14
T-DISP																				Summary		
	D.a	D.b	D.c	D.d	D.e	D.f	D.g	D.h	T.a	Q.a	Q.b	Q.c	S.a	S.c	S.d	F.a	E.a	C.a	I.a	O	X	N/A
SP	N/A	N/A	N/A	N/A	X	N/A	X	N/A	N/A	O	O	N/A	N/A	N/A	N/A	N/A	N/A	N/A	X	2	3	14
MA	N/A	N/A	N/A	N/A	O	N/A	O	N/A	N/A	O	O	N/A	N/A	N/A	N/A	N/A	N/A	N/A	X	4	1	14
ME	N/A	N/A	N/A	N/A	X	N/A	O	N/A	N/A	O	O	N/A	N/A	N/A	N/A	N/A	N/A	N/A	X	3	2	14
MI	N/A	N/A	N/A	N/A	O	N/A	O	N/A	N/A	O	O	N/A	N/A	N/A	N/A	N/A	N/A	N/A	X	4	1	14
HY	N/A	N/A	N/A	N/A	O	N/A	O	N/A	N/A	O	O	N/A	N/A	N/A	N/A	N/A	N/A	N/A	X	4	1	14
AC	N/A	N/A	N/A	N/A	O	N/A	O	N/A	N/A	O	O	N/A	N/A	N/A	N/A	N/A	N/A	N/A	X	4	1	14
D-RIDE																				Summary		
	D.a	D.b	D.c	D.d	D.e	D.f	D.g	D.h	T.a	Q.a	Q.b	Q.c	S.a	S.c	S.d	F.a	E.a	C.a	I.a	O	X	N/A
SP	N/A	O	N/A	N/A	N/A	N/A	X	N/A	O	O	O	N/A	O	X	N/A	O	O	N/A	X	7	3	9
MA	N/A	O	N/A	N/A	N/A	N/A	O	N/A	O	O	O	N/A	O	X	N/A	O	O	N/A	X	8	2	9
ME	N/A	O	N/A	N/A	N/A	N/A	O	N/A	O	O	O	N/A	O	X	N/A	O	O	N/A	X	8	2	9
MI	N/A	O	N/A	N/A	N/A	N/A	O	N/A	O	O	O	N/A	O	O	N/A	O	O	N/A	X	9	1	9
HY	N/A	O	N/A	N/A	N/A	N/A	O	N/A	O	O	O	N/A	O	O	N/A	O	O	N/A	X	9	1	9
AC	N/A	O	N/A	N/A	N/A	N/A	O	N/A	O	O	O	N/A	O	O	N/A	O	O	N/A	X	9	1	9

Table A-6. Traceability Matrix for FRATIS Bundle

F-ATIS																				Summary		
	D.a	D.b	D.c	D.d	D.e	D.f	D.g	D.h	T.a	Q.a	Q.b	Q.c	S.a	S.c	S.d	F.a	E.a	C.a	I.a	O	X	N/A
SP	O	N/A	X	X	N/A	N/A	X	X	O	O	O	N/A	N/A	N/A	N/A	O	O	X	X	6	6	7
MA	O	N/A	X	X	N/A	N/A	O	X	O	O	O	N/A	N/A	N/A	N/A	O	O	X	X	7	5	7
ME	O	N/A	X	X	N/A	N/A	O	X	O	O	O	N/A	N/A	N/A	N/A	O	O	X	X	7	5	7
MI	O	N/A	O	O	N/A	N/A	O	O	O	O	O	N/A	N/A	N/A	N/A	O	O	X	X	10	2	7
HY	O	N/A	O	O	N/A	N/A	O	X	O	O	O	N/A	N/A	N/A	N/A	O	O	X	X	9	3	7
AC	O	N/A	X	X	N/A	N/A	O	X	O	O	O	N/A	N/A	N/A	N/A	O	O	X	X	7	5	7
DR-OPT																				Summary		
	D.a	D.b	D.c	D.d	D.e	D.f	D.g	D.h	T.a	Q.a	Q.b	Q.c	S.a	S.c	S.d	F.a	E.a	C.a	I.a	O	X	N/A
SP	O	N/A	X	X	N/A	N/A	X	X	N/A	N/A	N/A	N/A	N/A	N/A	N/A	O	O	N/A	N/A	3	4	12
MA	O	N/A	X	X	N/A	N/A	O	X	N/A	N/A	N/A	N/A	N/A	N/A	N/A	O	O	N/A	N/A	4	3	12
ME	O	N/A	X	X	N/A	N/A	O	X	N/A	N/A	N/A	N/A	N/A	N/A	N/A	O	O	N/A	N/A	4	3	12
MI	O	N/A	O	O	N/A	N/A	O	O	N/A	N/A	N/A	N/A	N/A	N/A	N/A	O	O	N/A	N/A	7	0	12
HY	O	N/A	O	O	N/A	N/A	O	X	N/A	N/A	N/A	N/A	N/A	N/A	N/A	O	O	N/A	N/A	6	1	12
AC	O	N/A	X	X	N/A	N/A	O	X	N/A	N/A	N/A	N/A	N/A	N/A	N/A	O	O	N/A	N/A	4	3	12
F-DRG																				Summary		
	D.a	D.b	D.c	D.d	D.e	D.f	D.g	D.h	T.a	Q.a	Q.b	Q.c	S.a	S.c	S.d	F.a	E.a	C.a	I.a	O	X	N/A
SP	O	N/A	X	X	N/A	N/A	X	X	O	O	O	N/A	N/A	N/A	N/A	O	O	X	X	6	6	7
MA	O	N/A	X	X	N/A	N/A	O	X	O	O	O	N/A	N/A	N/A	N/A	O	O	X	X	7	5	7
ME	O	N/A	X	X	N/A	N/A	O	X	O	O	O	N/A	N/A	N/A	N/A	O	O	X	X	7	5	7
MI	O	N/A	O	O	N/A	N/A	O	O	O	O	O	N/A	N/A	N/A	N/A	O	O	X	X	10	2	7
HY	O	N/A	O	O	N/A	N/A	O	X	O	O	O	N/A	N/A	N/A	N/A	O	O	X	X	9	3	7
AC	O	N/A	X	X	N/A	N/A	O	X	O	O	O	N/A	N/A	N/A	N/A	O	O	X	X	7	5	7

Table A-7. Traceability Matrix for RESCUME Bundle

EVAC																				Summary		
	D.a	D.b	D.c	D.d	D.e	D.f	D.g	D.h	T.a	Q.a	Q.b	Q.c	S.a	S.c	S.d	F.a	E.a	C.a	I.a	O	X	N/A
SP	O	O	N/A	N/A	X	N/A	X	N/A	N/A	N/A	N/A	X	O	X	N/A	N/A	N/A	X	X	3	6	10
MA	O	O	N/A	N/A	O	N/A	O	N/A	N/A	N/A	N/A	X	O	X	N/A	N/A	N/A	X	X	5	4	10
ME	O	O	N/A	N/A	X	N/A	O	N/A	N/A	N/A	N/A	X	O	X	N/A	N/A	N/A	X	X	4	5	10
MI	O	O	N/A	N/A	O	N/A	O	N/A	N/A	N/A	N/A	O	O	O	N/A	N/A	N/A	X	X	7	2	10
HY	O	O	N/A	N/A	O	N/A	O	N/A	N/A	N/A	N/A	O	O	O	N/A	N/A	N/A	X	X	7	2	10
AC	O	O	N/A	N/A	O	N/A	O	N/A	N/A	N/A	N/A	X	O	O	N/A	N/A	N/A	X	X	6	3	10
RESP-SIG																				Summary		
	D.a	D.b	D.c	D.d	D.e	D.f	D.g	D.h	T.a	Q.a	Q.b	Q.c	S.a	S.c	S.d	F.a	E.a	C.a	I.a	O	X	N/A
SP	O	O	X	N/A	X	X	X	X	O	N/A	N/A	X	N/A	X	N/A	N/A	N/A	X	N/A	3	8	8
MA	O	O	X	N/A	O	X	O	X	O	N/A	N/A	X	N/A	X	N/A	N/A	N/A	X	N/A	5	6	8
ME	O	O	X	N/A	X	X	O	X	O	N/A	N/A	X	N/A	X	N/A	N/A	N/A	X	N/A	4	7	8
MI	O	O	O	N/A	O	O	O	O	O	N/A	N/A	O	N/A	O	N/A	N/A	N/A	X	N/A	10	1	8
HY	O	O	O	N/A	O	X	O	X	O	N/A	N/A	O	N/A	O	N/A	N/A	N/A	X	N/A	8	3	8
AC	O	O	X	N/A	O	O	O	X	O	N/A	N/A	X	N/A	O	N/A	N/A	N/A	X	N/A	7	4	8
INC-ZONE																				Summary		
	D.a	D.b	D.c	D.d	D.e	D.f	D.g	D.h	T.a	Q.a	Q.b	Q.c	S.a	S.c	S.d	F.a	E.a	C.a	I.a	O	X	N/A
SP	O	O	X	N/A	X	X	X	X	O	N/A	N/A	N/A	O	X	N/A	N/A	N/A	X	X	4	8	7
MA	O	O	X	N/A	O	X	O	X	O	N/A	N/A	N/A	O	X	N/A	N/A	N/A	X	X	6	6	7
ME	O	O	X	N/A	X	X	O	X	O	N/A	N/A	N/A	O	X	N/A	N/A	N/A	X	X	5	7	7
MI	O	O	O	N/A	O	O	O	O	O	N/A	N/A	N/A	O	O	N/A	N/A	N/A	X	X	10	2	7
HY	O	O	O	N/A	O	X	O	X	O	N/A	N/A	N/A	O	O	N/A	N/A	N/A	X	X	9	3	7
AC	O	O	X	N/A	O	O	O	X	O	N/A	N/A	N/A	O	O	N/A	N/A	N/A	X	X	8	4	7
MAYDAY																				Summary		
	D.a	D.b	D.c	D.d	D.e	D.f	D.g	D.h	T.a	Q.a	Q.b	Q.c	S.a	S.c	S.d	F.a	E.a	C.a	I.a	O	X	N/A
SP	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	X	0	1	18

MA	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	X	0	1	18
ME	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	X	0	1	18
MI	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	X	0	1	18
HY	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	X	0	1	18
AC	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	X	0	1	18

Appendix B. Data Needs Traceability Matrices

Table B-1. Data Needs Traceability Matrix for EATIS Bundle

	ATIS						S-PARK						T-MAP					
Data Need	SP	MA	ME	MI	HY	AC	SP	MA	ME	MI	HY	AC	SP	MA	ME	MI	HY	AC
Driving behavior (Car following characteristic)	X	X	X	O	O	X	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Traveler behavior (route choice, mode choice)	X	X	O	O	O	X	X	X	O	O	O	X	X	X	O	O	O	X
Network information: Roadways (Node, Link)	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
Network information: Traffic Control (sign, signal, etc.)	X	X	O	O	O	O	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Network information : Transit Route	X	O	X	O	O	O	X	O	X	O	O	O	X	O	X	O	O	O
Time-Dependent Demand (Auto)	X	X	O	O	O	O	X	X	O	O	O	O	X	X	O	O	O	O
Time-Dependent Demand (Transit)	X	X	X	O	O	O	X	X	X	O	O	O	X	X	X	O	O	O
Traffic composition	X	X	X	O	O	X	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Transit Schedule	X	O	X	O	O	O	X	O	X	O	O	O	X	O	X	O	O	O
Weather scenarios (precipitation, speed reduction, etc.)	O	O	O	O	O	O	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Map availability scenarios	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	O	N/A	N/A	N/A	N/A	N/A
Traffic information scenarios	O	O	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

	ATIS						S-PARK						T-MAP					
Data Need	SP	MA	ME	MI	HY	AC	SP	MA	ME	MI	HY	AC	SP	MA	ME	MI	HY	AC
Park and ride scenarios	O	O	O	O	O	O	O	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Benefit database	O	N/A	N/A	N/A	N/A	N/A	O	N/A	N/A	N/A	N/A	N/A	O	N/A	N/A	N/A	N/A	N/A
Number of Os	3	3	4	9	9	6	3	3	3	6	6	5	3	3	3	6	6	5
Number of Xs	8	6	5	0	0	3	5	3	3	0	0	1	5	3	3	0	0	1
Number of N/As	3	5	5	5	5	5	6	8	8	8	8	8	6	8	8	8	8	8

Table B-2. Data Needs Traceability Matrix for EATIS Bundle

	WX-INFO					
Data Need	SP	MA	ME	MI	HY	AC
Driving behavior (Car following characteristic)	X	X	X	O	O	X
Traveler behavior (route choice, mode choice)	X	X	O	O	O	X
Network information: Roadways (Node, Link)	O	O	O	O	O	O
Network information: Traffic Control (sign, signal, etc.)	X	X	O	O	O	O
Network information : Transit Route	X	O	X	O	O	O
Time-Dependent Demand (Auto)	X	X	O	O	O	O
Time-Dependent Demand (Transit)	X	X	X	O	O	O
Traffic composition	X	X	X	O	O	X
Transit Schedule	X	O	X	O	O	O
Weather scenarios (precipitation, speed reduction, etc.)	O	O	O	O	O	O
Map availability scenarios	N/A	N/A	N/A	N/A	N/A	N/A
Traffic information scenarios	O	N/A	N/A	N/A	N/A	N/A
Park and ride scenarios	N/A	N/A	N/A	N/A	N/A	N/A
Benefit database	O	N/A	N/A	N/A	N/A	N/A
Number of Os	4	4	5	10	10	7
Number of Xs	8	6	5	0	0	3
Number of N/As	2	4	4	4	4	4

Table B-3. Data Needs Traceability Matrix for INFLO Bundle

	Q-WARN						SPD-HARM						CACC					
Data Need	SP	MA	ME	MI	HY	AC	SP	MA	ME	MI	HY	AC	SP	MA	ME	MI	HY	AC
Network information: Roadways (Node, Link)	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
Network information: Traffic Control (sign, signal, etc.)	X	X	O	O	O	O	X	X	O	O	O	O	X	X	O	O	O	O
Network information : Transit Route	X	O	X	O	O	O	X	O	X	O	O	O	X	O	X	O	O	O
Driving behavior (Car following characteristic)	X	X	X	O	O	X	X	X	X	O	O	X	X	X	X	O	O	X
Time-Dependent Demand (Auto)	X	X	O	O	O	O	X	X	O	O	O	O	X	X	O	O	O	O
Time-Dependent Demand (Transit)	X	X	X	O	O	O	X	X	X	O	O	O	X	X	X	O	O	O
Time-Dependent Demand (Pedestrian)	X	X	X	O	O	O	X	X	X	O	O	O	X	X	X	O	O	O
Traffic composition	X	X	X	O	O	X	X	X	X	O	O	X	X	X	X	O	O	X
Weather scenarios (precipitation, speed reduction, etc.)	N/A	N/A	N/A	N/A	N/A	N/A	O	X	O	O	O	X	N/A	N/A	N/A	N/A	N/A	N/A
Number of Os	1	2	3	8	8	6	2	2	4	9	9	6	1	2	3	8	8	6
Number of Xs	7	6	5	0	0	2	7	7	6	0	0	3	7	6	5	0	0	2
Number of N/As	1	1	1	1	1	1	0	0	0	0	0	0	1	1	1	1	1	1

Table B-4. Data Needs Traceability Matrix for IDTO Bundle

	T-CONNECT						T-DISP						D-RIDE					
Data Need	SP	MA	ME	MI	HY	AC	SP	MA	ME	MI	HY	AC	SP	MA	ME	MI	HY	AC
Network information: Roadways (Node, Link)	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
Network information: Traffic Control (sign, signal, etc.)	X	X	O	O	O	O	X	X	O	O	O	O	X	X	O	O	O	O
Network information : Transit Route	X	O	X	O	O	O	X	O	X	O	O	O	X	O	X	O	O	O
Time-Dependent Demand (Auto)	N/A	N/A	N/A	N/A	N/A	N/A	X	X	O	O	O	O	X	X	O	O	O	O
Time-Dependent Demand (Transit)	X	X	X	O	O	O	X	X	X	O	O	O	X	X	X	O	O	O
Time-Dependent Demand (Pedestrian)	X	X	X	O	O	O	X	X	X	O	O	O	X	X	X	O	O	O
Traffic composition	X	X	X	O	O	X	X	X	X	O	O	X	X	X	X	O	O	X
Transit Schedule	X	O	X	O	O	O	X	O	X	O	O	O	X	O	X	O	O	O
Number of Os	1	3	2	7	7	6	1	3	3	8	8	7	1	3	3	8	8	7
Number of Xs	6	4	5	0	0	1	7	5	5	0	0	1	7	5	5	0	0	1
Number of N/As	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0

Table B-5. Data Needs Traceability Matrix for M-ISIG Bundle

	ISIG						TSP						PED-SIG					
Data Need	SP	MA	ME	MI	HY	AC	SP	MA	ME	MI	HY	AC	SP	MA	ME	MI	HY	AC
Network information : Roadways (Node, Link)	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
Network information : Traffic Control (sign, signal, etc.)	X	X	O	O	O	O	X	X	O	O	O	O	X	X	O	O	O	O
Network information : Transit Route	N/A	N/A	N/A	N/A	N/A	N/A	X	O	X	O	O	O	N/A	N/A	N/A	N/A	N/A	N/A
Time-Dependent Auto Demand	X	X	O	O	O	O	X	X	O	O	O	O	X	X	O	O	O	O
Time-Dependent Pedestrian Demand	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	X	X	X	O	O	O
Time-Dependent Truck Demand	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Traffic composition	X	X	X	O	O	X	X	X	X	O	O	X	N/A	N/A	N/A	N/A	N/A	N/A
Emergency vehicle route	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Transit Schedule	N/A	N/A	N/A	N/A	N/A	N/A	X	O	X	O	O	O	N/A	N/A	N/A	N/A	N/A	N/A
Number of Os	1	1	3	4	4	3	1	3	3	7	7	6	1	1	3	4	4	4
Number of Xs	3	3	1	0	0	1	6	4	4	0	0	1	3	3	1	0	0	0
Number of N/As	6	6	6	6	6	6	3	3	3	3	3	3	6	6	6	6	6	6

Table B-6. Data Needs Traceability Matrix for M-ISIG Bundle

	PREEMPT						FSP					
Data Need	SP	MA	ME	MI	HY	AC	SP	MA	ME	MI	HY	AC
Network information : Roadways (Node, Link)	O	O	O	O	O	O	O	O	O	O	O	O
Network information : Traffic Control (sign, signal, etc.)	X	X	O	O	O	O	X	X	O	O	O	O
Network information : Transit Route	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Time-Dependent Auto Demand	X	X	O	O	O	O	X	X	O	O	O	O
Time-Dependent Transit Demand	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Time-Dependent Pedestrian Demand	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Time-Dependent Truck Demand	N/A	N/A	N/A	N/A	N/A	N/A	X	X	X	O	O	X
Traffic composition	N/A	N/A	N/A	N/A	N/A	N/A	X	X	X	O	O	X
Emergency vehicle route	X	X	X	O	O	X	N/A	N/A	N/A	N/A	N/A	N/A
Transit Schedule	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Number of Os	1	1	3	4	4	3	1	1	3	5	5	3
Number of Xs	3	3	1	0	0	1	4	4	2	0	0	2
Number of N/As	6	6	6	6	6	6	5	5	5	5	5	5

Table B-7. Data Needs Traceability Matrix for FRATIS Bundle

	F-ATIS						DR-OPT						F-DRG					
Data Need	SP	MA	ME	MI	HY	AC	SP	MA	ME	MI	HY	AC	SP	MA	ME	MI	HY	AC
Benefit database	O	N/A	N/A	N/A	N/A	N/A	O	N/A	N/A	N/A	N/A	N/A	O	N/A	N/A	N/A	N/A	N/A
Driving behavior (Car following characteristic)	X	X	X	O	O	X	N/A	N/A	N/A	N/A	N/A	N/A	X	X	X	O	O	X
Network information : Roadways (Node, Link)	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
Network information : Traffic Control (sign, signal, etc.)	X	X	O	O	O	O	N/A	N/A	N/A	N/A	N/A	N/A	X	X	O	O	O	O
Incident Information	X	X	O	O	O	X	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Time-Dependent Auto Demand	X	X	O	O	O	O	N/A	N/A	N/A	N/A	N/A	N/A	X	X	O	O	O	O
Time-Dependent Truck Demand	X	X	X	O	O	X	X	X	X	O	O	X	X	X	X	O	O	X
Trip chain for each mode	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	X	X	X	O	X	O
Traffic composition	X	X	X	O	O	X	X	X	X	O	O	X	X	X	X	O	O	X
Shipment arrival schedule	N/A	N/A	N/A	N/A	N/A	N/A	X	X	X	O	X	X	N/A	N/A	N/A	N/A	N/A	N/A
Weather scenarios (precipitation, speed reduction, etc.)	X	X	O	O	O	X	N/A	N/A	N/A	N/A	N/A	N/A	X	X	O	O	O	X
Work zone information	X	X	O	O	O	X	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Number of Os	2	1	6	9	9	3	2	1	1	4	3	1	2	1	4	8	7	4

	F-ATIS						DR-OPT						F-DRG					
Data Need	SP	MA	ME	MI	HY	AC	SP	MA	ME	MI	HY	AC	SP	MA	ME	MI	HY	AC
Number of Xs	9	9	4	0	0	6	3	3	3	0	1	3	7	7	4	0	1	4
Number of N/As	2	3	3	3	3	3	7	8	8	8	8	8	3	4	4	4	4	4

Table B-8. Data Needs Traceability Matrix for RESCUME Bundle

	EVAC						RESP-STG						INC-ZONE					
Data Need	SP	MA	ME	MI	HY	AC	SP	MA	ME	MI	HY	AC	SP	MA	ME	MI	HY	AC
Benefit database	O	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	O	N/A	N/A	N/A	N/A	N/A
Current location and availability of emergency responders	X	X	X	O	X	X	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Driving behavior of emergency responders	X	X	X	O	X	X	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Driving behavior (Car following characteristic)	X	X	X	O	O	X	X	X	X	O	O	X	X	X	X	O	O	X
Network information : Roadways (Node, Link)	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
Network information : Traffic Control (sign, signal, etc.)	X	X	O	O	O	O	N/A	N/A	N/A	N/A	N/A	N/A	X	X	O	O	O	O
Time-Dependent Auto Demand	X	X	O	O	O	O	N/A	N/A	N/A	N/A	N/A	N/A	X	X	O	O	O	O
Traffic composition	X	X	X	O	O	X	X	X	X	O	O	X	X	X	X	O	O	X
Work zone information	N/	N/	N/	N/	N/	N/	N/	N/	N/	N/	N/	N/	X	X	O	O	O	X

	EVAC						RESP-STG						INC-ZONE					
Data Need	SP	MA	ME	MI	HY	AC	SP	MA	ME	MI	HY	AC	SP	MA	ME	MI	HY	AC
	A	A	A	A	A	A	A	A	A	A	A	A						
Evacuation scenarios	X	O	O	O	X	X	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Work zone scenarios and locations	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	O	O	O	O	O	O
Number of Os	2	2	4	8	5	3	1	1	1	3	3	1	3	2	5	7	7	4
Number of Xs	7	6	4	0	3	5	2	2	2	0	0	2	5	5	2	0	0	3
Number of N/As	2	3	3	3	3	3	8	8	8	8	8	8	3	4	4	4	4	4

Table B-9. Data Needs Traceability Matrix for RESCUME Bundle

	MAYDAY					
Data Need	SP	MA	ME	MI	HY	AC
Benefit database	N/A	N/A	N/A	N/A	N/A	N/A
Current location and availability of emergency responders	N/A	N/A	N/A	N/A	N/A	N/A
Driving behavior of emergency responders	N/A	N/A	N/A	N/A	N/A	N/A
Driving behavior (Car following characteristic)	N/A	N/A	N/A	N/A	N/A	N/A
Network information : Roadways (Node, Link)	O	O	O	O	O	O
Network information: Traffic Control (sign, signal, etc.)	X	X	O	O	O	O
Time-Dependent Auto Demand	N/A	N/A	N/A	N/A	N/A	N/A
Traffic composition	X	X	X	O	O	X
Work zone information	N/A	N/A	N/A	N/A	N/A	N/A
Evacuation scenarios	N/A	N/A	N/A	N/A	N/A	N/A
Work zone scenarios and locations	N/A	N/A	N/A	N/A	N/A	N/A
Number of Os	1	1	2	3	3	2
Number of Xs	2	2	1	0	0	1
Number of N/As	8	8	8	8	8	8

Appendix C. Modeling Function Traceability Matrix

The meaning of symbols used in the matrix is as below:

- √ indicates that the subject modeling tool can support the subject function without any API supports.
- EA indicates the subject function can be implemented with Existing APIs (might require slight modifications)
- NA indicates the subject function can be implemented with New APIs
- C indicates that the subject modeling tool must be customized by modifying its source code without adding new algorithms.
- CA indicates the subject modeling tool must be customized by modifying its source code with a new algorithm

Table C-1. Modeling Function Needs Traceability Matrix for EATIS Bundle

ATIS						
Functions required for application modeling	SP	MA	ME	MI	HY	AC
Detect real-time traffic information			C	√	√	C
Develops minimum time path for travelers based on dynamic assignment (single mode and multi modes)			C	EA	NA	C
Control travelers' route diversion, speed changes and modal shift to travel condition information.			CA	NA		CA
Implement dynamic route assignment and route shift for each mode			C	√	√	C
Provides for off –line demand adjustment by mode choice	√	√	√	√	√	√
Provides static assignment of route and mode for macroscopic and sketch planning tools	√	√	√	√	√	√
Develop estimate of travel time under various traffic condition scenarios	√	√	√	√	√	√
WX-INFO						
Functions required for application modeling	SP	MA	ME	MI	HY	AC
Detect real-time traffic information			C	√	√	C
Develop minimum time path for travelers (Route Guidance) by traffic information and off-line weather condition(capacity and speed change)			C	EA	NA	C
Control Traveler behaviors (compliance rate, route diversion, speed changes and modal shift) based on travel condition information and weather condition			CA	NA		CA
Multiple traveler compositions reflecting service market penetration rate and vehicle type			C	√	√	C
Off-line demand adjustment by weather condition	√	√	√	√	√	

Table C-2. Modeling Function Needs Traceability Matrix for EATIS Bundle

T-MAP						
Functions required for application modeling	SP	MA	ME	MI	HY	AC
Implement dynamic transit assignment by transit schedule			C	√	√	√
Develop minimum time path for travelers (Route Guidance) with adjusted demand by off-line T-MAP utilization ratios			C	EA	NA	C
Control Traveler behaviors (route diversion and mode shift) based on T-MAP information			CA	NA		CA
Multi traveler compositions including T-MAP-enabled traveler group			C	√	√	C
Sketch level travel time estimation under two different map availability scenarios given proper database	√	√	√	√	√	√
S-PARK						
Functions required for application modeling	SP	MA	ME	MI	HY	AC
Model parking facility (e.g., location, available spaces)			C	NA	NA	C
Calculate minimum time paths (Route Guidance) considering multi modes based on real-time parking information, transit schedule, and highway congestion.			C	EA	BA	C
Dynamically track available parking spaces and predicts availability on vehicle's expected arrival time at parking facility.			C	NA		C
Control Traveler behaviors (i.e., route diversion, destination change, and modal shift) based on parking lot information			CA	NA		CA
Multi traveler compositions including S-PARK users			C	√	√	C
Sketch level travel time estimation under two different park and ride scenarios given proper database	√	√	√	√	√	√

Table C-3. Modeling Function Needs Traceability Matrix for INFLO Bundle

Q-WARN						
Function required for application modeling	SP	MA	ME	MI	HY	AC
Model non-recurrent congestion (e.g., incident, work zone).			C	NA	NA	
Detect existing queues in real-time			C	√	NA	C
Generate warning messages for upstream vehicles.			CA	NA		
Provide upstream vehicles with Queue warning messages through the Connected Vehicle environment			CA	EA		
Control Traveler behaviors (driver compliance, route diversion, speed change) in response to queue warning information			CA	NA		CA
SPD-HARM						
Function required for application modeling	SP	MA	ME	MI	HY	AC
Model non-recurrent congestion (e.g., incident, work zone).			C	NA	NA	
Detect traffic congestion conditions (e.g., speed, density, etc.) in real-time			C	√	√	C
Determine target speed based on detected recurrent and non-recurrent traffic conditions				EA		
Provide target speed information to drivers through the Connected Vehicle environment				EA		
Control Traveler behaviors (e.g., driver compliance, speed change) in response to target speed information			CA	NA		CA
Presents information to motorist and provides information to CACC.				EA		
CACC						
Function required for application modeling	SP	MA	ME	MI	HY	AC
Model non-recurrent congestion (e.g., incident, work zone).			C	NA	NA	
Detect existing traffic congestion conditions in real-time			C	C	C	√
Calculate target speed and gap guidance for CACC-enabled vehicles based on traffic and incident conditions.				NA		
Provides target speed and gap guidance to CACC drivers				EA		
Control Traveler behaviors (e.g., driver compliance, speed change) in response to target speed information			CA	NA		CA

Table C-4. Modeling Function Needs Traceability Matrix for IDTO Bundle

T-CONNECT						
Function required for application modeling	SP	MA	ME	MI	HY	AC
Model a hold request from a pedestrian.				NA		
Model transit vehicles (e.g., positions of transit vehicles and their schedules and passenger loads).			C	√		
Determine feasibility of holding based on minimizing the total passenger delay (with proper logic and constraints).			CA	NA		
Manipulate dynamic transit operation based on pedestrian hold requests based on proper logic to determine its feasibility; Grants, if feasible the hold so that a passengers can make the connection; If not feasible, an alternative transit itinerary will be provided)				NA		
T-DISP						
Function required for application modeling	SP	MA	ME	MI	HY	AC
Provide dynamic transit route using fixed route and flexible route service based on real-time requests.				NA		
Determine the best route based on traffic conditions as well as the transit pick-up and drop-off requests.			CA	NA		
Control Traveler behaviors (driver compliance and route diversion) based on T-DISP information			CA	NA		CA
D-RIDE						
Function required for application modeling	SP	MA	ME	MI	HY	AC
Multiple vehicle compositions including ridesharing-enabled vehicle types.			C	√	√	
Model ride sharing requests on short notice (locations, request frequency and time)			C	NA		
Search for ridesharing vehicles to serve the requests (with proper logic to be developed)			C	NA		
Develop the best ridesharing option incorporating the information of transit schedule, availability, and location and real-time traffic condition.			CA	NA		
Control Traveler behaviors (ridesharing driver's compliance and route diversion)			CA	NA		CA

Table C-5. Modeling Function Needs Traceability Matrix for M-ISIG Bundle

ISIG						
Function required for application modeling	SP	MA	ME	MI	HY	AC
Detect real-time traffic congestions (e.g., speed, density, etc.)			C	√	√	C
Model traffic compositions to consider various modes (auto, transit, pedestrian, freight)			C	√	√	C
Determine optimal traffic signal timing by incorporating proper optimization algorithms that consider all traveler modes (vehicle, transit, pedestrian, freight)			CA	NA	NA	CA
Provides optimal signal timing control to travelers in real-time			C	√		C
Control Traveler behaviors (driver compliance, route diversion, speed change) in response to optimal traffic signal controls			CA	NA		CA
TSP						
Function required for application modeling	SP	MA	ME	MI	HY	AC
Dynamic transit simulation based on transit schedule				√	C	√
Detect real-time traffic congestions (e.g., speed, density, etc.)			C	√	√	C
Detect real-time transit vehicle information (e.g., position, speed, passenger load)				NA	NA	C
Determine optimal transit priority strategy by incorporating proper algorithms that consider auto, transit, and pedestrian modes				NA	NA	CA
Real-time intersection traffic signal control based on the optimal TSP strategy			C	NA	NA	C

Table C-6. Modeling Function Needs Traceability Matrix for M-ISIG Bundle

PED-SIG					y	
Function required for application modeling	SP	MA	ME	MI	HY	AC
Model multiple pedestrian types (e.g., normal pedestrian and visually impaired pedestrian)				NA		
Model pedestrian on-demand calls				NA		
Real-time intersection traffic signal control based on pedestrian demand calls				NA		
Provides visually impaired pedestrians with safe crossing guidance (not modeled).						
PREEMPT						
Function required for application modeling	SP	MA	ME	MI	HY	AC
Model emergency vehicles (e.g., departure time, desired speed, origin-destination)			C	NA	NA	C
Detect real-time emergency vehicle information (e.g., position, speed, passenger load)				NA		C
Generate preemption calls				NA		CA
Real-time intersection traffic signal control based on the preemption calls				NA	NA	
FSP						
Function required for application modeling	SP	MA	ME	MI	HY	AC
Model freight modes (e.g., type, departure time, desired speed, origin-destination)				NA	NA	C
Detect real-time freight vehicle or train information (e.g., position, speed, passenger load)				NA		
Generate preemption calls				NA		CA
Real-time intersection traffic signal control based on the preemption calls				NA	NA	

Table C-7. Modeling Function Needs Traceability Matrix for FRATIS Bundle

Freight Real-Time Traveler Information with Performance Measures						
Function required for application modeling	SP	MA	ME	MI	HY	AC
Model freight vehicles (e.g., truck or train and departure time, desired speed, origin-destination)				NA	NA	C
Model non-recurrent congestion (e.g., incident, work zone, weather condition).			C	NA	NA	C
Detect real-time traffic information			C	√	√	C
Provide freight operators with traffic information				NA	NA	C
Model freight operator behaviors (compliance, route diversion, and speed changes) based on traffic Information.			CA	NA	NA	CA
Multiple vehicle compositions (auto, transit, and freight)			C	√	√	√
Drayage Optimization						
Function required for application modeling	SP	MA	ME	MI	HY	AC
Model drayage vehicles (e.g., freight arrival time, loading/unloading time)				NA		
Determine optimal drayage vehicle operation by incorporating proper optimization algorithms			CA	NA	NA	CA
Freight Dynamic Route Guidance Information						
Function required for application modeling	SP	MA	ME	MI	HY	AC
Model freight vehicles (e.g., truck or train and departure time, desired speed, origin-destination)				NA	NA	C
Model non-recurrent congestion (e.g., incident, work zone, weather condition).			C	NA	NA	C
Detect real-time traffic information and create route-guidance by using a proper algorithm that considers the real-time traffic condition, restricted roadways, special weather issues, itinerary constraints			CA	NA	NA	CA
Provide freight operators with the route guidance information				NA	NA	C
Model freight operator behaviors (compliance, route diversion, and speed changes) based on traffic Information.			CA	NA	NA	CA
Multiple vehicle compositions (auto, transit, and freight)				√	√	√

Table C-8. Modeling Function Needs Traceability Matrix for RESCUME Bundle

Emergency Communication and Evacuation						
Function required for application modeling	SP	MA	ME	MI	HY	AC
Model passive evacuees who are not able to evacuate by their own by using proper database				NA		
Model special vehicles for passive evacuees (e.g., route, schedule)				NA		
Develop optimal path information for evacuees based on shelter location, grocery location, lodge information, ATM location			CA	NA	NA	CA
Provide active evacuees with the optimal path information			C	NA		
Provide passive evacuees with proper evacuation modes				NA		
Control evacuee behaviors (e.g., compliance, route diversion) based on the path information			CA	NA		CA
Multiple traveler compositions reflecting active and passive evacuees				NA	NA	
Incident Scene Pre-arrival Staging Guidance for Emergency Responder						
Function required for application modeling	SP	MA	ME	MI	HY	AC
Model emergency responder vehicles (e.g., route, departure time)				NA		
Model Incidents (e.g., location, occurrence time, duration, severity)				NA		
Detect real-time traffic congestions			C	√	√	C
Detect incidents in real-time			CA	NA		
Develop optimal route guidance for emergency responders such that responders, travelers, and crash victim are safe while less disruptive to traffic.			CA	NA	NA	CA
Provide route guidance with emergency responders				NA		

Table C-9. Modeling Function Needs Traceability Matrix for RESCUME Bundle

Incident scene Work zone Alerts for Drivers & Workers						
Function required for application modeling	SP	MA	ME	MI	HY	AC
Model incident scene (occurrence time, location, work zone size, severity)				NA		
Detect traffic congestions in real-time			C	√	√	√
Detect incidents in real-time			CA	NA		
Detect vehicles near the incident scene and identify dangerous vehicles				NA		
Determine safe speed for the vehicles near the incident scene			CA	NA	NA	
Provide the vehicles near the incident scene work zone with safe speed advisory				NA		
Control Traveler behaviors (e.g., compliance, speed change) in response to the speed advisory information			CA	NA	NA	CA
Mayday Relay						
Function required for application modeling	SP	MA	ME	MI	HY	AC
Model run-off crash situation (e.g., location, occurrence time, mayday dissemination)				NA		
Model wireless communications (e.g., coverage)				NA		
Multiple vehicle types (normal vehicles vs. communication device-equipped vehicles, market penetration rates)				√		

Appendix D. Gaps and Challenges

Table D-1. Gaps EATIS: ATIS

Modeling Tool	Gap
SP	- Unable to consider pedestrian-, truck- and transit-related performance - Limited to model traveler behaviors, local traffic control, time-dependent demands, and transit mode manipulation.
MA	- Not capable of producing pedestrian- and freight-related measures. - Not able to implement any time dependent analysis (e.g., real-time traffic information capture and real-time route guidance) - Not capable of precisely dealing with traffic signalized intersection operations.
ME	- Not capable of handling pedestrian, freight, and transit modes, resulting in no performance measure for such modes.
MI	- No proper methods to model traveler behaviors.
HY	- Unable to handle the pedestrian delay measure - API is not adequate to control multiple traveler behaviors.
AC	- No proper capabilities to create and disseminate route guidance information to travelers in the simulation model.

Table D-2. Challenges for EATIS: ATIS

Modeling Tool	Challenge
SP	- Need proper off-line ATIS scenarios and benefit databases from known projects for sketch planning level modeling tools. - Real-time traffic information collection and dissemination, optimal path development, traveler behavior control, and multi traveler type support are should be developed.
MA	- Real-time traffic information collection and dissemination, optimal path development, traveler behavior control, and multi traveler type support should be developed.
ME	- Real-time traffic information collection and dissemination, optimal path development, traveler behavior control, and multi traveler type support should be developed.
MI	- Need to develop new APIs for optimal path development and traveler behavior control, Real-time traffic information collection and dissemination should also be developed.
HY	- Traveler behavior control is not available, nor is Real-time traffic information collection and dissemination
AC	- Real-time traffic information collection and dissemination, optimal path development, traveler behavior control, and multi traveler type support should be developed.

Table D-3. Gaps for EATIS: WX-INFO

Modeling Tool	Gap
SP	- Incapable of measuring the performances other than auto mode. - No dynamic assignment support - Unable to handle travelers' behavior, traffic control, and time-dependent demand
MA	- Limited to implement real-time route guidance due to its static assignment nature - Insufficient to precisely simulate intersection operations - Not possible to capture the impact of pedestrian and freight modes
ME	- Support for only auto mode
MI	- No proper methods to model traveler behaviors.
HY	- Not available to handle travelers' behavior
AC	- Unable to disseminate route guidance information to travelers in the simulation model.

Table D-4. Challenges for EATIS: WX-INFO

Modeling Tool	Challenge
SP	Dynamic transit assignment, route guidance generation and dissemination, traveler behavior control, and multi-traveler compositions should be developed.
MA	Dynamic transit assignment, route guidance generation and dissemination, traveler behavior control, and multi-traveler compositions should be developed.
ME	Dynamic transit assignment, route guidance generation and dissemination, traveler behavior control, and multi-traveler compositions should be developed.
MI	Need to develop new APIs for route guidance generation and dissemination. Need a new API for traveler behavior control.
HY	Traveler behavior control is not available
AC	Route guidance generation and dissemination, traveler behavior control, and multi-traveler compositions should be developed.

Table D-5. Gaps for EATIS: T-MAP

Modeling Tool	Gap
SP	- Unable to produce transit vehicle delay and total traveler delay (D.g) - Incapable of not only building optimal paths for T-MAP application holder but also handling traveler behaviors.
MA	- Not possible to create optimal paths for T-MAP application holder and control traveler behaviors based on the optimal path.
ME	- Insufficient to produce transit-related performance measures
MI	- Need to develop proper APIs to generate optimal path generations for T-MAP travelers and control travelers.
HY	- Incapable of controlling traveler behaviors within the basic modeling functions
AC	- No proper methods to develop and disseminate the optimal path information for T-MAP travelers unless its source code is customized

Table D-6. Challenges for EATIS: T-MAP

Modeling Tool	Challenge
SP	Dynamic transit assignment, route guidance generation and dissemination, traveler behavior control, and multi-traveler compositions should be developed.
MA	Dynamic transit assignment, route guidance generation and dissemination, traveler behavior control, and multi-traveler compositions should be developed.
ME	Dynamic transit assignment, route guidance generation and dissemination, traveler behavior control, and multi-traveler compositions should be developed.
MI	Need to develop new APIs for route guidance generation and dissemination to T-MAP traveler. Need a new API for traveler behavior control.
HY	Traveler behavior control is not available.
AC	Route guidance generation and dissemination, traveler behavior control, and multi-traveler compositions should be developed.

Table D-7. Gaps for EATIS: S-PARK

Modeling Tool	Gap
SP	- Not able to produce transit vehicle delay - Incapable of dealing with several critical modeling items for this application, such as parking facilities, minimum time path for S-PARK travelers, traveler behavior controls.
MA	- No proper methods to explicitly deal with several critical modeling items such as parking facilities, minimum time path for S-PARK travelers, traveler behavior controls.
ME	- Insufficient to examine transit-related measures. - No proper interfaces to consider parking facilities, minimum time path for S-PARK travelers, traveler behavior controls.
MI	- Challenging to cover a large network and handle traveler behavior (e.g., route change, destination change).
HY	- Incapable of controlling traveler behaviors (e.g., route change, destination change).
AC	- Unsuitable to produce transit delay - No proper interfaces to consider parking facilities, minimum time path for S-PARK travelers, traveler behavior controls.

Table D-8. Challenges for EATIS: S-PARK

Modeling Tool	Challenge
SP	No proper capability to model parking facility. Route guidance generation and dissemination, traveler behavior control, and multi-traveler compositions should be developed.
MA	No proper capability to model parking facility. Route guidance generation and dissemination, traveler behavior control, and multi-traveler compositions should be developed.
ME	No proper capability to model parking facility. Route guidance generation and dissemination, traveler behavior control, and multi-traveler compositions should be developed.
MI	Need to develop new APIs for parking facility operations (e.g., location, parking space detection and availability prediction), route guidance generation and dissemination and traveler behavior control.
HY	No proper capability to model parking facility. Traveler behavior control is not available.
AC	No proper capability to model parking facility. Route guidance generation and dissemination, traveler behavior control, and multi-traveler compositions should be developed.

Table D-9. Gaps for INFLO: Q-WARN

Modeling Tool	Gap
SP	- Unable to detect queues in real-time - Modeling non-recurrent congestion condition is not available with SPT.
MA	- Not available to model non-recurrent incident - Unable to capture real-time queues and develop queue warning
ME	- Need to customize to model non-recurrent congestion, detect real-time queues, and generate queue warning information and disseminate it to travelers
MI	- Cover up to corridors level network - Difficult to handle travelers behavior
HY	- Challenging to generate warning message and disseminate it to travelers - Incapable of controlling traveler behaviors (i.e., driver compliance, route diversion, speed change) in response to queue warning information.

Modeling Tool	Gap
AC	- Needed to be customized to model non-recurrent congestion and detect queues in real-time - Insufficient to handle the behaviors of selected individual travelers advised by queue warning messages.

Table D-10. Challenges for INFLO: Q-WARN

Modeling Tool	Challenge
SP	Modeling non-recurrent condition (e.g., incident, workzone), real-time queue detection, queue warning message generation and dissemination, and traveler behavior control should be developed.
MA	Modeling non-recurrent condition (e.g., incident, workzone), real-time queue detection, queue warning message generation and dissemination, and traveler behavior control should be developed.
ME	Modeling non-recurrent condition (e.g., incident, workzone), real-time queue detection, queue warning message generation and dissemination, and traveler behavior control should be developed.
MI	Need to develop proper APIs for modeling non-recurrent condition (e.g., incident, workzone), queue warning message generation and dissemination, and traveler behavior control
HY	Modeling non-recurrent condition (e.g., incident, workzone) can be done by a proper API. Real-time queue detection, queue warning message generation and dissemination, and traveler behavior control should be developed.
AC	Modeling non-recurrent condition (e.g., incident, workzone), real-time queue detection, queue warning message generation and dissemination, and traveler behavior control should be developed.

Table D-11. Gaps for INFLO: SPD-HARM

Modeling Tool	Gap
SP	- Unable to detect traffic congestions in real-time - Unavailable to model non-recurrent congestion condition
MA	- Unable to model non-recurrent incident and to capture real-time queues
ME	- Need to customize the program source codes to capture the real-time traffic information and disseminate it to drivers through VMS. - Need to import external algorithm to generate target speed information by modifying its source code.
MI	- Insufficient to model drivers' behaviors unless proper methods are provided - Challenging to deal with large scale network bigger than corridor level.
HY	- Insufficient to model non-recurrent congestion and real-time traffic congestion detection without API support - Difficult to generate target speed and disseminate it to travelers - No proper methods to control traveler behaviors (i.e., driver compliance, route diversion, speed change) in response to the target speed.
AC	- Unable to model non-recurrent congestion and to detect queues in real-time without customizing the program source code - Insufficient to handle the behaviors of selected individual travelers advised by target speeds.

Table D-12. Challenges for INFLO: SPD-HARM

Modeling Tool	Challenge
SP	Modeling non-recurrent condition (e.g., incident, workzone), real-time congestion detection, target speed determination and dissemination, and traveler behavior control should be developed.
MA	Modeling non-recurrent condition (e.g., incident, workzone), real-time congestion detection, target speed determination and dissemination, and traveler behavior control should be developed.
ME	Modeling non-recurrent condition (e.g., incident, workzone), real-time congestion detection, target speed determination and dissemination, and traveler behavior control should be developed.
MI	Need new APIs for modeling non-recurrent condition (e.g., incident, workzone), target speed generation and dissemination, and traveler behavior control.
HY	Need new APIs for modeling non-recurrent condition (e.g., incident, workzone) target speed determination and dissemination and traveler behavior control should be developed.
AC	Modeling non-recurrent condition (e.g., incident, workzone), real-time congestion detection, target speed determination and dissemination, and traveler behavior control should be developed.

Table D-13. Gaps for INFLO: CACC

Modeling Tool	Gap
SP	- Not able to monitor real-time traffic condition to calculate target speed for CACC vehicles - Not available to Model non-recurrent congestion condition.
MA	- Cannot model non-recurrent incident and capture real-time traffic condition - Unable to generate CACC target speed
ME	- Without customizing the program source code, impossible to model non-recurrent congestion, detect real-time congestions, and generate target safe speed information for CACC.
MI	- Unsuitable to handle large network (i.e., regional level or larger)
HY	- Need APIs to deal with non-recurrent congestion modeling and real-time queue detection - Challenging to determine optimal target speed for CACC vehicles and to disseminate it to the CACC travelers - Incapable of controlling traveler behaviors (i.e., driver compliance, route diversion, speed change).
AC	- Need to customize the program source codes to handle non-recurrent congestion and capture real-time traffic condition - Insufficient to handle the behaviors of CACC travelers in response to the target speed.

Table D-14. Challenges for INFLO: CACC

Modeling Tool	Challenge
SP	Modeling non-recurrent condition (e.g., incident, workzone), real-time congestion detection, target speed and safe gap determination and dissemination, and traveler behavior control should be developed.
MA	Modeling non-recurrent condition (e.g., incident, workzone), real-time congestion detection, target speed and safe gap determination and dissemination, and traveler behavior control should be developed.
ME	Modeling non-recurrent condition (e.g., incident, workzone), real-time congestion detection, target speed and safe gap determination and dissemination, and traveler behavior control should be developed.
MI	Need new APIs for modeling non-recurrent condition (e.g., incident, workzone), real-time congestion detection and traveler behavior control should be developed. . Possible to import existing APIs for target speed and safe gap determination and dissemination.
HY	Need new APIs for modeling non-recurrent condition (e.g., incident, workzone). Real-time congestion detection ,target speed and safe gap determination and dissemination, and traveler behavior control should be developed. .
AC	Modeling non-recurrent condition (e.g., incident, workzone), real-time congestion detection, target speed and safe gap determination and dissemination, and traveler behavior control should be developed.

Table D-15. Gaps for MMITS: ISIG

Modeling Tool	Gap
SP	- Not able to capture real-time traffic congestion information for determining optimal signal timing plan - Not able to control intersection signal operation in real-time.
MA	
ME	- Incapable of generating optimal signal timing plans and handling travelers' behavior in response to the optimal signal control without customizing the program source code. - Not possible to produce pedestrian-related performance measures.
MI	- Insufficient to cover large network.
HY	- Not able to control traveler behaviors in response to the optimal timing plans - Incapable of producing pedestrian-related performance measure.
AC	- Not possible to generate optimal timing plans based on the detected real-time traffic congestion information and to control traveler behaviors in response to the optimal timing plans without customizing program source code. - Insufficient to produce pedestrian-related performance measures.

Table D-16. Challenges for MMITS: ISIG

Modeling Tool	Challenge
SP	Real-time congestion detection, modeling various modes(auto, transit, freight), real-time optimal signal timing generation, real-time signal control, traveler behavior control should be developed. .
MA	Real-time congestion detection, modeling various modes(auto, transit, freight), real-time optimal signal timing generation, real-time signal control, traveler behavior control should be developed. .
ME	Real-time congestion detection, modeling various modes(auto, transit, freight), real-time optimal signal timing generation, real-time signal control, traveler behavior control should be developed. .
MI	Need APIs for real-time congestion detection, modeling various modes(auto, transit, freight), real-time optimal signal timing generation, real-time signal control, traveler behavior control.
HY	Real-time optimal signal timing generation, real-time signal control, and traveler behavior control should be developed. .
AC	Real-time congestion detection, modeling various modes(auto, transit, freight), real-time optimal signal timing generation, real-time signal control, traveler behavior control should be developed.

Table D-17. Gaps for MMITS: TSP

Modeling Tool	Gap
SP MA	- Unable to capture the real-time information of a transit vehicle (e.g., position, speed, and number of passengers) - Incapable of implementing intersection's transit priority signal. - Insufficient to produce intersection crash measure.
ME	- Incapable of detecting the real-time information of a transit vehicle.
MI	- Insufficient to cover regional level or larger study area.
HY	- Not available to handle real-time transit vehicle detection, optimal TSP generation, and travelers' behavior control without new APIs
AC	- No proper capabilities to model transit vehicles for TSP operations and generate the optimal TSP plans without source code modification.

Table D-18. Challenges for MMITS: TSP

Modeling Tool	Challenge
SP	Dynamic transit assignment based on transit schedule, real-time congestion detection, real-time transit vehicle information capture, real-time optimal transit priority strategy, and real-time signal control should be developed.
MA	Dynamic transit assignment based on transit schedule, real-time congestion detection, real-time transit vehicle information capture, real-time optimal transit priority strategy, and real-time signal control should be developed.
ME	Dynamic transit assignment based on transit schedule, real-time congestion detection, real-time transit vehicle information capture, real-time optimal transit priority strategy, and real-time signal control should be developed.
MI	Need new APIs for real-time transit vehicle information capture, real-time optimal transit priority strategy, and real-time signal control should be developed. . Possible to use TSP logic APIs from existing projects
HY	Real-time optimal transit priority strategy, and real-time signal control should be developed. .
AC	Dynamic transit assignment based on transit schedule, real-time congestion detection, real-time transit vehicle information capture, real-time optimal transit priority strategy, and real-time signal control should be developed.

Table D-19. Gaps for MMITS: PED-SIG

Modeling Tool	Gap
SP	- Not available to model pedestrian-based signal on-demand calls and various types of pedestrians (e.g., normal and visually impaired pedestrians)
MA	- In capable of modeling pedestrian mode
ME	
MI	- Unable to model pedestrian calls and visually impaired pedestrian without new APIs
HY	- In capable of modeling pedestrian mode
AC	

Table D-20. Challenges for MMITS: PED-SIG

Modeling Tool	Challenge
SP	Modeling multiple pedestrian types(e.g., normal pedestrian and visually impaired pedestrian), modeling on-demand pedestrian calls, real-time signal control reflecting pedestrian call should be developed.
MA	Modeling multiple pedestrian types(e.g., normal pedestrian and visually impaired pedestrian), modeling on-demand pedestrian calls, real-time signal control reflecting pedestrian call should be developed.
ME	Modeling multiple pedestrian types(e.g., normal pedestrian and visually impaired pedestrian), modeling on-demand pedestrian calls, real-time signal control reflecting pedestrian call should be developed.
MI	Need new APIs for modeling on-demand pedestrian calls, real-time signal control reflecting pedestrian call.
HY	Modeling multiple pedestrian types(e.g., normal pedestrian and visually impaired pedestrian), modeling on-demand pedestrian calls, real-time signal control reflecting pedestrian call should be developed.
AC	Modeling multiple pedestrian types(e.g., normal pedestrian and visually impaired pedestrian), modeling on-demand pedestrian calls, real-time signal control reflecting pedestrian call should be developed.

Table D-21. Gaps for MMITS: PREEMPT

Modeling Tool	Gap
SP	- Not able to model emergency vehicles (e.g., departure time, route, and desired speed) - Cannot produce emergency vehicle travel times
MA	
ME	
MI	- Insufficient to handle large study area
HY	- Unable to handle preemption operation without new APIs.
AC	- Challenging to capture preemption vehicles, place preemption calls, and control intersection signal in real-time without customizing the program source code

Table D-22. Challenges for MMITS: PREEMPT

Modeling Tool	Challenge
SP	Modeling emergency vehicles(e.g., departure time, desired speed, origin-destination), real-time emergency vehicle information capture, preemption call generation, and real-time signal control should be developed.
MA	Modeling emergency vehicles(e.g., departure time, desired speed, origin-destination), real-time emergency vehicle information capture, preemption call generation, and real-time signal control should be developed.
ME	Modeling emergency vehicles(e.g., departure time, desired speed, origin-destination), real-time emergency vehicle information capture, preemption call generation, and real-time signal control should be developed.
MI	Need new APIs for modeling emergency vehicles(e.g., departure time, desired speed, origin-destination), real-time emergency vehicle information capture, preemption call generation, and real-time signal control.
HY	Modeling emergency vehicles(e.g., departure time, desired speed, origin-destination), real-time emergency vehicle information capture, preemption call generation, and real-time signal control should be developed.
AC	Modeling emergency vehicles(e.g., departure time, desired speed, origin-destination), real-time emergency vehicle information capture, preemption call generation, and real-time signal control should be developed.

Table D-23. Gaps for MMITS: FSP

Modeling Tool	Gap
SP	- Not able to capture the real-time information (e.g., position, speed, number of passengers) of a freight vehicle (e.g., truck, train) - Cannot implement intersection's priority signal.
MA	
ME	
MI	- Not able to handle real-time intersection signal control for freight vehicles without new APIs. - Insufficient to cover regional level or lager study area.
HY	- Insufficient to capture freight vehicles' real-time information. - Incapable of generating preemption calls and control intersection in response to the preemption of freight vehicle within the HYT framework.
AC	- Not able to model freight vehicle and control the intersection based on preemption calls without modifying the program source code

Table D-24. Challenges for MMITS: FSP

Modeling Tool	Challenge
SP	Model freight modes (e.g., type, departure time, desired speed, origin-destination), real-time freight vehicle information capture, preemption call generation, and real-time signal control should be developed.
MA	Model freight modes (e.g., type, departure time, desired speed, origin-destination), real-time freight vehicle information capture, preemption call generation, and real-time signal control should be developed.
ME	Model freight modes (e.g., type, departure time, desired speed, origin-destination), real-time freight vehicle information capture, preemption call generation, and real-time signal control should be developed.
MI	Need new APIs for model freight modes (e.g., type, departure time, desired speed, origin-destination), real-time freight vehicle information capture, preemption call generation, and real-time signal control should be developed.
HY	Model freight modes (e.g., type, departure time, desired speed, origin-destination), real-time freight vehicle information capture, preemption call generation, and real-time signal control should be developed.
AC	Model freight modes (e.g., type, departure time, desired speed, origin-destination), real-time freight vehicle information capture, preemption call generation, and real-time signal control should be developed.

Table D-25. Gaps for IDTO: T-CONNECT

Modeling Tool	Gap
SP	- Not able to model pedestrian hold message requests and transit vehicles in response to the hold message.
MA	- Unable to determine the feasibility of the holding for passenger delay minimization - Cannot calculate transit vehicle occupant delay
ME	- Incapable of modeling pedestrian-based hold message requests but it can determine the holding messages without source code modification. - Not possible to control a transit vehicle in response to the holding message.
MI	- Limited spatial coverage up to corridor level study area - Challenging to model pedestrian hold message requests and transit vehicles without new APIs
HY	- Not able to model pedestrian hold message requests and transit vehicles in response to the hold message.
AC	

Table D-26. Challenges for IDTO: T-CONNECT

Modeling Tool	Challenge
SP	Dynamic transit assignment, modeling pedestrian calls, modeling transit vehicle operation (e.g., position, schedule, passengers), determining the feasibility of pedestrian call should be developed.
MA	Dynamic transit assignment, modeling pedestrian calls, modeling transit vehicle operation (e.g., position, schedule, passengers), determining the feasibility of pedestrian call should be developed.
ME	Dynamic transit assignment, modeling pedestrian calls, modeling transit vehicle operation (e.g., position, schedule, passengers), determining the feasibility of pedestrian call should be developed.
MI	Need customized APIs for modeling pedestrian calls, modeling transit vehicle operation (e.g., position, schedule, passengers), determining the feasibility of pedestrian call.
HY	Modeling pedestrian calls, modeling transit vehicle operation (e.g., position, schedule, passengers), determining the feasibility of pedestrian call should be developed.
AC	Modeling pedestrian calls, modeling transit vehicle operation (e.g., position, schedule, passengers), determining the feasibility of pedestrian call should be developed.

Table D-27. Gaps for IDTO: T-DISP

Modeling Tool	Gap
SP	- Not available to model dynamic transit routes changes in response to real-time requests.
MA	- Unable to develop the best route for transit vehicles to pick up the requesters
ME	- Challenging to handle dynamic transit routes changes and best transit route selections without customizing the program source code
MI	- Not possible to model dynamic transit routes changes and to generate the best paths for specialized transit vehicles without new APIs
HY	Incapable of modeling dynamic transit routes changes and best transit route selections.
AC	

Table D-28. Challenges for IDTO: T-DISP

Modeling Tool	Challenge
SP	Modeling transit vehicle operation (e.g., position, schedule, passengers), dynamic transit route generation and dissemination, traveler behavior controls should be developed.
MA	Modeling transit vehicle operation (e.g., position, schedule, passengers), dynamic transit route generation and dissemination, traveler behavior controls should be developed.
ME	Modeling transit vehicle operation (e.g., position, schedule, passengers), dynamic transit route generation and dissemination, traveler behavior controls should be developed.
MI	Need customized APIs for modeling transit vehicle operation (e.g., position, schedule, passengers), dynamic transit route generation and dissemination, traveler behavior controls should be developed.
HY	Modeling transit vehicle operation (e.g., position, schedule, passengers), dynamic transit route generation and dissemination, traveler behavior controls should be developed.
AC	Modeling transit vehicle operation (e.g., position, schedule, passengers), dynamic transit route generation and dissemination, traveler behavior controls should be developed.

Table D-29. Gaps for IDTO: D-RIDE

Modeling Tool	Gap
SP	- Not available to model ride-sharing request and ride-sharing vehicles
MA	
ME	- Not possible to model ride-sharing request and ride-sharing vehicles without modifying the program source code
MI	- Need new APIs to handle ride-sharing request and ride-sharing vehicles
HY	Incapable of modeling the ride-sharing request (e.g., locations and request frequency and time) and ride-sharing vehicles' behaviors.
AC	

Table D-30. Challenges for IDTO: D-RIDE

Modeling Tool	Challenge
SP	Vehicle compositions, modeling ridesharing requests, searching for the ridesharing-enabled vehicles, generation of optimal ridesharing strategies, and traveler behavior controls should be developed.
MA	Vehicle compositions, modeling ridesharing requests, searching for the ridesharing-enabled vehicles, generation of optimal ridesharing strategies, and traveler behavior controls should be developed.
ME	Vehicle compositions, modeling ridesharing requests, searching for the ridesharing-enabled vehicles, generation of optimal ridesharing strategies, and traveler behavior controls should be developed.
MI	Need new APIs for modeling ridesharing requests, searching for the ridesharing-enabled vehicles, generation of optimal ridesharing strategies, and traveler behavior controls
HY	Modeling ridesharing requests, searching for the ridesharing-enabled vehicles, generation of optimal ridesharing strategies, and traveler behavior controls should be developed.
AC	Vehicle compositions, modeling ridesharing requests, searching for the ridesharing-enabled vehicles, generation of optimal ridesharing strategies, and traveler behavior controls should be developed.

Table D-31. Gaps for FRATIS: F-ATIS

Modeling Tool	Gap
SP	- Unable to produce truck-related performance measures (e.g., commercial vehicle occupant delay). - Cannot handle freight vehicle and its operator's behaviors (e.g., driving characteristics, route or mode changes), and real-time traffic information detection for generating route guidance information.
MA	- Insufficient to produce freight-related measures - Not able to handle real-time traffic information capture and real-time route guidance generation and dissemination.
ME	- Incapable of modeling freight vehicles - Unable to detect real-time traffic information and generate route guidance information without source code customization
MI	- Not able to fully control truck mode behavior without developing new API
HY	- Challenging to model freight vehicles (e.g., truck or train and departure time, desired speed, origin-destination) and control truck operator's behaviors (e.g., route change, destination change).
AC	- Not available to deal with freight-related functions (e.g., modeling freight vehicles and freight operator behaviors), performance measures (e.g., commercial vehicle delays) and route guidance for freight modes without customizing the program

Table D-32. Challenges for FRATIS: F-ATIS

Modeling Tool	Challenge
SP	Modeling freight vehicles and non-recurrent congestions, real-time traffic condition capture, truck driver controls, and multiple vehicle composition should be developed.
MA	Modeling freight vehicles and non-recurrent congestions, real-time traffic condition capture, truck driver controls, and multiple vehicle composition should be developed.
ME	Modeling freight vehicles and non-recurrent congestions, real-time traffic condition capture, truck driver controls, and multiple vehicle composition should be developed.
MI	Need APIs for freight vehicle modeling, non-recurrent condition modeling, real-time congestion detection, and traveler (auto and truck drivers) behavior control
HY	Modeling freight vehicles and freight vehicle drivers are not avialble. Need APIs for freight vehicle modeling, non-recurrent condition modeling, real-time congestion detection, and traveler (auto and truck drivers) behavior control
AC	Modeling freight vehicles and non-recurrent congestions, real-time traffic condition capture, truck driver controls, and multiple vehicle composition should be developed.

Table D-33. Gaps for FRATIS: DR-OPT

<table>
<tr><th>Modeling Tool</th><th>Gap</th></tr>
<tr><td>SP</td><td rowspan="2">- Not able to produce freight-related performance measures (e.g., commercial vehicle occupant delay and goods inventory delay). - Cannot model drayage vehicles (e.g., arrival time and loading/unloading time).
- Challenging to incorporate proper drayage optimization methods to determine optimal drayage operations.</td></tr>
<tr><td>MA</td></tr>
<tr><td>ME</td><td>- Unable to model drayage vehicles even without the source code modifications.</td></tr>
<tr><td>MI</td><td>- Not possible to implement optimal drayage operation without new APIs</td></tr>
<tr><td>HY</td><td>- Not able to support drayage vehicles modeling and to incorporate drayage optimization methods determining the best drayage optimization strategies.</td></tr>
<tr><td>AC</td><td>- No proper methods to model drayage vehicles and to implement optimal drayage operation strategies without program customization.</td></tr>
</table>

Table D-34. Challenges for FRATIS: DR-OPT

Modeling Tool	Challenge
SP	Modeling drayage vehicles and optimal drayage vehicle strategy generation should be developed. No proper API capabilities
MA	Modeling drayage vehicles and optimal drayage vehicle strategy generation should be developed. No proper API capabilities
ME	Modeling drayage vehicles and optimal drayage vehicle strategy generation should be developed. No proper API capabilities
MI	Need APIs for drayage vehicles modeling (e.g., freight arrival time, loading/unloading time) and optimal drayage operation schedules.
HY	Modeling drayage vehicles and optimal drayage vehicle strategy generation should be developed. No proper API capabilities
AC	Modeling drayage vehicles and optimal drayage vehicle strategy generation should be developed. No proper API capabilities

Table D-35. Gaps for FRATIS: F-DRG

Modeling Tool	Gap
SP	- Cannot consider truck-related performance measures (e.g., commercial vehicle occupant delay). - Cannot model freight vehicles (e.g., truck or train, departure time, desired speed, origin-destination) and detect real-time traffic information
MA	- Insufficient to produce freight-related measures. - Not able to capture real-time traffic information and generate real-time route guidance.
ME	- Unable to implement route guidance feature and to produce freight-related performance measure without customizing the program source code
MI	- Unsuitable to implement the application for large study network
HY	- Difficult to model freight vehicles (e.g., truck or train, departure time, desired speed, and origin-destination) and to produce freight vehicle delay measure.
AC	- Not able to deal with freight-related functions, performance measures, and route guidance for freight modes without modifying the program source code.

Table D-36. Challenges for FRATIS: F-DRG

Modeling Tool	Challenge
SP	Modeling freight vehicles and non-recurrent congestions, real-time traffic condition capture, truck driver controls, and multiple vehicle composition should be developed.
MA	Modeling freight vehicles and non-recurrent congestions, real-time traffic condition capture, truck driver controls, and multiple vehicle composition should be developed.
ME	Modeling freight vehicles and non-recurrent congestions, real-time traffic condition capture, truck driver controls, and multiple vehicle composition should be developed.
MI	Need new APIs for freight vehicles modeling and driver control (e.g., compliance, driving behavior), and optimal route guidance generation and dissemination
HY	Modeling freight vehicles, real-time traffic condition capture, truck driver controls, and multiple vehicle composition should be developed. No proper APIs to detect real-time traffic information and generate route-guidance strategies.
AC	Modeling freight vehicles and non-recurrent congestions, real-time traffic condition capture, truck driver controls, and multiple vehicle composition should be developed. No proper APIs to detect real-time traffic information, generate route-guidance strategies.

Table D-37. Gaps for RESCUME: EVAC

Modeling Tool	Gap
SP	- Cannot model evacuees and special vehicles for evacuees - Impossible to create real-time evacuation guidance by using real-time traffic information - Not able to support the measures of emergency vehicle route travel time and crashes at intersections.
MA	- Unable to capture real-time traffic information and generate real-time route guidance for evacuees. - Incapable of capturing the measures of emergency vehicle route travel time.
ME	- Incapable of handling special vehicles for evacuees
MI	- Not suitable for large evacuation study area
HY	- Not capable of modeling passive evacuees and controlling special vehicles for evacuations.
AC	Unable to deal with passive evacuees and to control such specific travelers.

Table D-38. Challenges for RESCUME: EVAC

Modeling Tool	Challenge
SP	No APIs supported. Modeling passive evacuees and special vehicles for passive evacuees should be developed. Optimal evacuation route generation and dissemination for both active and passive evacuees should be developed. Evacuees behaviors (e.g., compliance, route change) are not possible
MA	No APIs supported. Modeling passive evacuees and special vehicles for passive evacuees should be developed. Optimal evacuation route generation and dissemination for both active and passive evacuees should be developed. Evacuees behaviors (e.g., compliance, route change) are not possible
ME	No APIs supported. Modeling passive evacuees and special vehicles for passive evacuees should be developed. Optimal evacuation route generation and dissemination for both active and passive evacuees should be developed. Evacuees behaviors (e.g., compliance, route change) are not possible
MI	Need to develop new APIs for modeling both passive and active evacuees and special vehicles for passive evacuees control (arrival time, route). Enhance existing APIs or develop new APIs for optimal evacuation path generation and dissemination
HY	Modeling passive evacuees and special vehicles for passive evacuees should be developed and evacuees behaviors (e.g., compliance, route change) controls should be developed. Need APIs for optimal evacuation path finding and dissemination
AC	No APIs supported. Modeling passive evacuees and special vehicles for passive evacuees should be developed. Optimal evacuation route generation and dissemination for both active and passive evacuees should be developed. Evacuees behaviors (e.g., compliance, route change) are not possible

Table D-39. Gaps for RESCUME: RESP-SIG

Modeling Tool	Gap
SP	- Not able to model emergency responder and incidents.
MA	- Incapable of producing he measures of transit-, and freight-related measures and emergency vehicle route travel time
ME	- Unable to deal with emergency responders as special individual modes.
MI	- Not available to model hypothetical incident situations without new API
HY	- Difficult to model emergency responder’s behaviors and is not insufficient to produce the emergency vehicle travel time measure.
AC	- Not possible to model emergency responders and incident situations

Table D-40. Challenges for RESCUME: RESP-SIG

Modeling Tool	Challenge
SP	Modeling emergency responder vehicles (e.g., route, departure time) and incidents (location, occurrence time, duration, severity) should be developed. Detecting real-time traffic congestions and incidents are not possible. No proper methods to develop optimal routes for emergency responders and to disseminate them.
MA	Modeling emergency responder vehicles (e.g., route, departure time) and incidents (location, occurrence time, duration, severity) should be developed. Detecting real-time traffic congestions and incidents are not possible. No proper methods to develop optimal routes for emergency responders and to disseminate them.
ME	Modeling emergency responder vehicles (e.g., route, departure time)and incidents (location, occurrence time, duration, severity) should be developed. Detecting real-time traffic congestions and incidents are not possible. No proper methods to develop optimal routes for emergency responders and to disseminate them.
MI	Need to develop new APIs to model emergency responder vehicles and incident. Need proper algorithms for incident detections. Use existing or new APIs for optimal route guidance information for emergency responders.
HY	Modeling emergency responder vehicles (e.g., route, departure time) and incidents (location, occurrence time, duration, severity) should be developed. Detecting real-time incidents are not possible. No proper methods to disseminate optimal routes to emergency responders.
AC	Modeling emergency responder vehicles (e.g., route, departure time) and incidents (location, occurrence time, duration, severity) should be developed. Detecting real-time traffic congestions and incidents are not possible. No proper methods to develop optimal routes for emergency responders and to disseminate them.

Table D-41. Gaps for RESCUME: INC-ZONE

Modeling Tool	Gap
SP	- Not able to make incident situation and detect it in real-time. - Unable to control vehicles adjacent to the incident scene
MA	
ME	
MI	- Not possible to model incident scene (e.g., occurrence time, location, work zone size, severity) and to control the vehicles near the incident scene to provide safe speed advisory information without developing new API
HY	- Not possible to model incident scene
AC	

Table D-42. Challenges for RESCUME: INC-ZONE

Modeling Tool	Challenge
SP	Modeling incidence scene(occurrence time, location, work zone size) should be developed. Detecting real-time traffic congestions, incidents, and vehicle near the incident zone) are not possible. No proper methods to determine safe speed for vehicles near the incident zone. Traveler behaviors control should be developed.
MA	Modeling incidence scene(occurrence time, location, work zone size) should be developed. Detecting real-time traffic congestions, incidents, and vehicle near the incident zone) are not possible. No proper methods to determine safe speed for vehicles near the incident zone. Traveler behaviors control should be developed.
ME	Modeling incidence scene(occurrence time, location, work zone size) should be developed. Detecting real-time traffic congestions, incidents, and vehicle near the incident zone) are not possible. No proper methods to determine safe speed for vehicles near the incident zone. Traveler behaviors control should be developed.
MI	Need new APIs for incidence scene modeling. Need proper incident detection algorithms for new APIs needed to generate safe speeds for the vehicles near the incident work zone area. Additional APIs are needed to control traveler behaviors (e.g., compliance, speed change)
HY	No proper methods to model incidence scene(occurrence time, location, work zone size). Detecting incidents and vehicle near the incident zone are not possible. Need a new AP to determine safe speed for vehicles near the incident zone. Traveler behaviors control should be developed.
AC	Modeling incidence scene(occurrence time, location, work zone size) should be developed. Detecting real-time traffic congestions, incidents, and vehicle near the incident zone) are not possible. No proper methods to determine safe speed for vehicles near the incident zone. Traveler behaviors control should be developed.

Table D-43. Gaps for RESCUME: MAYDAY

Modeling Tool	Gap
SP	Impossible to model run-off crashes (e.g., location, occurrence time, mayday dissemination)
MA	
ME	
MI	Unable to model run-off crashes without developing new APIs
HY	Impossible to model run-off crashes
AC	

Table D-44. Challenges for RESCUME: MAYDAY

Modeling Tool	Challenge
SP	Proper capability to model run-off crashes situation (e.g., location, occurrence time) and external APIs provided by the modeling tool to consider multiple vehicle types and wireless communication performances should be developed.
MA	Proper capability to model run-off crashes situation (e.g., location, occurrence time) and external APIs provided by the modeling tool to consider multiple vehicle types and wireless communication performances should be developed.
ME	Proper capability to model run-off crashes situation (e.g., location, occurrence time) and external APIs provided by the modeling tool to consider multiple vehicle types and wireless communication performances should be developed.
MI	Need to develop new APIs for run-off crash situation. Simple wireless communication performance model can be employed. API can support multiple vehicle types (e.g., normal vehicles vs. communication device-equipped vehicles, market penetration rates)
HY	Proper capability to model run-off crashes situation (e.g., location, occurrence time) and external APIs provided by the modeling tool to consider multiple vehicle types and wireless communication performances should be developed.
AC	Proper capability to model run-off crashes situation (e.g., location, occurrence time) and external APIs provided by the modeling tool to consider multiple vehicle types and wireless communication performances should be developed.

Appendix E. List of Acronyms

Acronym	Definition
AC or ACT	Activity-based modeling tool
AMS	Adaptive Message Scheduling
API	Application programming interface
ATIS	Advanced Traveler Information Services
ATM	Active traffic management
AVL	Automatic vehicle location
C.a	Average incident clearing time
C.a	Average incident clearing time
CACC	Cooperative Adaptive Cruise Control
CAD	Computer aided design
COM	Component object model
CVIC	Cooperative Vehicle Intersection Control
D.a	Vehicle system delay
D.b	Private passenger vehicle occupant delay
D.c	Commercial vehicle occupant delay
D.d	Goods inventory delay
D.e	Transit vehicle delay
D.e	Transit vehicle occupant delay
D.f	Pedestrian delay
D.g	Total traveler delay
D.g	Total traveler delay
D.h	Commercial vehicle delay
D.i	Drayage delay
DMA	Dynamic Mobility Application
DMS	Dynamic message signs
DP	Dynamic programming
D-RIDE	Dynamic Ridesharing
DR-OPT	Drayage Optimization
DSRC	Dedicated Short Range Communication
DTA	Dynamic traffic assignment
E.a	Emissions
EAR	Exploratory Advanced Research
E-ATIS	Enable Advanced Traveler Information Systems
EMS	Emergency Medical Service
EPA	Environmental Protection Agency
EV	Emergency vehicle
EVAC	Emergency Communications and Evacuation
F.a	Fuel consumption
F-ATIS	Freight Real-Time Traveler Information with Performance Monitoring
F-DRG	Freight Dynamic Route Guidance
FHWA	Federal Highway Administration
FLC	Fuzzy Logic Control

Acronym	Definition
FRATIS	Freight Advanced Traveler Information System
FSP	Freight signal priority
FV	Freight vehicles
GIS	Geographic Information Systems
GPS	Global Positioning System
HILS	Hardware-in-the-loop simulation
HYT	Hybrid modeling tool
I.a	Perceived adequacy
IDTO	Integrated Dynamic Transit Operations
INC-ZONE	Incident Scene Work Zone Alerts for Drivers and Workers
INFLO	Intelligent Network Flow Optimization
ISIG	Intelligent Traffic Signal System
JPO	Joint Programs Office
LHD	Latin Hypercube Design
LP	Linear programming
MA	Macroscopic modeling tool
ME	Mesoscopic modeling tool
MI	Microscopic modeling tool
M-ISIG	Multi-Modal Intelligent Signal Control
MMITS	Multi-Modal Intelligent Transportation Systems
MPH	Miles per hour
NHTSA	National Highway Travel Safety Adminstration
OSADP	Open Source Applications Development Portal
OBE	On-board equipment
OBU	On-board unit
OD	Origin-Destination
PARC	Parking Access Revenue and Control
PED-SIG	Mobile Accessible Pedestrian Signal System
PREEMPT	Emergency Vehicle Preemption
Q.a	Route travel time
Q.b	Route travel time reliability
Q.c	Emercency vehicle route travel time
Q-WARN	Queue Warning
RESCUME	Response, Emergency Staging, Communications, Uniform Management and Evacuation
RESP-SIG	Incident Scene Pre-Arrival Staging Guidance for Emergency Responders
RP	Revealed preference
RSE	Roadside Equipment
RTE	Run-time extension
S.a	Freeway crashes
S.c	Crashes at intersections
S.d	Work zone-related crashes
S.d	Work zone related crashes
SILS	Software-in-the-loop simulation
SP	Stated preference
S-PARK	Smart Park

Acronym	Definition
SPD-HARM	Dynamic Speed Harmonization
SPT	Sketch planning tool
SSAM	Surrogate Safety Assessment Model
T.a	Throughput
T-CONNECT	Connection Protection
T-DISP	Dynamic Transit Operations
T-MAP	Universal Map Application
TMC	Traffic management center
TSP	Transit signal priority
USDOT	United States Department of Transportation
VANETs	Vehicle Ad Hoc Networks
VHT	Vehicle hours traveled
VMT	Vehicle miles traveled
VSL	Variable speed limit
WX-INFO	Real-time route-specific weather information

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