Integrated Corridor Management

Analysis, Modeling, and Simulation for the I-15 Corridor in San Diego, California

Post-Deployment Assessment Report

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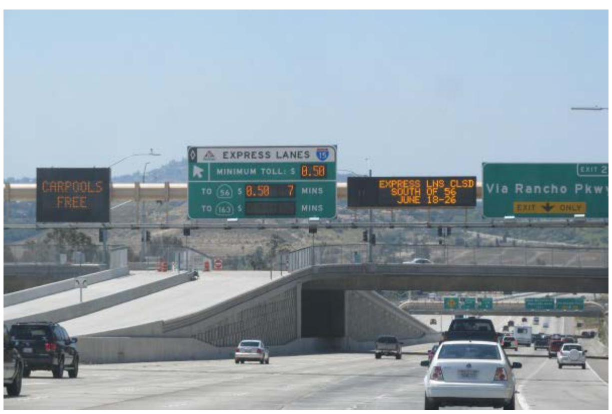

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16. Abstract

The U.S. Department of Transportation Integrated Corridor Management (ICM) Initiative aims to advance the state of the practice in transportation corridor operations to manage congestion. Through the deployment of ICM at the two selected Demonstration Sites (Dallas, Texas and San Diego, California), this initiative thoroughly investigated and documented the impacts of the ICM deployments, especially in regards to improved agency coordination. Analysis, Modeling and Simulation (AMS) efforts assisted corridor partners to optimize their ICM deployment, and supported the broader evaluation effort for the entire ICM Initiative. Using AMS enabled corridor partners to identify the strategies to include in their ICM System that would be most effective against their specific corridor congestion issues, by providing measureable results for multiple alternatives. The focus of this ICM Post-Deployment assessment is to investigate the impacts of the ICM system in its "as deployed" state on I-15 in San Diego, using AMS tools and techniques developed and refined under both the current and previous phases of the program.

The localized ICM strategies deployed include an active decision support system, coordinated incident management, freeway coordinated ramp metering, improved multi-modal traveler information, upgrades to selected traffic signal systems, and active arterial routing. A framework of the key activities required for post-deployment AMS, namely model enhancements, model calibration and validation, cluster analysis and incident matching, and alternatives analysis, is presented. Mobility performance results for the site's peak directions of travel indicate an expected annual savings of 267,850 person hours, while expected cumulative annual variability improvements amounted to 188,816 hours.

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Executive Summary

The objective of the *Integrated Corridor Management (ICM)* initiative is to demonstrate how intelligent transportation systems (ITS) technologies can efficiently and proactively manage the movement of people and goods in major transportation corridors. In the context of this ICM initiative, a "corridor" refers to a largely linear geographic band defined by existing and forecasted travel patterns involving both people and goods. The corridor serves a particular travel market (or markets) that are affected by similar transportation needs and mobility issues. The corridor includes various combinations of facility type and mode, also known as networks (e.g., limited access facilities, surface arterials, transit, bicycle, pedestrian pathways, waterways, etc.) that provide similar or complementary transportation functions. Additionally, the corridor includes cross-network connections that permit the individual networks to be readily accessible from each other. The ICM initiative aims to pioneer innovative multimodal and multijurisdictional strategies and combinations of strategies that optimize existing infrastructure to help manage recurring and nonrecurring congestion in our nation's corridors.

Through the deployment of ICM at the two selected Demonstration Sites (Dallas, Texas and San Diego, California), this initiative thoroughly investigated and documented the impacts of the ICM deployments. Analysis, Modeling and Simulation (AMS) efforts assisted corridor partners to optimize their ICM deployment and supported the broader evaluation effort for the entire ICM Initiative. Using AMS enabled corridor partners to identify the strategies to include in their integrated corridor management system (ICMS) that would be most effective against their specific corridor congestion issues, by providing measureable results for multiple alternatives. A key benefit of using AMS is its ability to produce system level assessments of mobility and environmental impacts that cannot be observed directly from field data.

The focus of this ICM Post-Deployment assessment is to evaluate to what extent ICM technologies can efficiently and proactively manage the movement of goods and people in a major transportation corridor. Specifically, this project investigates the impacts of the ICM system in its "as deployed" state on Interstate 15 (I-15) in San Diego, using AMS tools and techniques developed and refined under both the current and previous phases of the program. Results from traveler behavior surveys conducted in the vicinity of the I-15 corridor by the Volpe Center were used to inform model assumptions and to enable more accurate representation of true driver behaviors on I-15.

The San Diego ICM Demonstration site corridor covers a 21 mile section of I-15 from just north of State Route (SR) 52 in the City of San Diego to SR 78 in the City of Escondido. As one of two major freeways that connect commuters and interregional goods movement between San Diego, Orange and Riverside counties and people traveling to and from Mexico, the I-15 is one of the busiest sections of freeway in the region. The Corridor study area includes the freeway, ramp metered interchanges, 20 miles of continuous Express Lanes (otherwise known as managed lanes) – 16 miles which are reversible, a bus rapid transit (BRT) line that runs on the I-15 Express Lanes, BRT stations, direct access ramps, major arterial streets, and ITS technologies.

Specific examples of practices the San Diego site team employed include:

- Provided corridor users with the operational condition of all corridor networks and components, such as travel times, incident information, and expected delays using changeable message signs (CMS), a new 511 app, and other commercial travel time information sources.
- Used a decision support system with real-time simulation, predictive algorithms, and analysis to evaluate potential congestion mitigation and select/implement the optimal combination of mitigation strategies for the corridor.
- Established, improved, and automated joint agency action plans for traveler information, traffic signal timing, ramp metering, transit and Express Lanes (or managed lanes).
- Identified means of enhancing corridor management across all networks, including shared control multi-jurisdictional coordination of field devices such as lane controls, traveler information messages, traffic signal timing plans, and transit priority.

The ICM strategies implemented in the "as-deployed" ICM system, which were replicated in the models used for post-deployment AMS include:

- Active Decision Support System;
- Coordinated incident management;
- Freeway coordinated ramp metering;
- Actionable traveler information (en-route and pre-trip via CMS, a new 511 app, and other commercial sources);
- Upgrades to selected traffic signal systems (new traffic signal coordination timings, responsive traffic signal control); and
- Alternate route wayfinding signs.

The AMS serves to assess the performance of various components of the ICM system under different operational conditions (e.g., time of day, direction of traffic, duration until the incident was cleared, etc.). Cluster analysis was used to group together workday travel characteristics between March 1, 2012 and February 28, 2013 in days where operational conditions were more similar to each other, than to those in other groups (clusters). Clusters were prioritized based on the total magnitude of expected incident impact for representative days in each cluster. The clusters in the northbound PM peak and southbound AM peak periods were of primary interest for ICM AMS because they reflect the periods of highest traffic demands. Field observed incidents that occurred in the year after ICM deployment were matched to high-impact clusters sharing similar operational conditions. Eight scenarios, representing the top eight high-impact clusters were analyzed "with" and "without" ICM. One additional hypothetical scenario was also analyzed in order to evaluate the impact of one of the managed lane strategies (i.e., opening the Express Lanes to all travelers in the event of a severe incident).

Key Findings

Overall, the I-15 corridor post-deployment AMS results show consistent travel time improvements in the two peak directions as a result of ICM implementation. The weighted average of travel time beneficiaries in the northbound PM aggregated scenario is +2.65%; in the southbound PM aggregated scenario the weighted average of travel time beneficiaries is +4.01%. For the two peak directions combined (southbound AM and northbound PM), the expected daily travel time savings are 1,403 person hours of travel; expected annual savings are 267,850 person hours of travel.

The post-deployment AMS results for the I-15 corridor generally show travel time reliability and variability improvements during both peak directions; the expected cumulative annual travel time variability improvement is 188,816 hours.

A hypothetical AMS exercise examined the potential benefit of opening the Express Lanes to all traffic during a severe incident. No travel time benefits were found in AMS resulting from this potential action for the scenario analyzed. Overall, in six out of the eight scenarios (excluding the hypothetical scenario), more travelers benefited from ICM, compared to the ones who did not.

A key benefit of using AMS is its ability to focus on system level assessments of mobility and environmental impacts that cannot be observed directly from field data; this information will be used to support of the broader Integrated Corridor Management evaluation effort. The scenarios used in alternatives analysis were chosen to fill in missing elements where observed data could not be used to make meaningful condition-to-condition comparisons, as well as to calculate unobservable system-level impacts.

Lessons Learned

The ICM methodology encourages transportation professionals to manage the transportation corridor as a multimodal system, as opposed to managing individual assets. The San Diego ICM demonstration involved the coordination of operations along the I-15 corridor, including increased communication and coordination among partner agencies, facilitated by the deployment of an interagency-dependent decision support system (DSS). AMS aids in the broader goals of ICM Evaluation by providing a framework that can be used to quantify potential and actual benefits of localized ICM strategies. Unlike traditional corridor studies, which often focus on a specific element of a corridor, ICM AMS is a comprehensive approach that analyzes different operational conditions across time and modes and across a large enough geographic area to absorb all impacts.

One major benefit of the ICM AMS methodology is that it instigated the use of performance measures to inform and refine the response plans. This allowed AMS to provide insights through measurable results, a major factor that can help agencies determine which transportation investments are worthwhile. AMS allows agencies to “see around the corner”, producing simulations of possible future conditions, allowing agencies to react proactively. AMS offers the flexibility of trying different combinations of traffic mitigation strategies, opening up an envelope of potential benefits. Transportation professionals can integrate the AMS methodology with ICM decision support systems to facilitate predictive, real-time, and scenario-based operational decision-making. Overall, this helps agencies create a better, more informed product.

Chapter 1. Introduction and Background

The objective of the *Integrated Corridor Management (ICM)* initiative is to demonstrate how intelligent transportation systems (ITS) technologies can efficiently and proactively manage the movement of people and goods in major transportation corridors. In the context of this ICM initiative, a "corridor" refers to a largely linear geographic band defined by existing and forecasted travel patterns involving both people and goods. The corridor serves a particular travel market (or markets) that are affected by similar transportation needs and mobility issues. The corridor includes various combinations of facility type and mode, also known as networks (e.g., limited access facilities, surface arterials, transit, bicycle, pedestrian pathways, waterways, etc.) that provide similar or complementary transportation functions. Additionally, the corridor includes cross-network connections that permit the individual networks to be readily accessible from each other. The ICM initiative aims to pioneer innovative multimodal and multijurisdictional strategies and combinations of strategies that optimize existing infrastructure to help manage both recurring and nonrecurring congestion in our nation's corridors. There are many corridors in the country with underutilized capacity in the form of additional transit capacity—bus, rail, bus rapid transit (BRT), etc.—under saturated parallel arterials, and inefficient utilization of principal facility resources. Each of these corridors could benefit from the application of ICM technologies and strategies.

The maturation of ITS technologies, growing availability of supporting data, and emerging multiagency institutional frameworks make ICM both practical and feasible. Several freeway, arterial, and transit optimization strategies are in widespread use across the United States, with most currently managed by individual local agencies on an asset-by-asset basis. For those that are managed by a larger regional agency, the approach is still generally uncoordinated and involves little or no integration among the different resources available on the corridor. By appropriately applying ICM strategies, the agencies responsible for managing these corridors can reduce severe congestion and improve overall productivity. Furthermore, providing travelers with relevant information on transportation alternatives can encourage a redistribution of trips to less congested routes, modes, or times of day, which further reduces congestion and affords travelers a greater mobility and increased safety.

Through the deployment of ICM at the two selected Demonstration Sites (Dallas, Texas and San Diego, California), this initiative thoroughly investigated and documented the impacts of the ICM deployments, especially in regards to improved agency coordination. Getting as many corridor partners and stakeholders (e.g., roadway agencies, transit agencies, law enforcement, planning organizations, fleet operations, project evaluators, corridor travelers, etc.) involved in the design of the ICM from the very beginning adds significant value to the project—from adding precision to the design and informing travel demand modelers, to proactively addressing agency regulations. The role of Analysis, Modeling and Simulation (AMS) is to enable corridor partners to identify the strategies to include in their integrated corridor management system (ICMS) that will be most effective against their localized corridor congestion issues, by providing measureable results for multiple alternatives. The AMS methodology was applied to the ICM deployments in both Dallas and San Diego. A key benefit of using AMS is its ability to focus on system level assessments of mobility and environmental impacts that cannot be observed directly from field data; this information will be used to support of the broader evaluation effort.

Based on the experience gained from the ICM deployments at the Dallas and San Diego Demonstration Sites, the ICM initiative developed an AMS methodology to assist corridor managers in forecasting and assessing the potential benefits and implications of ICM in their corridors of interest. The ICM AMS Guide has been incorporated into the Federal Highway Administration (FHWA) Traffic Analysis Toolbox (Volume XIII). The AMS approach is intended to be a flexible and iterative process adaptable to a wide variety of conditions, strategies, and situations. This flexibility is intended to provide practitioners with sufficient structure to enable a rigorous analysis suitable to complex strategies that at the same time is not so rigid as to limit the ability to restructure and rerun the analysis to address project contingencies as they occur. The AMS approach is designed to be implemented in conjunction with the ICM system development and design process and to provide a tool for continuous improvement of corridor performance as depicted in Figure 1. This ICM implementation process is generally representative of the Systems Engineering process followed by the ICM Demonstration Sites. Regular periodic conduct of ICM AMS also supports continuous improvement of the supporting ICM system, and the analysis tools themselves.

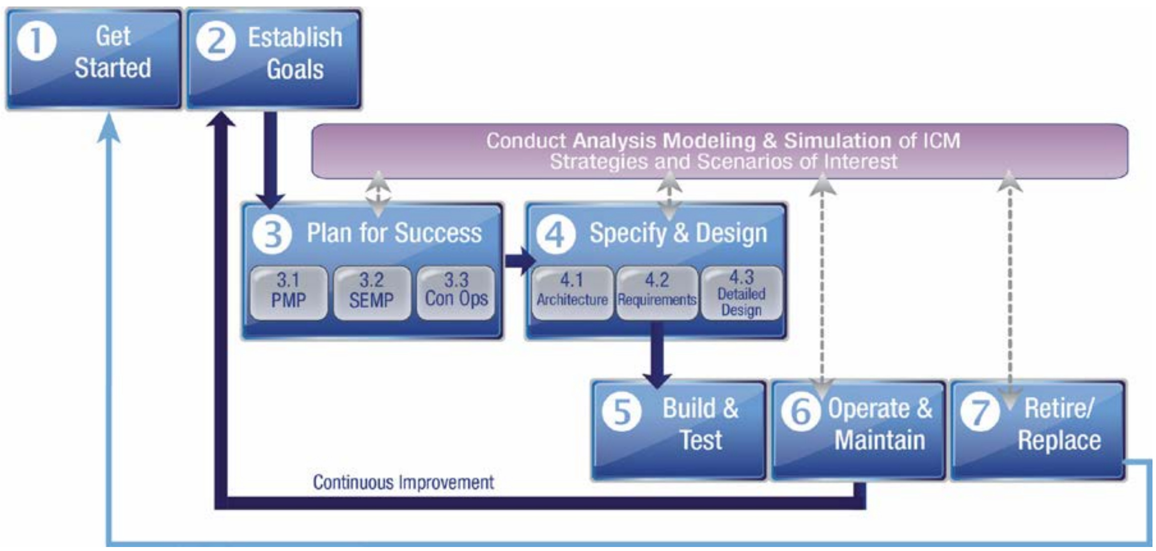

Figure 1. Flowchart. Integrated Corridor Management implementation process.
(Source: Office of the Assistant Secretary for Research and Technology, ITS JPO.)

The United States Department of Transportation (US DOT) has published multiple reports throughout the ICM initiative which can be used as references to aid transportation professionals in implementing their own ICM projects. In addition to the subset of reports listed below which are currently available, reports covering analytical and institutional lessons learned and the broader Evaluation Report will also be published.

- "Integrated Corridor Management Analysis, Modeling and Simulation (AMS) Methodology"
- "Traffic Analysis Toolbox Volume III: Guidelines for Applying Traffic Microsimulation Modeling Software"
- "Traffic Analysis Toolbox Volume XIII: Integrated Corridor Management Analysis, Modeling, and Simulation Guide"
- "Integrated Corridor Management: Implementation Guide and Lessons Learned"

- “Operations and Maintenance Plan for the I-15, San Diego Integrated Corridor Management (ICM) Demonstration Project”
- “ICM Stage 2 Data Collection Plan for the I-15 Corridor in San Diego, California”
- “I-15 San Diego, California ICM AMS Analysis Plan”
- “U.S. 75 Dallas, Texas, ICM AMS Analysis Plan”
- “I-394 Minneapolis, Minnesota, ICM AMS Analysis Plan”
- “I-15 San Diego, California, Model Validation and Calibration Report”
- “U.S. 75 Dallas, Texas, Model Validation and Calibration Report”
- “I-394 Minneapolis, Minnesota ICM AMS Model Calibration and Validation Report”
- “Integrated Corridor Management Modeling Results Report: Dallas, Minneapolis, and San Diego”
- “Stage 3A Analysis, Modeling, and Simulation for the I-15 Corridor in San Diego, California: Final Pre-Deployment Analysis Plan”
- “Stage 3A Analysis, Modeling, and Simulation for the I-15 Corridor in San Diego, California: Pre-Deployment AMS Assessment Report”
- “Analysis, Modeling, and Simulation for the I-15 Corridor in San Diego, California: Post-Deployment Analysis Plan”
- “Integrated Corridor Management Initiative: Traveler Response Panel Survey – San Diego”

As the AMS process continues in parallel with the ICM system development and design process, it is likely that new strategies, alternatives and scenarios will emerge that will need to be evaluated within the AMS process; therefore, the flexibility to foresee and account for several iterations of analysis is critical. The design process may reveal new strategies or alternatives that may need to be analyzed in the AMS, prompting modifications to the AMS structure. Likewise, the AMS process may reveal parts of the concept of operations that are unworkable or uncover opportunities that may be leveraged that result in changes to the ultimate ICM design.

The advanced analysis capabilities of the AMS approach provides practitioners with enhanced opportunities to conduct detailed alternatives analysis to identify optimal combinations of strategies and to test and refine how the strategies may be most optimally implemented. Due to the complexity and resources required of the AMS, this level of analysis is typically most appropriate in the later planning stages after the preliminary screening of alternatives has winnowed out a smaller set of strategies and alternatives to be evaluated. The AMS will often continue through the design phase—being used to fine-tune strategies in an iterative function as the realities of the design process progress or to assess the impacts of sequencing the improvements to identify the optimal deployment phasing of the strategies.

The focus of this ICM Post-Deployment assessment is to evaluate to what extent ICM technologies can efficiently and proactively manage the movement of goods and people in a major transportation corridor. Initially, the discussion on performance-driven corridor management among the participating ICM Pioneer Sites was focused on measures derived from observed data. In the AMS phase of the effort however, attention turned to producing comparable measures derived from the outputs of different traffic simulation tools. This enabled hypothetical scenarios to be modeled, testing the impacts of potential ICM strategies before implementation and therefore reducing the chance of very expensive missteps in implementation.

This project investigates the impacts of the ICM system in its "as deployed" state in 2014 and 2015 on Interstate 15 (I-15) in San Diego, using AMS tools and techniques developed and refined under both the current and previous phases of the program. Results from traveler behavior surveys conducted in the vicinity of the I-15 corridor by the Volpe Center were used to inform model assumptions and to enable more accurate representation of true driver behaviors on I-15. The results of the post-deployment AMS were then used to assess and validate the estimated impacts resulting from the ICM deployment on I-15 in San Diego.

The following is a summary of additional project objectives used to support these overall goals:

- Develop a post-deployment AMS Plan in collaboration with the ICM Demonstration Site staff to promote coordination of analysis efforts and coherent alignment of goals among this effort, the ICM Demonstration Site staff, and the ICM Evaluation team.
- Support the objective evaluation efforts of the Demonstration Site staff and enhance the ability of the modeling tools to accurately represent the deployed ICM strategies by identifying and facilitating improvements to AMS tools, techniques, and inputs.
- Manage the successful transition of modeling responsibilities from AMS Contractor to the ICM Demonstration Site staff and organizations, with workshops to promote the transfer of knowledge and technology.
- Support the integration of AMS tools and techniques into ongoing corridor management practices by the Demonstration Site staff.
- Provide technical documentation of AMS tool development, data sources, data processing methods, model calibration and validation procedures, and analysis techniques used to represent and evaluate ICM impacts.

One aspect of the ICM program is the enhancement of analytical techniques and tools to support ICM impact assessment. In an effort to advance ICM impact assessment, the main objective for the AMS team within the ICM Initiative was to refine AMS tools and strategies, assess the Pioneer Sites' data capabilities, conduct AMS for a subset of the ICM Pioneer Sites, and conduct pre- and post-demonstration evaluations using AMS tools.

The AMS methodology applied to the Dallas and San Diego Demonstration Sites were documented in FHWA's "Traffic Analysis Toolbox Volume XIII: Integrated Corridor Management Analysis, Modeling and Simulation Guide". This guide is used to assist corridor managers in forecasting and assessing the potential benefits and implications of ICM in their corridors of interest. The ICM AMS methodology is rooted firmly in the US DOT's established modeling guidelines and frameworks, as defined in the FHWA Traffic Analysis Toolbox. Unlike traditional corridor studies, which often focus on a specific element of a corridor (i.e., a freeway or freeway and frontage road during a specific time of day), ICM AMS is a comprehensive approach that analyzes different operational conditions across time and modes and across a large enough geographic area to absorb all impacts.

The following items outline the key roles of AMS in the ICM Program:

- Identifying when and where ICM strategies will be the most beneficial;
- Assists in forecasting and assessing the potential implications of ICM;
- Developing methodologies that support the process for continuous improvement;
- Supporting the ICM Evaluation;

- Enables agencies to understand system dynamics at the corridor level; and
- Developing the analytical capital within each site so that the analyses can be conducted on a regular basis to support ICM decision-making (either in planning mode or Decision Support System (DSS) mode).

The post-deployment scope of work for the AMS team includes:

- Project Management and Program Support
- Develop Analysis Plans
- Enhance Tools to Reflect As-Deployed Corridor Management
- Tool Calibration – Reasonableness Assessment
- Conduct Post-Deployment Alternatives Analysis
- Post-Deployment AMS Assessment Reports and Briefings
- Support AMS Transfer to Site
- Update AMS Guide
- AMS Knowledge and Technology Transfer

This *Post-Deployment ICM AMS Assessment Report for the I-15 Corridor* outlines the core tasks associated with the realization of the project goals and objectives described earlier. The organization of this report is as follows:

- **Chapter 2** provides a brief description of the I-15 Corridor in San Diego, California.
- **Chapter 3** provides an overview of the innovative I-15 ICMS and corresponding response plans.
- **Chapter 4** describes the ICM strategies comprising the ICM deployment on the corridor.
- **Chapter 5** describes the AMS methodology applied to the corridor.
- **Chapter 6** describes the performance measures used in the AMS.
- **Chapter 7** details the post-deployment AMS approach to model enhancements and model calibration and validation.
- **Chapter 8** summarizes main findings from alternatives analysis and the significant benefits of AMS.

Chapter 2. I-15 Corridor Description

The Interstate 15 (I-15) study corridor in San Diego, California, extends from State Route (SR) 52 at its southern end to SR 78 at its northern end, for an overall length of approximately 20 miles. Along this freeway corridor are arterials with the following interchanges with the freeway:

- Centre City Parkway;
- Pomerado Road;
- Rancho Bernardo Road;
- Camino Del Norte Road;
- Ted Williams Parkway (SR 56);
- Black Mountain Road; and
- Scripps Parkway.

The I-15 corridor in San Diego has been utilized as a test bed for various intelligent transportation system (ITS) strategies identified in consultation with the San Diego Association of Governments (SANDAG), the metropolitan planning organization who is responsible for transportation planning in the region and the lead for San Diego's Integrated Corridor Management (ICM) initiative, and other local stakeholders. The strategies incorporated into the deployed ICM system are described in greater detail in Chapter 4. The following sections provide an overview of the study corridor.

In San Diego, the I-15 freeway carries eight to 10 lanes of traffic and functions as an important link between the urban core of San Diego and suburban cities to the northeast, including Poway, San Diego, and Escondido, making it a heavily used commuter link between northern San Diego County and major employment centers to the south. It is one of three major north-south transportation corridors in San Diego County and is the principal inland route, serving local, regional, and interregional trips. The route is part of a major interregional goods movement corridor, as it connects Mexico to the south with Riverside County, San Bernardino County, and Las Vegas, Nevada, to the north. As of December 2011, average weekday traffic volumes ranged from 170,000 to 290,000 vehicles on the general purpose lanes of I-15, with approximately 20,000 additional vehicles using Express Lanes. The peak direction of travel is southbound in the morning and northbound in the afternoon. Public transportation along the corridor includes bus rapid transit (BRT) that runs on the I-15 Express Lanes, and local bus transit lines that run on the neighboring arterials.

Recent population and housing growth in southwestern Riverside County, one of the fastest growing areas in California, has resulted in significant interregional commuter travel into San Diego County on I-15. Likewise, increasing commercial traffic moving to and from the Otay Mesa and Inland Empire commercial vehicle operations gateways have significantly impacted traffic on the corridor. Due to geographic/land use constraints, a lack of contiguous parallel roadways, and the limited number of alternative routes, peak-period delays are further exacerbated by incidents, special events, and/or inclement weather. Future (year 2020) forecasts for the I-15 corridor indicate a 30 percent increase in weekday traffic, which will result in even longer corridor delays and travel times. Corridor travel is anticipated to increase significantly in what are now non-peak travel directions.

Figure 2 and Figure 3 provide geographic context for the corridor and indicate the extent of the study area. Figure 2 displays three separate segments along the I-15 corridor: North Segment (pink), Middle Segment (orange) and South Segment (green), which indicates the phased construction of the Express Lanes.

In anticipation of the growing traffic congestion along the I-15 corridor, SANDAG, has continually worked with its regional partners to improve mobility along the corridor. These efforts, such as the opening of two-lane reversible Express Lanes in 2012 and continued construction of transit stations and direct access ramps (allowing buses and high-occupancy vehicles (HOV) to directly access the Express Lanes without yielding to traffic in the general purpose lanes), have been carried out in parallel with the design and implementation of the integrated corridor management system (ICMS). The Express Lanes are being operated in a 2+2 configuration except on Thursday mornings where it uses a 3 southbound + 1 northbound configuration. California Department of Transportation (Caltrans) and SANDAG are currently assessing the performance of the corridor to determine whether other weekdays warrant additional configuration changes. BRT operation in the Express Lanes helps increase traffic capacity, while dynamic variable pricing helps manage traffic flow. This ITS infrastructure, along with existing road sensors, cameras, dynamic ramp metering, adaptive control on roads parallel to the interstate, and systems which can disseminate incident information, made the I-15 corridor an ideal ICM test bed environment.

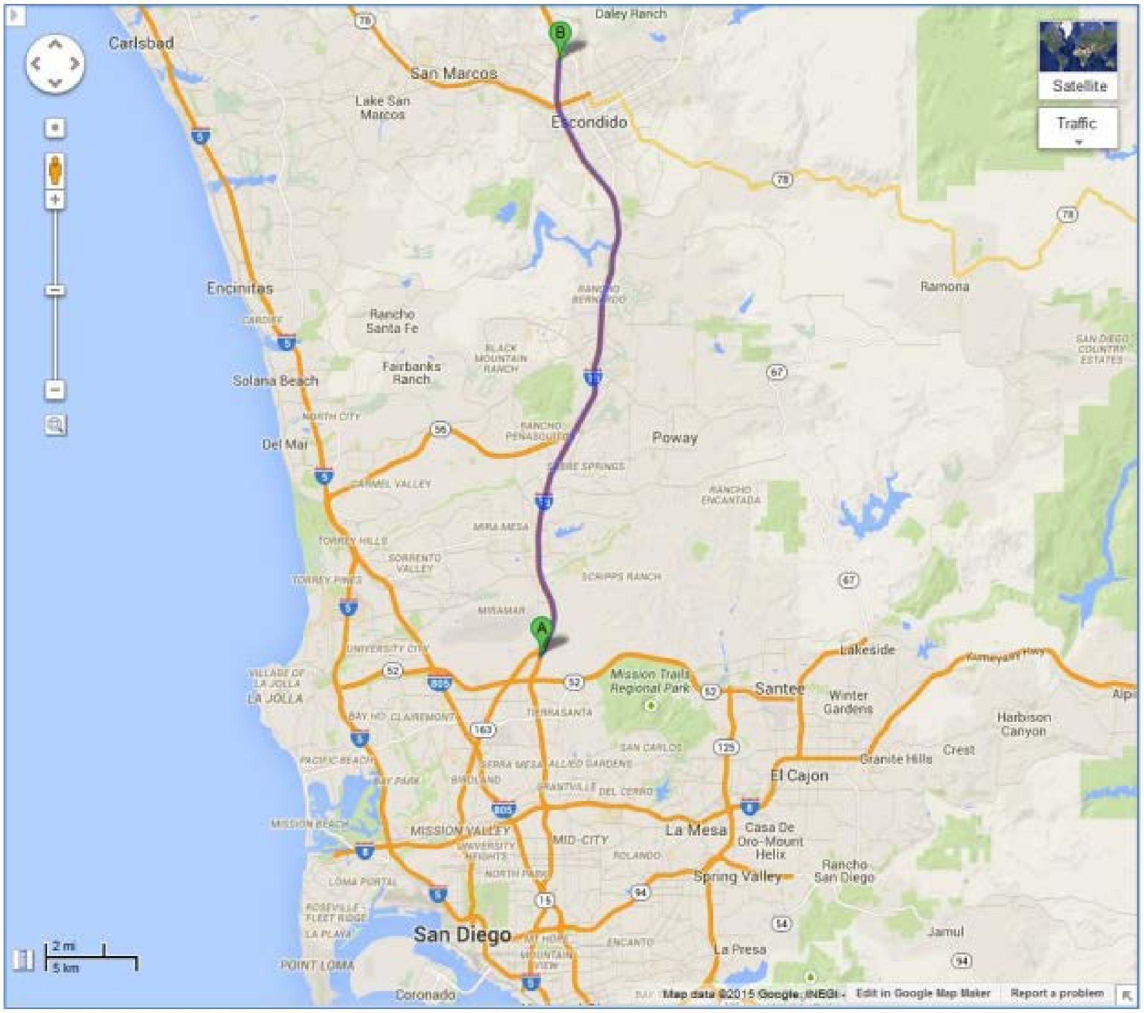

Figure 2. Map. Location and geographic boundaries of corridor.
(Source: San Diego I-15 Demonstration Integrated Corridor Management System PATH Report on Stage 3: Site Demonstration and Evaluation, UCB-ITS-PRR-2015-03, p. 15.)

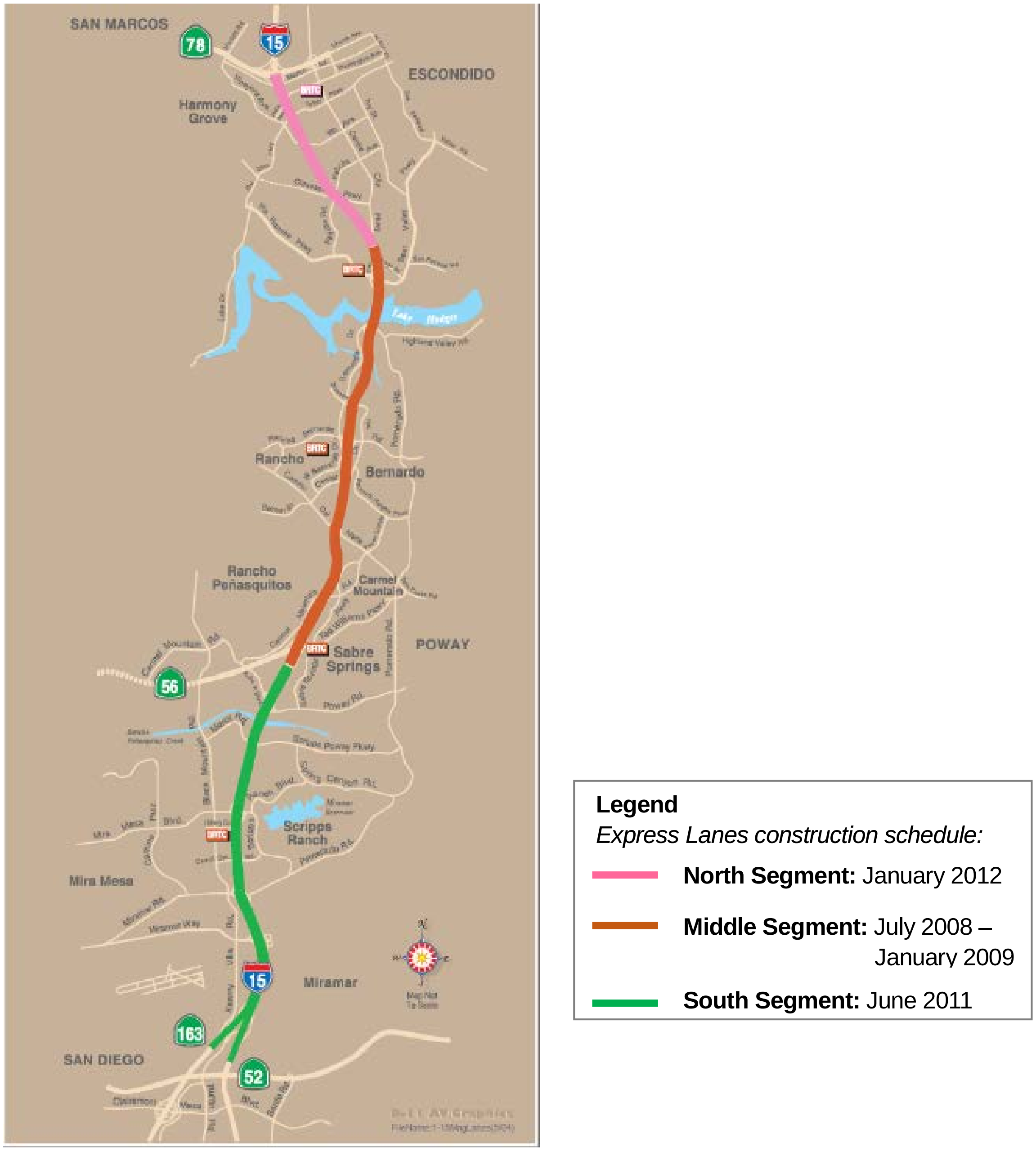

Figure 3. Map. Study area I-15 corridor in San Diego, California.
(Source: Scope and Summary: I-15 ICMS Corridor in San Diego, U.S. Department of Transportation.)

Chapter 3. Integrated Corridor Management System and Response Plans

The San Diego Interstate (I-15) Integrated Corridor Management system (ICMS) integrated existing systems with new or updated systems. The ICMS system design can be seen in Figure 4. The ICMS consists of the following key components: 1) Data Hub – collection of external systems operated by corridor stakeholder agencies providing data to the ICMS and/or receiving control requests from the system via a standardized regional communication network called the Intermodal Transportation Management System (IMTMS); 2) Decision Support System (DSS) – tool to help system operators identify incidents and implement response plans aimed at minimizing the impacts of identified incidents on corridor operations; and 3) System Services – services to assist with data management, system management, system maintenance, and training activities (e.g., ICMS data stores, corridor performance management).

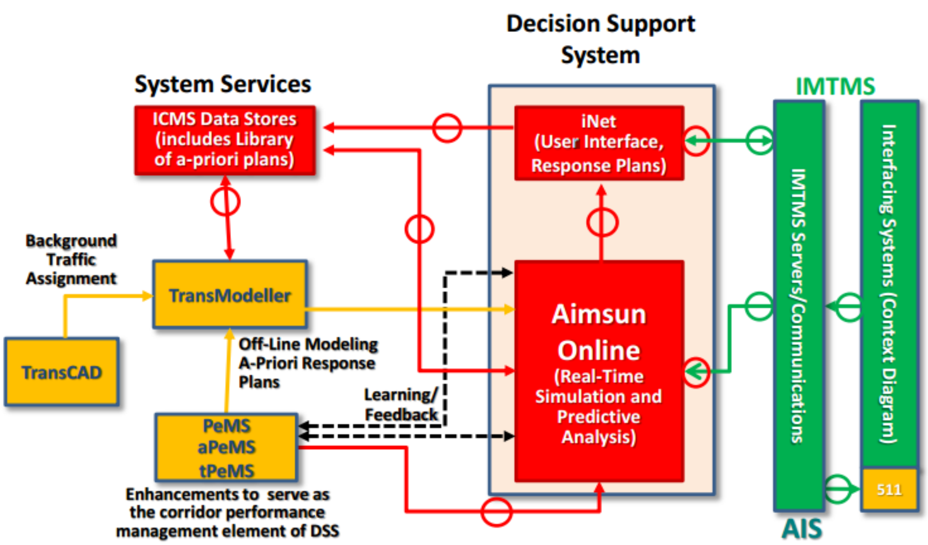

Figure 4. Diagram. San Diego I-15 Integrated Corridor Management system design.
(Source: ITS 3C Summit San Diego I-15 Integrated Corridor Management System presentation, 9/16/14, unpublished.)

As shown in Figure 5, the ICMS interfaces with a variety of systems (color coded based on facility type/functionality) that are managed by different agencies, including freeway systems in turquoise – Lane Closure System, Ramp Meter Information System, Advanced Traffic Management System, Congestion Pricing System, Express Lanes Control System; arterial systems in yellow – Regional Arterial Management System; transit systems in lavender – Regional Transit Management System, Smart Parking System); public safety in purple – Regional Event Management System; and advanced traveler information systems (ATIS) in orange – Arterial Travel Time System, Traveler Information Systems, Weather Information System.

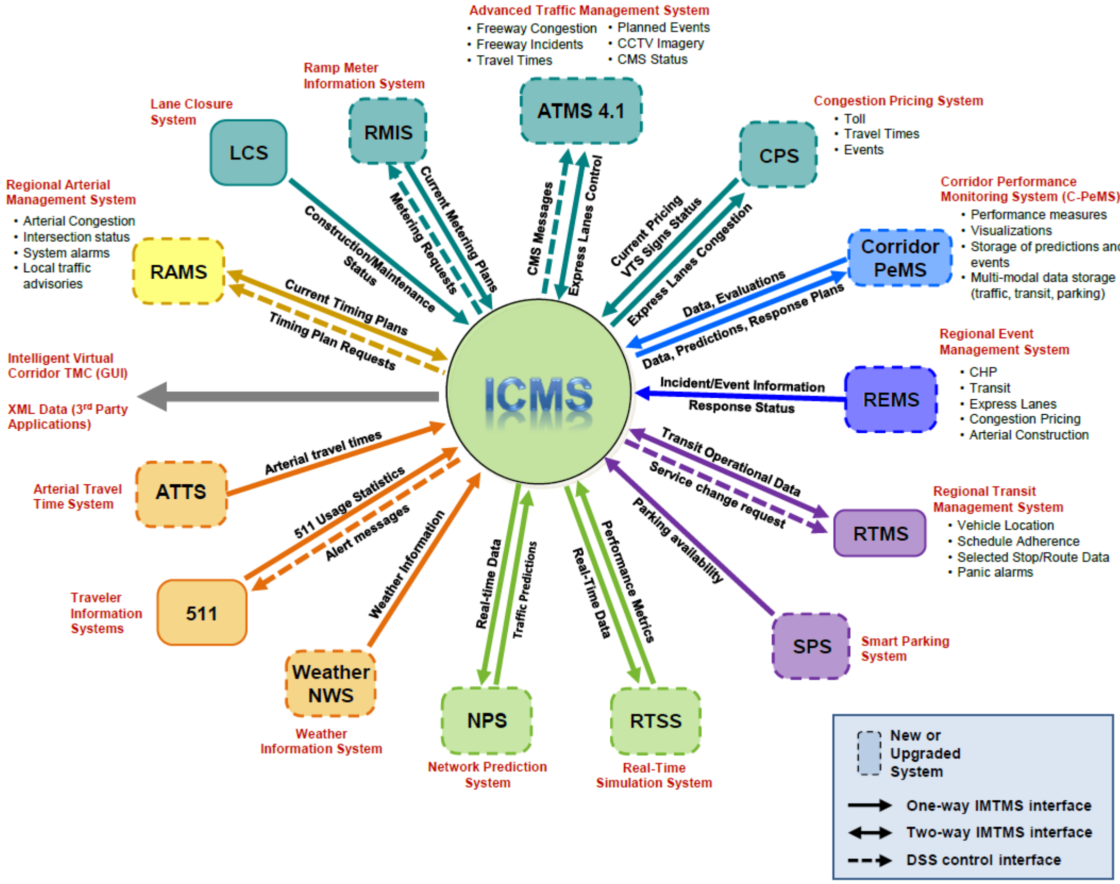

Figure 5. Diagram. San Diego I-15 Integrated Corridor Management system inputs and outputs.
(Source: San Diego I-15 Demonstration Integrated Corridor Management System PATH Report on Stage 3: Site Demonstration and Evaluation, UCB-ITS-PRR-2015-03, p. 32.)

The innovative element of the DSS lies in its ability to forecast and simulate corridor performance issues using near real-time simulation and continuous predictive analysis, promoting proactive courses of action for recurrent and non-recurrent conditions (e.g., bottlenecks, incidents) which are coordinated among *all* corridor stakeholders. While the existing IMTMS network already facilitated decision-making by enabling interagency information sharing, it did not offer the functionality needed to integrate this information into actionable traffic control strategies. The DSS filled this gap by providing improved data fusion capabilities and a new decision-making process capable of generating (automatically or semi-automatically) multimodal response plans to events affecting corridor operations. The multimodal DSS, shown in the Decision Support System component in Figure 4, or the green Network Prediction System and Real-Time Simulation System in Figure 5, integrates two tools: 1) iNET – an automatic traffic management system for field device monitoring and control, center-to-center data fusion, event management and response plan generation; and 2) Aimsun Online – for real-time traffic prediction and simulation-based evaluation of incident response or congestion management strategies. When responding to an event, the DSS continues to monitor travel conditions within the corridor and issues updated recommendations when necessary, allowing the DSS to account for unforeseen changes in travel patterns or other events affecting corridor operations *in addition* to the original event.

Roles and responsibilities have been diligently defined for all agencies/entities involved (e.g., San Diego Association of Governments (SANDAG); California Department of Transportation (Caltrans); City Traffic Divisions of San Diego, Poway, and Escondido; Metropolitan Transit System (MTS) and North County Transit District (NCTD) transit agencies; California Highway Patrol (CHP); local first responders and law enforcement, county emergency services) for the following scenarios:

- Daily operations;
- Freeway incidents;
- Arterial incidents;
- Transit incidents;
- Special event; and
- Disaster response scenarios.

As shown in Figure 6, San Diego stakeholders organized response "postures" around a combination of demand conditions on the network (light, moderate, or heavy) and predicted event impact (low, medium, or high). Within this framework, organized as a matrix, they then determined whether they would be likely to take "conservative," "moderate" or "aggressive" measures to manage the impacts of an event. They coded their joint response plans accordingly.

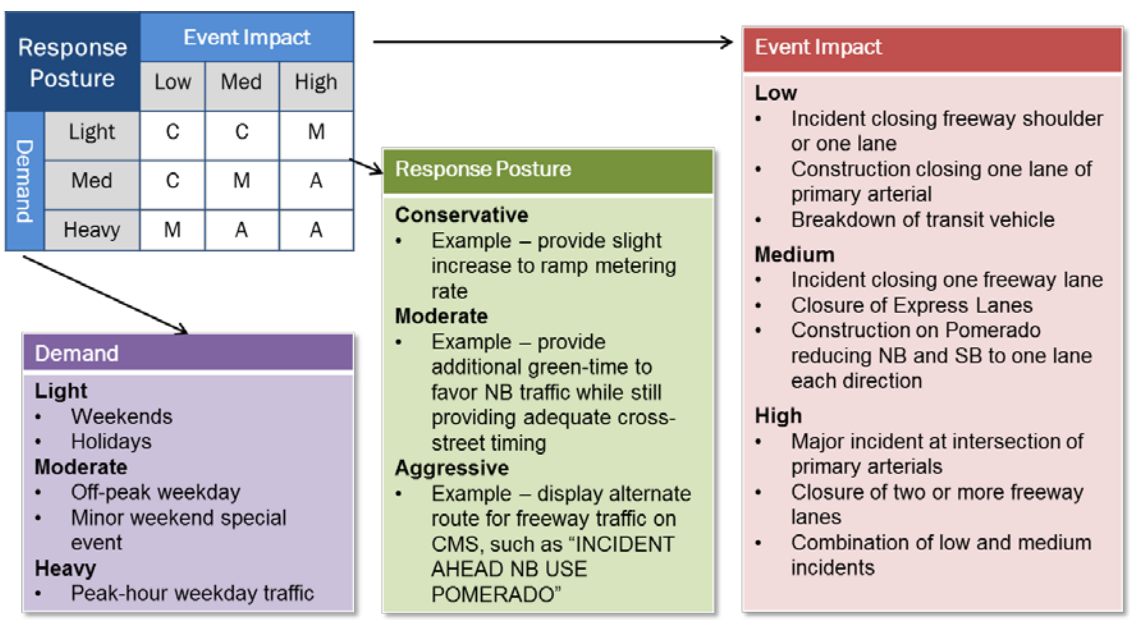

Figure 6. Diagram. I-15 Integrated Corridor Management response postures.
(Source: San Diego Association of Governments, 3/6/14.)

The San Diego DSS is dynamic, meaning there is no "set number" of defined response plans that could be recommended by the DSS. Figure 7 and Figure 8 show how a combination of subsystem action plans are used to define an individual response plan based on agreed upon response posture responsiveness. Between the 156 alternate routes, 260 local arterial intersections, 18 ramp metered interchanges, 20 changeable message signs (CMS), five bus rapid transit (BRT) stations (with six extra buses in the metro area for adding transit capacity when needed), 20 miles of Express Lanes (16 miles which are reversible using a movable barrier) and 30 miles of traffic-responsive 511 within the study area, this provides enough assets that can be combined to generate *billions* of different response plans. However, the DSS is limited to recommending no more than 15 response plans at any time based on asset restrictions, availability conditions, and thresholds to select "next move" relationships. It should also be noted that response plans rely on how quickly field elements can be changed – e.g., the stakeholders are required to have time to actually implement recommended signal timing plans. The San Diego ICMS is capable of changing response plans every five minutes, but it is not practical to change these so frequently since it takes approximately 20 minutes to evaluate and implement (out in the field) a response plan. Although the San Diego DSS implements response plans without requiring human intervention, it does have the ability for a transportation operator to object to a recommended response plan and prevent it from being implemented.

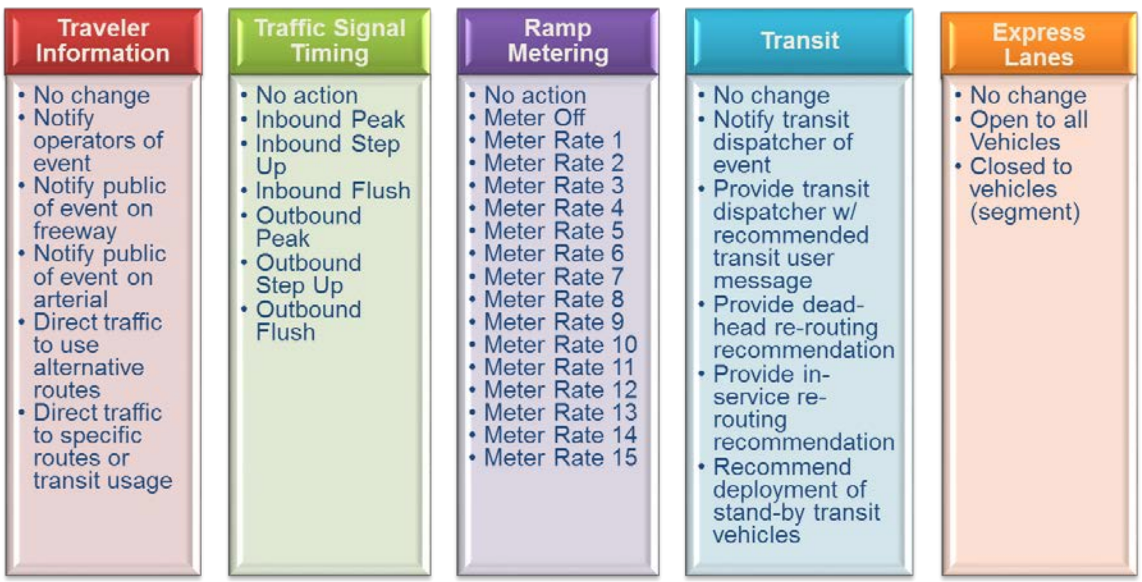

Figure 7. Diagram. I-15 Decision Support System defined subsystem action plans.
(Source: San Diego Association of Governments, 3/6/14.)

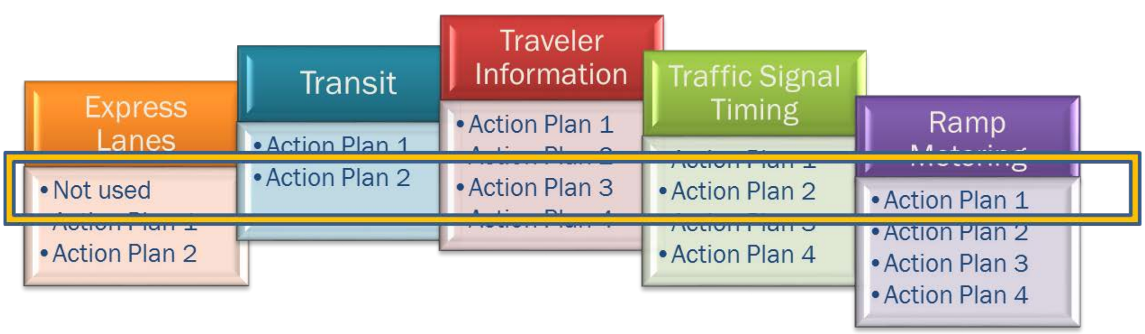

Figure 8. Diagram. I-15 Decision Support System multi-modal response plans.
(Source: San Diego Association of Governments, 3/6/14.)

Figure 9 shows an example of a response plan which was implemented at Rancho Bernardo Rd. during the northbound afternoon peak period for an event involving major congestion levels. This response plan triggered the following CMS message: "SLOWING AT // RANCHO BERNARDO // EXPECT DELAYS", ramp metering timing adjustments for two ramp meters, as well as traffic signal coordination timings for 15 signals in the cities of San Diego and Poway.

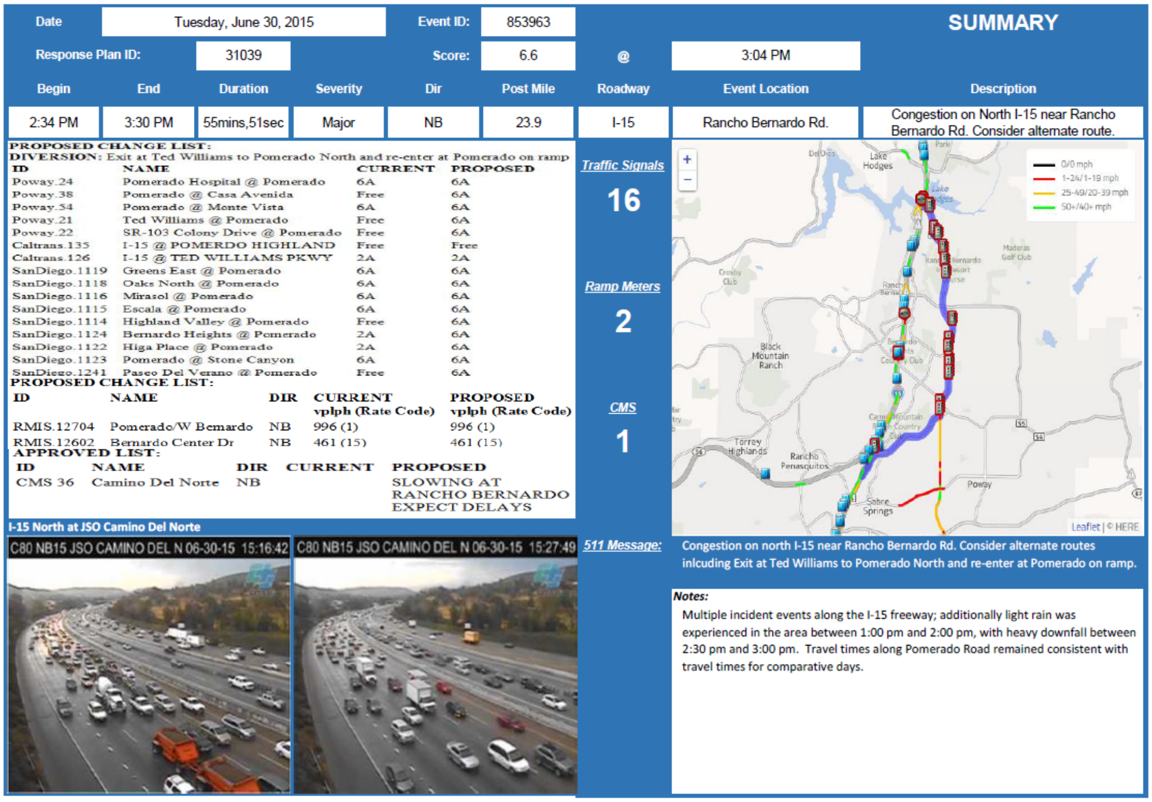

Figure 9. Illustration. Example response plan for northbound afternoon peak period congestion at Rancho Bernardo Rd.

(Source: I-15 ICM III – PDT Meeting #59, San Diego Association of Governments, 7/15/15, p. 28, unpublished.)

Chapter 4. Integrated Corridor Management Strategies

The San Diego Integrated Corridor Management (ICM) focuses on five primary ICM goals:

1. The corridor's multimodal and smart-growth approach shall improve accessibility to travel options and attain an enhanced level of mobility for corridor travelers.
2. The corridor's safety record shall be enhanced through an integrated multimodal approach.
3. The corridor's travelers shall have the informational tools to make smart travel choices within the corridor.
4. The corridor's institutional partners shall employ an integrated approach through a corridor-wide perspective to resolve problems.
5. The corridor's networks shall be managed holistically under both normal operating and incident/event conditions in a collaborative and coordinated way.

To achieve these goals, San Diego Association of Governments (SANDAG) and its partnering agencies used investments in intelligent transportation systems (ITS) to implement a "smart" transportation management system that combines road sensors, transit management strategies, video, and traveler information to reduce congestion. The smart system is expected to deliver information to commuters via the Internet and message signs, and enable managers to adjust traffic signals and ramp meters to direct travelers to high-occupancy vehicle (HOV) and Express Lanes, bus rapid transit (BRT), and other options.

Specific examples of practices the San Diego site team employed include:

- Provided corridor users with the operational condition of all corridor networks and components, such as travel times, incident information, and expected delays using changeable message signs (CMS), a new 511 app, and other commercial travel time information sources.
- Used a decision support system (DSS) with real-time simulation, predictive algorithms, and analysis to evaluate potential congestion mitigation and select/implement the optimal combination of mitigation strategies for the corridor.
- Established, improved, and automated joint agency action plans for traveler information, traffic signal timing, ramp metering, transit and Express Lanes.
- Identified means of enhancing corridor management across all networks, including shared control multi-jurisdictional coordination of field devices such as lane controls, traveler information messages, traffic signal timing plans, and transit priority.

Main components of the ICM deployment in San Diego included:

- A DSS that utilizes incoming monitoring data to assess conditions, forecast conditions up to 60 minutes in the future, and then formulate and evaluate proactively recommended response plans (including selecting from pre-approved plans) for consideration by operations personnel.
- The Intermodal Transportation Management System (IMTMS), an existing data acquisition and dissemination network within the San Diego region, which was enhanced using ICM funding to connect certain regional systems with the ICM System (ICMS).
- En-route and pre-trip traveler information using CMS, a new 511 app, and other commercial travel time information sources.
- Adjustments to ramp meter timing to support diversion to or from the freeway.
- Upgrades to selected traffic signal systems, including new traffic signal coordination timings and responsive traffic signal control on two arterial streets paralleling Interstate 15 (I-15), as well as on arterials connecting the freeway to parallel arterials (concept shown in Figure 10).
- Alternate route wayfinding signs with the aid of highway CMS to help diverted drivers return to the freeway downstream of the incident.

These components increased the number of different ICM action plan categories (e.g., traveler information, traffic signal timing, ramp metering, transit, and Express Lanes) are available to the DSS to be included in a response plan. The thresholds and performance elements behind each category triggers different action plans. The combination of action plans triggered from each category formulates a recommended response plan.

Additional infrastructure investments made outside of the ICM Initiative not only improved mobility along the I-15 corridor as an isolated system, but also worked to supplement the corridor-wide ICM strategies implemented. For example, the tracking technology that were installed on the BRT buses (gathers data on the speed, location and passenger loads) and additional traffic detectors that were installed on arterials helped to enhance the transit and arterial network information that is used for real-time simulation of traffic conditions.

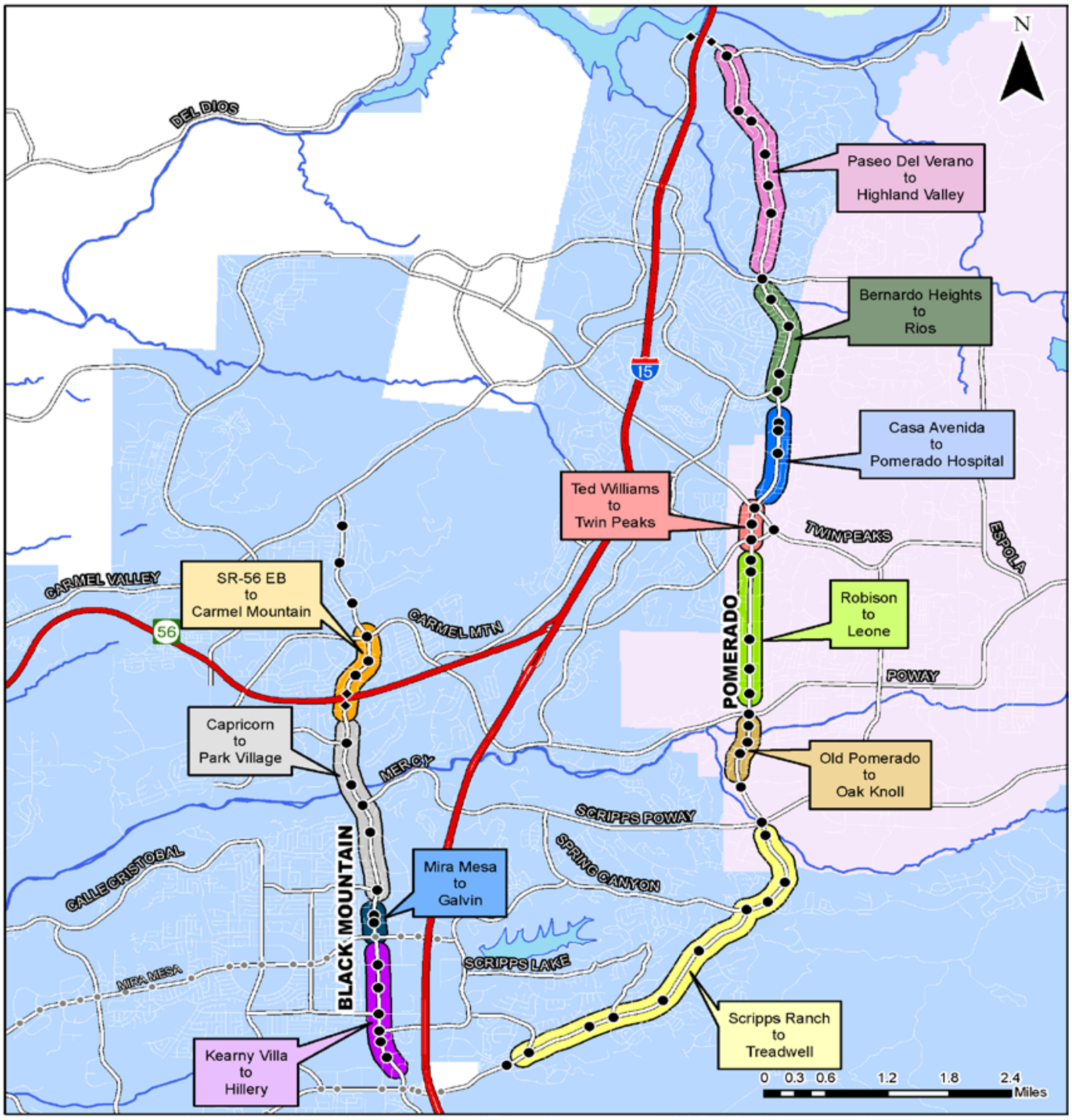

Figure 10. Map. I-15 responsive signal operations arterial groups.
(Source: Integrated Corridor Management Stage 3A Analysis, Modeling, and Simulation for the I-15 Corridor in San Diego, California Pre-Deployment AMS Assessment Report, FHWA-JPO-13-007, p. 56.)

Chapter 5. Analysis, Modeling and Simulation Methodology

The Analysis, Modeling and Simulation (AMS) methodology applied to the San Diego Demonstration Site was documented in the Federal Highway Administration's (FHWA) "Traffic Analysis Toolbox Volume XIII: Integrated Corridor Management, Analysis, Modeling, and Simulation Guide", a guide designed to help corridor stakeholders implement the Integrated Corridor Management (ICM) AMS methodology successfully and effectively. This guide provides a framework for developing an effective analysis plan to support selection and application of available tools and models specifically conducive to ICM.

Every tool type represents a tradeoff between geographic scope and level of resolution (scale versus complexity). Figure 11 shows the different types of analysis tools that can be incorporated into AMS. Less detailed tool types are tractable for large networks, while more detailed tool types are restricted to smaller networks. Depending on corridor size and the types of analyses required, all tool types are potentially valuable for ICM AMS. Microscopic simulation models, for example, are effective at analyzing system optimization strategies, such as freeway ramp metering and arterial traffic signal coordination, while mesoscopic simulation models are less effective, and travel demand models do not have this analysis capability. Travel demand models are better at estimating mode shift, but microscopic and mesoscopic simulation models are better at estimating route shifts. Mesoscopic tools can estimate regional dynamic diversion of traffic, while microscopic tools can estimate route shift at a smaller geographic scale. Finally, mesoscopic simulation tools are better at analyzing traveler responses to congestion pricing. The ICM AMS offers corridor managers greater capability than is available in any single existing tool.

Modeling Components

The approach used to model the Interstate 15 (I-15) ICM corridor integrated a range of proven AMS tools and ICM analysis resources to form a single coherent system that can be used for corridor planning, design, and operations. This involves combining tools with inherently different analysis resolutions— macroscopic-level simulations for modeling travel demand and microscopic-level simulations for modeling detailed driver behavior—to evaluate a variety of ICM strategies and scenarios.

For AMS of the I-15 corridor, macroscopic models were used to produce Origin-Destination (OD) trip tables that were supplied as inputs to the microscopic simulation models. The microscopic models were then used to simulate the behavior of individual drivers in response to various control strategies on the corridor and at junctions (e.g., freeway interchanges or arterial intersections), including shifts within and between travel modes. The methodology also provided methods for connecting the different analysis tools, including post-processing modules that enable analysis of benefits and costs and the measurement of performance metrics.

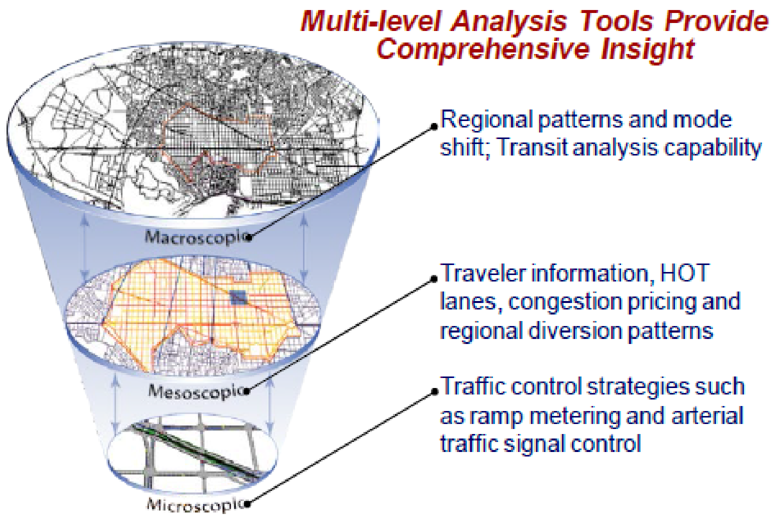

Figure 11. Illustration. The Integrated Corridor Management Analysis, Modeling and Simulation Methodology blends up to three classes of modeling tools for comprehensive corridor-level modeling and analysis.

(Source: Cambridge Systematics, Inc., September 2009.)

An overview of the various components used in the AMS framework is provided in the following sections.

Travel Demand Forecasting Model

Predicting travel demand requires analysis tools that appropriately consider destination choice, mode choice, time-of-day travel choice, and route choice, given a traffic state for each link in the network. When combined into a coherent demand modeling framework, the result can be used to predict future travel patterns from current traffic levels, forecasted household characteristics, and predicted employment characteristics.

The San Diego Association of Governments (SANDAG) regional Coordinated Travel – Regional Activity Based Modeling Platform (CT-RAMP) travel demand model (TDM) was used to develop the broader OD matrices for the I-15 Corridor, which were then disaggregated by travel analysis zones to provide finer trip modeling resolution for simulation. Parameters from the TDM were used to model mode shifts in response to congestion and to ICM strategies.

Microscopic Simulation Model

Microscopic simulation models simulate the movement, behavior, and decisions of individual drivers, based on models of car-following and lane-changing and a variety of population parameters. Typically, the analytical engine (which drives the simulation) begins by adding vehicles to the network at unconnected link entrances and at mid-block locations (representing new trips from origins along that link). These new trips are generated according to a specified distribution (e.g., Poisson, Uniform), with the shape parameters for these distributions based on user-defined values and the trip tables provided to the simulation. Similarly, driver characteristics (e.g., driver aggressiveness, following distance, acceleration or deceleration profile) are assigned for each vehicle at the time it first enters the simulation network according to statistical distributions. Each generated vehicle is also given a desired destination, and its progress toward that destination is simulated in small time increments (e.g., half a second) or "simulation steps." Microscopic simulation models generally also consider roadway characteristics—including grade, lane width, and design speed—when evaluating the movement of individual vehicles on each link, with the effects of each roadway parameter being modeled according to relationships established by past research. Once a model is built, it must then be calibrated through the adjustment of driver and roadway parameters to achieve an optimal alignment between the route choices and link capacities observed in the model and measured in the field.

The microscopic simulation engine that was used for analysis of the I-15 ICM corridor is Aimsun, developed by Transport Simulation Systems (TSS). Figure 12 shows the model network that was used in post-deployment AMS. This model is currently being used as part of the decision support system (DSS) employed in the I-15 ICM system. This software suite is capable of simulating the details of ICM traffic control strategies, such as adaptive freeway ramp metering, arterial traffic signal coordination, and managed-use lane operations. At each step in the simulation, individual vehicles may be rerouted to different paths based on network conditions (e.g., congestion) and driver characteristics (e.g., driver willingness to divert, availability of traffic information to the driver). These routing decisions are based on the evaluated generalized costs (e.g., travel time) of each potential path to the traveler's destination. Some drivers, designated as "informed," were assumed to have perfect knowledge of real-time travel information (by means of a smartphone, global positioning system (GPS) device, etc.), and dynamically routed themselves through the network based on the currently evaluated shortest time paths to their destinations. Other drivers who are not considered to have access to real-time travel information in the simulation evaluated whether to divert to alternate routes in the face of heavy congestion based on historical travel time information, which these drivers would have learned through experience.

In addition to modeling traveler choices and network conditions, the simulation can also inform appropriate actions to take in response to congestion. Because Aimsun can realistically simulate the operation of various ICM components and the effects of changes to the network (e.g., lane blockages, real-time changes to speed limits), it can be used to evaluate the impacts of different operational decisions on congestion, bottleneck performance, or other metrics.

The traffic assignment method within Aimsun allows the use of static and dynamic assignment methods based on requirements of different study types. Traffic assignment models were used to estimate the flow of traffic on a network. These models take as input a matrix of flows that indicate the volume of traffic between OD pairs. The flows for each OD pair were loaded onto the network based on the travel time or impedance of the alternative paths that could carry this traffic. For traffic simulation models, the flow on a network was modeled by representing individual vehicle movements, and subsequently the link-based performance measures were evaluated based on movements of these individual vehicles as they rest in queues, travel in free flow, or maneuver through congestion. Whether all vehicles traveling a given path reach all links on the path within a given analysis period was dependent on time-variant travel conditions in the network (Source: AIMSUN Microsimulator and Mesosimulator User's Manual.).

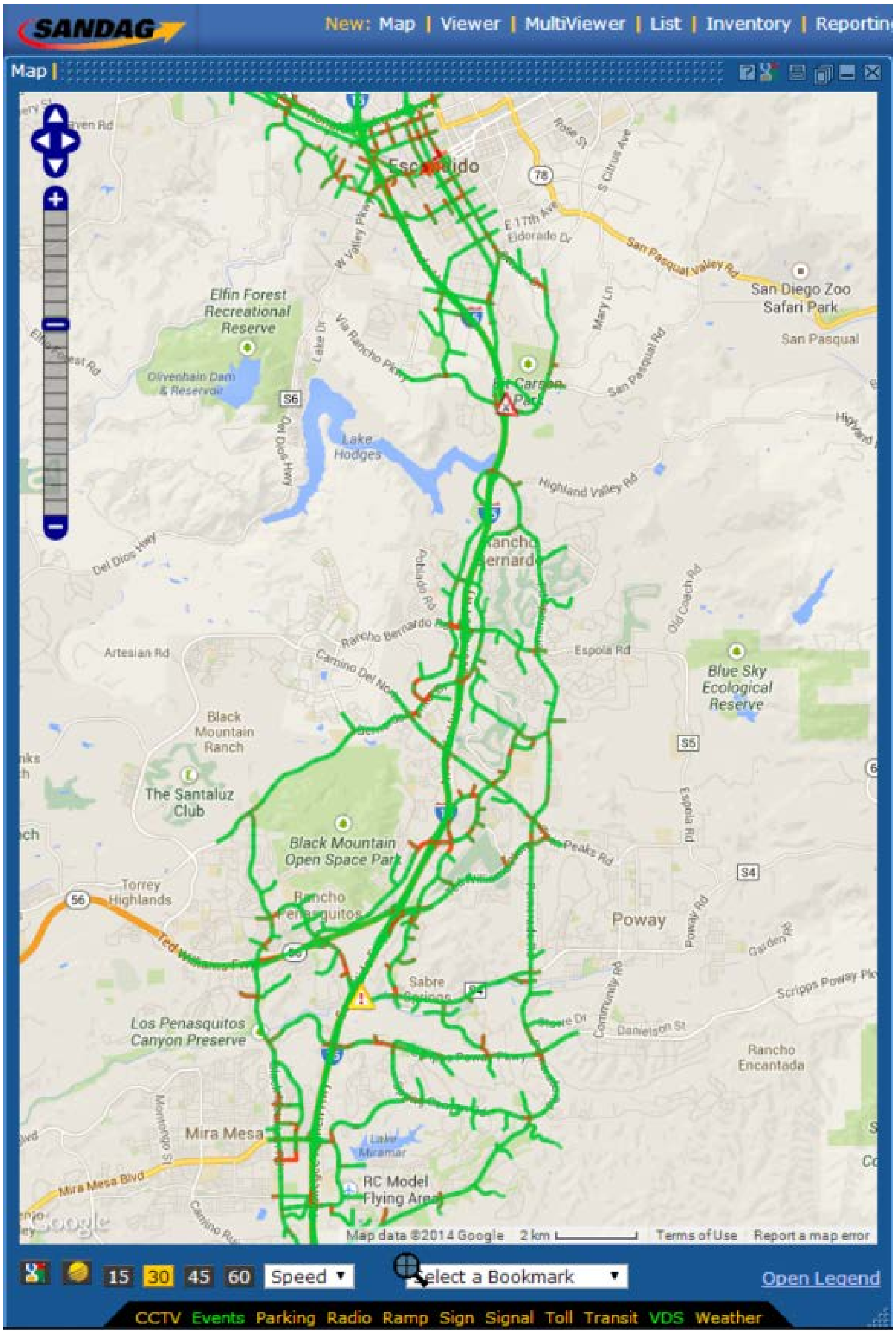

Figure 12. Map. Model network I-15 for post-deployment Analysis, Modeling, and Simulation.
(Source: San Diego: Integrated Corridor Management System, Transport Simulation Systems.)

The key behavioral assumptions underlying the User Equilibrium (UE) assignment model are that every traveler has perfect information concerning the attributes of network alternatives, all travelers choose a route that minimizes their travel time or travel costs, and all travelers have the same valuations of network attributes. At UE, no individual travelers can unilaterally reduce their travel time by changing paths. A consequence of the UE principle is that all used paths for an OD pair have the same minimum cost. An alternative and more realistic equilibrium model is known as Stochastic User Equilibrium or SUE. This model is premised on the assumption that travelers have imperfect information about network paths and/or vary in their perceptions of network attributes. At SUE, no travelers believe that they can increase their expected utility by choosing a different path. Because of variations in traveler perceptions and also in the level of service experienced, utilized paths do not necessarily have identical generalized costs. The SUE model is consistent with the concept of applying discrete choice models for the choice of route, but with the necessary aggregation and equilibrium solution.

Temporal Analytical Resolution

Microscopic simulation models require travel demand data in the form of O-D tables to properly generate and distribute (e.g., by mode, by route) trips on the network. These tables are generated on the macroscopic level by regional travel demand models and supplied as inputs to the microsimulation engine in Aimsun. Generally, these regional models lack the temporal resolution to be suitable for use with microsimulation, with the macroscopic trip tables being aggregated into intervals of several hours each and the microscopic simulations requiring inputs on the order of 15-minute increments to achieve realistic and reasonable results. However, SANDAG has developed a travel demand model that produces trip tables in 15-minute intervals, making it suitable for use with Aimsun's microsimulation engine.

Modeling Integrated Corridor Management Strategies

Modeling ICM strategies is discussed in further detail in the ensuing sections.

Pre-Trip Traveler Information

Pre-trip traveler information includes any travel information accessible to the public that can be used in planning trip routes, estimating departure times, and/or choosing travel mode. Such information can be available through the 511 system, via the phone, the Internet, or public access television. The analysis captured the impacts of such information on traveler's route choice and departure times. The fraction of I-15 users (pre-ICM and post-ICM), who access such information prior to making their trip, was estimated based on findings from the Volpe Center's "Integrated Corridor Management Initiative: Traveler Response Panel Survey – San Diego" and was buttressed using data sources available in the region, such as available information on utilization of features like 511 and traffic web sites in San Diego. Subsequently, this portion of the traveling population (the "informed travelers") was identified as a particular traveler class within the model.

As shown in Table 1, 93 percent of travelers were considered to have access to pre-trip traveler information before the ICMS was deployed (pre-ICM). Despite the fact that more valuable traveler information was made available after deployment (post-ICM), a*wareness* levels remained stagnant. *Compliance* to pre-trip information increased 0.4 percent post-ICM to 8 percent.

En-Route Traveler Information

As part of the I-15 ICM system an enhanced 511 system was deployed in the region with predictive traveler information. AMS analyzed the impact of en-route information available to travelers on changes in route choice. Changes in route choice relate to real-time change in route choice of travelers based on travel time or congestion updates they receive via radio, 511, smart phones, or wireless-equipped GPS devices. This feature was incorporated into the analysis as a fixed percentage of drivers who would be likely to have this information, along with a corresponding "compliance ratio" representing travelers who would consider changing route if faced with congestion.

To facilitate AMS of traveler responses to CMS, modeling sensors were coded in the model along the route upstream of the message sign. As drivers approach the message sign, they pass through these sensors, which in turn calls up a macro that updates these drivers' route choice decisions. When the macro is activated, new routes are assigned to the percentage of drivers that divert their routes based on the posted information. Depending on the scenario or type of incident that may have occurred, compliance rates associated with each message sign varies, and hence the amount of route diversion also differs throughout the simulation runtime.

Table 1 provides a summary of modeling assumptions used in pre- and post-deployment AMS regarding awareness, use, and compliance to pre-trip and en-route traveler information for both pre- and post-ICM implementation. The post-deployment contents (both pre-ICM and post-ICM) in this table were refined based on the findings resulting from the traveler survey conducted by the Volpe Center in the I-15 corridor, detailed in the report titled "Integrated Corridor Management Initiative: Traveler Response Panel Survey – San Diego".

As shown in Table 1, *awareness* of en-route traveler information increased from 83 percent pre-ICM to 84 percent post-ICM. *Use* levels increased by less than one percent post-ICM, from 12.3 percent to 12.6 percent, indicating a slight increase in the relevance of en-route information, while *compliance* levels also increased by less than one percent post-ICM, from 10.2 percent to 10.6 percent.

Note: "Use" does not necessarily result in an action, unless the proposed mode-route option is more attractive than the "historical route," based on the diversion rules. Therefore, "use" reflects an upper bound on the percent of travelers who might divert as a response to the information, with the actual percentage dependent on the attractiveness of the new route and referred to as "compliance."

Table 1. Modeling assumptions regarding awareness, use, and compliance to traveler information.

	Pre-Trip *(Agency websites, 511, public access TV, local radio, etc.)*			**En-Route** *(CMS, radio, 511, GPS devices, etc.)*		
	Awareness	**Use**	**Compliance**	**Awareness**	**Use**	**Compliance**
Pre-Deployment: ***“Awareness” percentages were based on expected adoption rates of GPS devices and Personal Digital Assistants. The pre-deployment AMS tool (TransModeler) did not require “use” and “compliance” rates.***						
Pre-ICM	5%	N/A	N/A	5%	N/A	N/A
Post-ICM	30%	N/A	N/A	30%	N/A	N/A
Post-Deployment: ***Based on overall findings from panel surveys of I-15 corridor users, conducted by the Volpe Center (not pulse surveys).***						
Pre-ICM	93%	8.2%	7.6%	83%	12.3%	10.2%
Post-ICM	93%	8.6%	8%	84%	12.6%	10.6%

(Source: Integrated Corridor Management Analysis, Modeling, and Simulation for the I-15 Corridor in San Diego, California Post-Deployment Analysis Plan, FHWA-JPO-16-393, p. 29 and Integrated Corridor Management Initiative: Traveler Response Panel Survey San Diego - Draft, Volpe National Transportation Systems Center, July 2016.)

Ramp Metering

The I-15 freeway currently has a number of ramps that are metered in both the northbound and southbound directions. The meters operate on a local occupancy-based algorithm working off the San Diego Ramp Metering Software. The analysis modeled a corridor-coordinated ramp metering algorithm implemented under the Intermodal Transportation Management System (IMTMS) framework for both pre- and post-deployment ICM.

Traffic Signal Timing

In the San Diego ICM network, most of the signalized intersections are operated with actuated signal control whose parameters are defined by different cities and authorities (i.e., Caltrans, Cities of San Diego, Poway, San Marcos, and Escondido). In the model, signal timing plans are operating according to a fixed time-of-day schedule for the base scenario. For each intersection, there are approximately eight different coordinated control plans and one available non-coordinated one.

When a response plan is triggered due to a congestion event, some intersections along the alternative routes switch control plans to provide additional green time to support the increase of traffic. This causes the iNET system to send Aimsun the details for each response plan (including ramp metering, signal timing changes and diverging route). Each diversion route has a predefined set of signal changes that are activated in the model via a traffic management action that starts when the response plan is activated and lasts for the duration of the congestion event.

Chapter 6. Performance Measures

This chapter provides an overview of the performance measures used in the Analysis, Modeling and Simulation (AMS) of Integrated Corridor Management (ICM) strategies for the I-15 Corridor.

The performance measures analyzed by the AMS team focused on the following key areas.

Mobility

Mobility describes how well the corridor moves people and freight. The mobility performance measures are readily forecast by the AMS tools used. Three primary types of measures were used to quantify mobility in the Interstate 15 (I-15) Corridor, including:

- **Travel time—**This is defined as the average travel time for the entire length of the corridor or segment within the corridor by facility type (e.g., mainline, high-occupancy vehicle (HOV) lanes, and surface streets), mode, link, individual traveler, and by direction of travel. Travel times were computed for each peak period analyzed.
- **Delay—**This is defined as the total observed travel time less the travel time under uncongested conditions, and is reported both in terms of vehicle-hours and person-hours of delay. Delays were calculated for freeway mainline and HOV facilities, transit, and surface streets, for all travelers individually and cumulatively, in all analysis scenarios.
- **Throughput—**Throughput is measured by comparing the total number of vehicles entering the network and reaching their destination within the simulation time period. The measure ensures that the throughput of the entire system can be utilized as a performance measure for all the scenarios. The corresponding Vehicle Miles Traveled (VMT), Person Miles Traveled (PMT), Vehicle Hours Traveled (VHT), and Person Hours Traveled (PHT) were reported as a macroscopic measure of the general mobility of the corridor.

Reliability and Variability of Travel Time

Reliability and variability capture the relative predictability of the public's travel time. Unlike mobility, which measures how many people are moving at what rate, the reliability and variability measures focus on how much mobility varies from day to day. Travel time reliability was reported in terms of changes in the Buffer Time and Planning Time Index, while travel time variability was reported in terms of changes in the standard deviation of average travel time. The Planning Time Index is a ratio of the 95th percent peak period travel time to the free flow travel time. A value of 2.50 indicates that for a trip that takes 30 minutes in light traffic, a person should budget 75 minutes (30 minutes x 2.50) to ensure on-time arrival 95 percent of the time. The Buffer Time represents the additional time (or time cushion) that travelers must add to their average travel time when planning trips to ensure on-time arrival. Since a microscopic model was used (Aimsun), the AMS Team used post-processors to calculate the impacts on the reliability and variability of travel time. Appendix B describes the methodology that was used in calculating reliability and variability impacts.

Other Measures

Emissions and Fuel Consumption

The I-15 Corridor AMS also produced model outputs for use by the Evaluation Contractor to estimate emissions and fuel consumption, associated with the deployment of ICM strategies. The emissions analysis methodology incorporated reference values to identify the emissions and fuel consumption rates based on variables, such as facility type, vehicle mix, speed ranges, and acceleration ranges. The emissions and fuel consumption rates were based on available sources. Emissions that are principal pollutants of concern include nitrogen oxides (NO_x), particulate matter (PM), hydrocarbons (HC), volatile organic compounds (VOCs), carbon monoxide (CO), sulfur dioxide (SO_2), hazardous air pollutants (toxics), and greenhouse gases (CO_2). Emissions are generally measured in terms of kilograms of output and computed by pollutant, mode, and facility type. Fuel consumption is typically computed by fuel type, mode, and facility type. Fuel consumption is generally measured in terms of gallons of fuel consumed. The broader Evaluation Report will contain the results on the specific measures used to evaluate the impact of ICM strategies on emissions and fuel consumption.

Cost Estimation

For the identified ICM strategies and based on input by the Evaluation Contractor, planning-level cost estimates will be prepared by the Evaluation team for life-cycle costs (capital, operating, and maintenance costs) and therefore, were not a part of this analysis. Typically, analyzed scenarios representing different operating conditions will be combined together, weighted by the probability of occurrence to arrive at a total annual benefit, net annual benefit, and benefit-cost. Please refer to the full Evaluation Report (scheduled to be published in 2017) for the final benefit-cost assessment.

Safety

Although safety is an important performance measure to consider, currently, available safety analysis methodologies are not sensitive to ICM strategies. At best, available safety analysis methods rely on crude measures, such as a volume-to-capacity ratio (V/C), and cannot take into account ICM effects on smoothing traffic flow. Clearly, this is an area deserving of new research and as such, no explicit safety analysis was conducted as part of this effort.

Summary of Performance Measures

Table 2 provides a summary of the mobility, reliability, and variability performance measures used to analyze the impacts of ICM. Performance measures which are typically used in evaluating emissions, fuel consumption, and cost estimation are listed.

Table 2. Summary of performance measure categories and operational characteristics for analysis.

Category	Performance Measure
Mobility	Travel time: average travel time
	Delay: vehicle-hours of delay, person-hours of delay
	Throughput: vehicle miles traveled, person miles traveled, vehicle hours traveled, person hours traveled
Travel Time Reliability	Buffer Time, Planning Time Index
Travel Time Variability	Changes in the standard deviation of average travel time
Emissions	Kilograms of Nitrogen oxides (NO_x), particulate matter (PM), hydrocarbons (HC), volatile organic compounds (VOCs), carbon monoxide (CO), sulfur dioxide (SO_2), hazardous air pollutants (toxics), and greenhouse gases (CO_2)
Fuel Consumption	Gallons consumed for each fuel type
Cost Estimation	Infrastructure costs and incremental costs for capital costs, operating costs, and maintenance costs
Operational Characteristics	
Facility Type	Mainline, High-Occupancy Vehicle (HOV) lanes, Surface Streets
Mode Type	Drive, Transit
Direction of Travel	Northbound, Southbound
Time of Day	AM peak period, PM peak period
Scenarios	With-ICM, without ICM

(Source: Cambridge Systematics, Inc., 2016)

Chapter 7. Post-Deployment Analysis, Modeling and Simulation Approach

Pre-deployment Analysis, Modeling and Simulation (AMS) activities were associated with AMS support prior to the deployment and activation of Integrated Corridor Management (ICM) systems. Pre-Deployment AMS activities focused on the expected impacts and benefits of ICM associated with "as planned" ICM strategies prior to deployment. Pre-Deployment AMS activities were intended to both refine and prepare AMS capabilities to represent the "as planned" ICM strategies and to inform an ICM evaluation regarding the type, location, and intensity of potential benefits.

Post-Deployment AMS activities focus on identifying impacts and benefits of the "as-deployed" ICM system. The "as-deployed" ICM strategies may differ from "as-planned" ICM strategies. The differences could include ICM strategies that were not successfully deployed, ICM strategies that were deployed differently from planned because of technical issues, and ICM strategies that were deployed differently to take advantage of enhancements or impacts not anticipated pre-deployment. Further, Post-Deployment AMS activities should take full advantage of site-specific traveler behavior and response characterization efforts conducted by the ICM Evaluation team. This includes the refinement of parameters and methods in tools to most accurately reflect traveler behavior in response to ICM strategies.

This chapter describes the post-deployment AMS activities that supported the ICM system for the Interstate 15 (I-15) corridor. During post-deployment AMS, the tools and methodologies developed in previous AMS efforts were revisited and further evaluated in order to improve the capability of the site-specific tools to represent and evaluate the ICM system. The key objectives of post-deployment AMS include the following:

- Identify and facilitate further enhancements to tools, data, and methods developed from previous AMS activities.
- Conduct modeling analysis using enhanced tools in order to assess the impacts of the ICM strategies deployed in the corridor.
- Provide guidance for the site's ICM deployment and support for the integration of the AMS tools and methods developed with their ongoing corridor management practices.
- Support Demonstration Site-Specific ICM Demonstration Evaluation efforts.
- Manage the successful transition of modeling leadership responsibilities from the AMS contractor to the ICM Demonstration site staff and organizations.
- Provide technical documentation of ICM AMS tool development, data collection and analysis, model calibration and validation methods, and analytical methods deployed to both represent and evaluate ICM impacts.

To achieve these objectives, post-deployment AMS included the following tasks in order to evaluate the impacts and readiness of the deployed ICM system. Subsequent sections provide further detail on each of the following tasks:

- Enhance tools to reflect as-deployed corridor management. Adjust tools and methods to differentiate the “as-deployed with-ICM” and “without-ICM” alternatives in analytical tools—this was accomplished by modifying model inputs, assumptions, and analytical approaches to reflect as deployed ICM strategies and observed traffic conditions.
- Conduct post-deployment alternatives analysis using most impactful scenarios from cluster analysis and incident matching.

Model Enhancements

This section describes the task items related to coordination and support of the alteration of tool inputs, analytical methodology, and enhancements to analytical software to reflect post-deployment corridor management technologies and strategies. The AMS team coordinated with the I-15 ICM team and the Evaluation team to confirm, refine, and validate the parameters and assumptions that serve as the basis for modeling traveler responses and impacts related to ICM strategies currently present in the models used in the real-time decision support efforts. San Diego Association of Governments (SANDAG) and local stakeholders reviewed the model parameter assumptions to ensure that they sufficiently capture travel characteristics for the corridor and system response times according to the capabilities of their transportation management systems.

Post-deployment AMS work captured the nature of the as-deployed system, including a good representation of traveler responses to ICM strategies, based on site-specific measurements of traveler responses and reactions, conducted in other parts of the ICM program. The AMS team coordinated with both the ICM Demonstration Site and the Evaluation team to clearly identify whether the deployed capability matches the assumptions made for modeling and simulation.

Analysis Tool for Post-Deployment AMS

Early in the AMS process, a decision was needed regarding whether to conduct AMS in: 1) the simulation platform (Aimsun) used in real-time decision support in the I-15 ICM and currently incorporated into the ICM management software, or 2) in the simulation platform used in pre-deployment AMS (TransModeler). Factors considered included:

- The Aimsun model needed modifications to allow it to: 1) meet certain model validation benchmarks, 2) represent the full peak periods, instead of hourly traffic conditions, 3) conduct real-time mode shift analysis, and 4) conduct real-time analysis of parking demand and capacity. On the positive side the Aimsun model: 1) included all current ICM strategies already coded in the model; 2) had archived data associated with different operational conditions (incidents, high demand, etc.); 3) was available for both the AM and PM peak periods; and 4) its use would ensure better consistency with the ICM evaluation effort as both efforts would rely on the same datasets.
- The TransModeler model was already calibrated but it used 2003 data for its baseline (effects of the recent economic recession may not have been properly accounted for), and still needed to be made consistent with current travel demand and ICM deployment data, and focused on the AM peak only.

Upon discussion with the I-15 project team (including SANDAG and their partners and contractors) the Aimsun platform was selected as the modeling tool to be used in post-deployment AMS. Choosing to switch to the Aimsun Online platform was a catalyst that transformed agency practice in the San Diego region, becoming the standard tool used by transportation agencies in the area.

Ensure I-15 ICM System is Accurately Represented in the Model

To more precisely model the operation of the ICM system and evaluate its benefits, the AMS team used the ICM test system and operational model to check and test the operation of the response plans within the system. This allows the Aimsun Online model to estimate impacts of the response plans and approximate the decision support system (DSS) process. It was important to use the test system as the implementation of response plans has to date been limited. In addition to calibrating the model for a typical day the San Diego I-15 team also conducted a reasonableness assessment for an incident day. The selected real incident occurred on October 16th, 2014 and blocked two to three lanes on northbound I-15 south of Pomerado Boulevard interchange near Lake Hodges between 5:30 PM and 7:00 PM. This day was chosen because it had a major I-15 incident that met the criteria that the system is expected to respond to and show a significant benefit through the rerouting of traffic combined with the managing of the arterials signals, ramps meters, and variable message signs.

The I-15 Model Better Represents the Congestion Pricing System

Along the I-15 corridor the Express Lanes can be used for free by high-occupancy vehicles (HOV), and single-occupancy vehicles (SOV) vehicles with transponders pay a variable toll that is generated by the Congestion Pricing System (CPS). In assigning vehicle types the I-15 model relies on the vehicle mix defined by the SANDAG regional model where vehicles are categorized as SOV Toll and SOV Nontoll, as well as HOV Toll and HOV nontoll. The CPS generates the toll rate per mile that applies to SOV vehicles and is used in the drivers' deciding whether the cost of the toll is greater than the cost of lost time when using the general-purpose lanes.

Improvements and changes were needed as it was observed that the regional model underestimated the number of CPS users and so the AMS team conducted sensitivity tests on the percentage of SOV Toll vehicles by adjusting the travel demands of the offline AM and PM peak period models. The sensitivity tests compared the mainline and CPS volumes greater than 2,000 vehicles per hour along the corridor under congested conditions where the variable toll was greater than the minimum value. The tests and modifications resulted in an increase in the number of SOV Toll vehicles and a decrease in the SOV Nontoll vehicles. With these changes, the peak directions of the CPS system were matched with a higher level of accuracy.

The I-15 AMS Tool Enhancement to Allow for the Creation of Multi-Hour Models

The I-15 ICM Online system was running simulations for a 60-minute duration. For the AMS analysis the simulations need to run for a longer duration to be able to analyze the impacts over the complete peak. As part of the ICM system, a tool was used to extract simulations run as part of the online system, either for the predictions or for the evaluations of response plans to be used for offline review and analysis. This tool was modified to allow the modeler to enter the time range and date of the offline simulation model to be generated. Using the stored input data files from the ICM system, the tool collects the adjusted 15-minute demand files, network device status files (signals, ramps, signs…)

and all event data over the duration of the model. This tool is an integral part of being able to correctly analyze the impacts and benefits of the suggested or implemented response plans over the longer durations. This tool was used to generate the initial models used for the Post-Deployment AMS Reasonableness Assessment described in the Model Calibration & Reasonableness Assessment section of Chapter 7.

Traveler Information Sensitivity Analysis

One of the major efforts to enhance the post-deployment model was refining model parameters and structure by modifying traveler information availability to better represent route diversion and mode shift based on Volpe Center surveys. The Volpe Center gathered behavioral data for travelers in the area of the I-15 ICM project through panel surveys. The ICM Evaluation team collected and analyzed field data for the post-deployment period, and the AMS team modeled different operating scenarios (with and without ICM) using post-deployment data as well. Collaboration between efforts was needed to ensure that any major events (i.e., incidents) that occur on the corridor were properly captured/analyzed by all three teams. Furthermore, traveler information parameters and assumptions were collected by both the Volpe Center travel surveys and by the ICM evaluation effort.

The following Volpe survey measures were used in the AMS analysis:

- Percent travelers who made a travel change based on pre-trip information (percent of travelers who changed time of departure, route, mode, destination, or decided not to make trip); and
- Percent travelers who made a change to their trip (en-route) based on information (percent of travelers who changed route, mode, and destination).

A panel survey approach was selected whereby the same individuals are surveyed both before and after the deployment of ICM. Since the impacts of ICM are expected to be greatest during incident conditions, the methodology included a series of “pulse” surveys that were administered immediately following incidents in each of the corridors. This enabled the measurement of trip-specific behavior during incident conditions.

The study population included “regular” users of the main facility in the I-15 corridor. In order to qualify for the survey, individuals had to travel on the facility three or more weekdays per week in either the AM peak period (6-10 AM) and/or the PM peak period (3-7 PM). The study population was constrained in this way for two reasons:

1. Regular users are familiar with the performance of the facility and are likely to be more sensitive to any changes in corridor performance.
2. In order to successfully conduct the pulse surveys, the Volpe Center required a panel of travelers who are regularly on the facility (particularly at congested times of the day, such as the AM and PM peak), so that they maximize the pool of respondents who are eligible to be pulsed for any given incident (and thus increase the likelihood of obtaining responses to the pulse surveys).

The purpose of the survey was to measure the impacts of ICM on travelers in each of the corridors. More specifically, the survey addresses:

- Changes in peak period travel behavior (mode, route, timing, frequency, etc.) due to conditions in the corridor and due to improved traveler information;
- Changes in satisfaction regarding travel/trip experiences in the corridor;

- Ability of travelers to detect improvement in the quality of service in the corridor;
- Changes in awareness of traveler information sources;
- Changes in reported utilization of (frequency, method, timing, etc.) traveler information sources; and
- Changes in satisfaction regarding traveler information/sources.

These measures were identified for comparable incidents in the pre- and post-ICM periods (and when a response plan was implemented in the post-ICM period). The "Post-Deployment" section of Table 1 outlines the model parameter values derived for awareness and use, based on real data collected from traveler surveys.

Other Model Enhancements

Additional model enhancements were conducted as follows:

- Network Changes**—**Three main types of changes were made to the network for both offline and online use, including: a) Geometric changes including edits to intersections and new Direct Access Ramps (DAR); b) Transit updates including new bus routes or new bus services; and c) Signal updates to make sure that any new signals or signals added to the Regional Arterial Management System were included.
- Demand Changes**—**The following steps were involved with the update to the travel demands using more recent travel demand data. Step 1) Review and update of detection to account for the updates of the external systems. Step 2) New data collection to update the historical patterns for the Monday, Tuesday/Thursday, Wednesday and Friday day types. Step 3) Creation of patterns for the different day types using various types of filtering mechanisms. Step 4) Creating and training the models. Step 5) Generation of demand matrices for each typical day.
- Online System Files**—**For microscopic simulations, it was necessary to upload a path assignment file and an initial state file to start each simulation. The initial state files were created at the same time that the dynamic adjustments were run. Every 15 minutes a dynamic adjustment was run and a new initial state was saved after 15 minutes of simulation, so that the following simulation for the dynamic adjustment could start with this new initial state created with the adjusted matrices.
- Post-Processors**—**Currently the Aimsun model does not have the ability to calculate impacts on the reliability of travel time, and includes internal processors to calculate impacts on vehicular emissions and fuel consumption based on European standards. The model was enhanced so that it could calculate travel time reliability impacts as well as produce estimates of emissions and fuel consumption impacts based on California standards for San Diego. The AMS team provided post-processors which produced inputs to the Evaluation Contractor's travel time reliability impacts, as well as estimates of emissions and fuel consumption impacts.

Summary of Analysis Settings

A summary of the ICM strategies implemented in the "as-deployed" ICM system, which were replicated in the models used for post-deployment AMS include:

- Active Decision Support System;
- Coordinated incident management;
- Freeway coordinated ramp metering;
- Actionable traveler information (en-route and pre-trip via changeable message signs (CMS), a new 511 app, and other commercial sources);
- Upgrades to selected traffic signal systems (new traffic signal coordination timings, responsive traffic signal control); and
- Alternate route wayfinding signs.

Based on the Volpe Center traveler surveys, the “Post-Deployment” section of Table 1 presents the parameters that were used in the AMS related to the travelers’ awareness, use and compliance to traveler information:

- “Awareness” represents the portion of travelers who have access to information. For awareness the AMS used the percentages from the Volpe Center’s baseline/endline surveys, and they were both in the mid 80 to 90-percent range.
- “Use” represents a traveler’s intent to take action, but does not necessarily result in an action, unless the proposed mode-route option is more attractive than the “historical route,” based on the model’s diversion rules. Therefore, “use” reflects an upper bound on the percent of travelers who might divert as a response to the information, with the actual percentage dependent on the attractiveness of the new route and referred to as “Compliance.” For better linearity of model functions (non-jumpiness across steps) the model uses this convention, where “compliance”=”awareness” * “use”.
- This AMS effort (as reported in the “Post-Deployment” section of Table 1) used the compliance numbers reported in the pulse summary surveys provided by the Volpe Center.

Table 3 shows the analysis settings used for conducting Post-Deployment AMS for the San Diego I-15 corridor.

Table 3. San Diego I-15 corridor—*summary of post-deployment analysis settings.*

Parameter	Value	Comment
Analysis year	2015	The analysis year was derived from the anticipated completion of design, testing, and deployment of ICM.
Time period of analysis	AM peak period (6 AM to 10 AM) PM peak period (3 PM to 7 PM)	Several incidents and bottleneck events that occurred in days representative of different clusters, and for which response plans were activated were selected to represent AM and PM peak periods. Also, one hypothetical scenario was selected for analysis, including opening all Express Lanes to all traffic during a major incident.
Simulation period	4 hours in each peak period	6-10 AM and 3-7 PM were selected to represent the AM and PM analysis periods.
Freeway incident locations and durations	Based on cluster analysis and presented in Table 8	These locations experienced incidents, offered the potential for route diversion, had a response plan activated, and had a high impact on corridor travel.

(Source: Integrated Corridor Management Analysis, Modeling, and Simulation for the I-15 Corridor in San Diego, California Post-Deployment Analysis Plan, FHWA-JPO-16-393, p. 29.)

Model Calibration & Reasonableness Assessment

Accurate calibration is a necessary step for proper simulation modeling. This is especially critical for the real-time modeling done in I-15's ICM system, which requires models to be accurate on a daily basis in order for the ICMS to function properly. Before modeling ICM strategies, model calibration ensures that base scenarios represent reality, creating confidence in the scenario comparison. Each simulation software program has a set of user-adjustable parameters that enable the practitioner to calibrate the software to better match specific local conditions. Calibration improves the ability of the model to accurately reproduce local traffic conditions. The calibration efforts conducted as part of the ICM initiative exceeded standard calibration efforts by introducing innovative methods such as having specific calibration criteria for incident days and transit. The key steps in model calibration include:

- Identification of necessary model calibration targets;
- Selection of the appropriate calibration parameter values to best match locally measured street, highway, freeway, and intersection capacities;
- Selection of the calibration parameter values that best reproduce current route choice patterns; and
- Calibration of the overall model against overall system performance measures, such as travel time, delay, and queues.

Available data on bottleneck locations, traffic flows, and travel times were used for calibrating the simulation model for the analysis of the I-15 corridor. The I-15 Corridor calibration strategy was based on the three-step strategy recommended in the Federal Highway Administration (FHWA) Guidelines for Applying Traffic Microsimulation Modeling Software (Source: Dowling, R., A. Skabardonis, and V. Alexiadis, *Traffic Analysis Toolbox Volume III: Guidelines for Applying Traffic Microsimulation Modeling Software*, U.S. DOT-HRT-04-040, Federal Highway Administration, July 2004.):

- **Capacity calibration.** An initial calibration was performed to identify the values for the capacity adjustment parameters that cause the model to best reproduce observed traffic capacities in the field. A global calibration was first performed, followed by link-specific fine-tuning. The capacity calibration for the I-15 Corridor was performed utilizing volume data collected from the Caltrans Performance Measurement System (PeMS) database for the year 2003 between the periods of September to November.
- **Route choice calibration.** Because the I-15 Corridor includes parallel arterial streets, route choice calibration plays a significant role in the overall calibration effort. After capacity calibration, this second calibration process was performed with the route choice parameters. A global calibration was first performed, followed by link-specific fine-tuning.
- **System performance calibration.** Finally, the overall model estimates of system performance (travel times and queues) was compared to the field measurements for travel times and queues. Fine-tuning adjustments are made to enable the model to better match the field measurements.

Post-Deployment AMS Tool Reasonableness Assessment

Full recalibration of the model system was not expected to be required in the Post-Deployment AMS Phase. However, a Reasonableness Assessment was conducted, where the model inputs and parameters were modified as necessary so that the model can reasonably match Post-Deployment field conditions, including location, extent, and severity of bottlenecks. The objective of the Reasonableness Assessment was to review the post-deployment simulation model, and modify the model inputs accordingly in order to ensure that the model sufficiently replicates and simulates observed travel conditions and congestion patterns on the field during the post-deployment stage of ICM.

Methodology

The Reasonableness Assessment Methodology involved the comparison of the I-15 year 2014 model volumes, travel times, and speeds (including bottleneck locations) with field observed data in 2014. In order to perform this assessment, the methodology included four steps, as detailed in the following sections.

Step 1. Data Collection

The first step in the Reasonableness Assessment was to obtain the necessary data inputs. The data inputs for this assessment of the I-15 corridor included volumes observed in the field and speeds from the following sources: Freeway General Purpose, Mainline Lanes; Freeway Express Lanes – HOV and Single-Occupancy Vehicles (tolled); On and Off Freeway Ramps; and, Arterials.

The data used corresponded to a typical day and to a day with an incident. In calculating the typical day, data were used from a day that was clear of incidents during the peak periods. In the initial calibration of the I-15 model, as part of the implementation process, both static counts and live data from the external systems were used as limited arterial data were available. In the recalibration effort, further arterial data was added to the external data and was included as part of this Reasonableness Assessment. The data sources included Caltrans Advanced Traffic Management System (ATMS), the Ramp Metering Information System (RMIS), and the Regional Arterial Management System (RAMS). Since the last update to the on-line model, a number of improvements had been made to the ATMS stations and hence this effort included data from the stations currently in use and the stations that have been updated since the last model update using PeMS data. Where available, PeMS data were used and whenever an issue occurred, external system data were used, filling the gaps with pattern data; this gave a higher level of fidelity to the volume and bottleneck checks compared to using only the current online data set.

Step 2. Reasonableness Assessment Criteria

The Reasonableness Assessment methodology employed similar elements of the model calibration criteria detailed in the United States Department of Transportation (US DOT) “Guidelines for Applying Traffic Microsimulation Modeling Software”, including two types of data comparisons:

1. **Volume Comparison.** The first part determined whether the 2014 I-15 post deployment model reasonably replicates observed volume data for 2014. The criteria for comparing hourly flows between model and observed values are summarized in Table 4. Note that peak periods are defined as 6:00 AM to 9:59 AM for the AM peak period and 3:00 PM to 7:00 PM for the PM peak period.

2. **Travel Speeds and Bottlenecks.** The reasonableness assessment of the model’s speeds was based on a visual audit that compared speed contour diagrams from detector data from a typical weekday with modeled speed data, as summarized in Table 5. The speed contour diagrams depict typical weekday speeds along the I-15 corridor during the AM, Mid-Day and PM peak periods as defined above.

Table 4. Reasonableness Assessment criteria and acceptance targets.

Calibration Criteria and Measures	Calibration Acceptance Targets
Traffic flows within 15% of observed volumes for links with peak-period volumes greater than 2,000 vph	For 85% of cases for links with peak-period volumes greater than 2,000 vph
Sum of all link flows	Within 5% of sum of all link counts
Visual Audits *Individual Link Speeds: Visually Acceptable Speed-Flow Relationship*	To analyst’s satisfaction
Visual Audits *Bottlenecks: Visually Acceptable Queuing*	To analyst’s satisfaction

(Source: Integrated Corridor Management I-15 San Diego, California Analysis Plan, FHWA-JPO-10-039, p. 38.)

Step 3. Model vs. Observed Data Comparison

The third step of the Reasonableness Assessment involved comparing the 2014 model outputs/ performance measures against field data along the I-15 Corridor. The criteria established in Step 2 were then utilized to determine whether the model results adequately replicated the field data.

Step 4. Travel Demand and Network Adjustments

Based on the results of the initial comparison conducted in Step 3, additional work was needed in order to adjust the overall utilization of the Express Lanes in the northbound direction during the peak hour. The main step in this was to adjust the travel demand distribution of vehicles that can access the Express Lanes as HOVs or SOVs with a toll responder. After these changes were made a better fit to the real values was achieved.

Step 5. Incident Day Model Assessment

For an incident day, the following criteria were used within the context of the model calibration reasonableness assessment:

- **Freeway bottleneck locations.** Should be on a modeled segment that is consistent with the location, design, and attributes of the representative roadway section.
- **Duration of incident-related congestion.** Duration where observable within 25 percent.
- **Extent of queue propagation**. Should be within 20 percent.

Results – Typical Day

Link Count Comparisons

A total of 86 freeway mainline stations and seven Express Lanes stations in the AM peak period, 89 mainline stations and seven Express Lanes stations during the PM peak period and 70 mainline stations in the MD peak period had over 8,000 vehicles (equivalent of 2,000 vph). None of the available arterial stations meet the 8,000-vehicle threshold.

Table 5 shows the link count comparison for all I-15 locations that met the thresholds for the typical day. For a typical day with no incident, the sum of all link counts fall within the five percent acceptance target.

Table 5. Count comparison for all I-15 locations above VPH threshold – typical day.

Model		Observed		Differences		Percent Error	
6-10 AM	3-7 PM	6-10 AM	3-7 PM	6-10 AM	3-7 PM	6-10 AM	3-7 PM
2,407,128	2,625,769	2,407,567	2,613,164	439	12,604	0.0%	0.5%

(Source: San Diego I-15—Post-Deployment Analysis, Modeling and Simulation (AMS) Reasonableness Assessment and Tool Modification Technical Memorandum—Final, Cambridge Systematics, Texas A&M Transportation Institute, and Southern Methodist University, December 2015, p. 4, unpublished.)

The summary of link count reasonableness assessment results for a typical, no incident day include:

- 91 of the 93 links (97 percent) met the 15 percent comparison criterion described in Table 5 for the AM peak – Criterion 1 is met for the AM Peak.
- 91 of the 96 links (94 percent) meet the 15 percent comparison criterion described in Table 5 for the PM peak period- Criterion 1 is met for the PM Peak.

- 69 of the 70 links (98 percent) meet the 15 percent comparison criterion described in Table 5 for the MD peak period – Criterion 1 is met for the MD Peak.
- The sum of all model link flows across all periods 6,881,464 while the sum of observed link counts is 6,879,777. These volume sums are well within 5 percent and thus Criterion 2 is met for the three combined periods.
- The sum of all model link flows in the AM peak period is 2,407,128 while the sum of observed link counts is 2,407,567. These volume sums are within 5 percent and thus Criterion 2 is met for the AM peak period.
- The sum of all model link flows in the PM peak period is 2,625,769 while the sum of observed link counts is 2,613,164. These volume sums are within 5 percent and thus Criterion 2 is for the PM peak period.
- The sum of all model link flows in the Inter peak period is 1,848,567 while the sum of observed link counts is 1,859,046. These volume sums are within 5 percent and thus Criterion 2 is for the MD peak period.
- For all the peak periods none of the arterial counts meet the required 2,000 veh/hr, thus there is no criterion to meet. Although there are differences between observed and modeled arterial volumes these counts are all included with the model sums for each period and hence the general flow of traffic along freeways and arterials meets Criterion 2.

Delay, Speed and Bottleneck Comparisons

Another component of the reasonableness assessment criteria listed in Table 4 is the visual audit of model speeds and bottlenecks. Modeled versus field-observed speeds and bottlenecks can be compared using speed contour diagrams. Figure 13 through Figure 16 compare the speed contours of southbound and northbound I-15 during a typical day, generated using detector speed data from the average of PeMS for the general-purpose lanes over the February to May 2015 period (Tuesdays and Thursdays only), and the offline simulation outputs.

Comparisons of the detector and model speed contour plots show that the model was able to represent the bottleneck temporal and spatial extents for both southbound and northbound I-15 sufficiently realistically. The comparison shows that recurring congestion exists along the freeway during the AM peak in the southbound direction and during the PM peak in the northbound direction. Modeled congestion is within acceptable thresholds for observed temporal and spatial extents of observed congestion on the I-15 freeway. One exception is the observed queuing in the observed speeds in the southbound direction during PM conditions for a Typical Day, as well as an Incident day. This congestion was not represented in the model as it was caused by a reoccurring condition downstream from the study area and is the representation of spillback from that condition.

Results – Incident Day

In addition to assessing the model's reasonableness for a typical day, the San Diego AMS Team also conducted a reasonableness assessment for an incident day. A PM multiple lane northbound incident for October 16th, 2014 was used, and the incident data were determined using a combination of the Aimsun Online input data and the Caltrans incident report. The incident included three right lanes closed out of a total of five lanes. The duration of the incident was from 5:30 PM for approximately one hour and 45 minutes.

Figure 17 and Figure 18 show observed and modeled speed contours for that incident day. Comparisons of the detector and modeled speed contour plots show that the model was able to sufficiently represent the bottleneck temporal and spatial extents for both northbound and southbound I-15 PM peak directions during an incident. The model also realistically captured the diversion to the arterials as some travelers looked for a faster option.

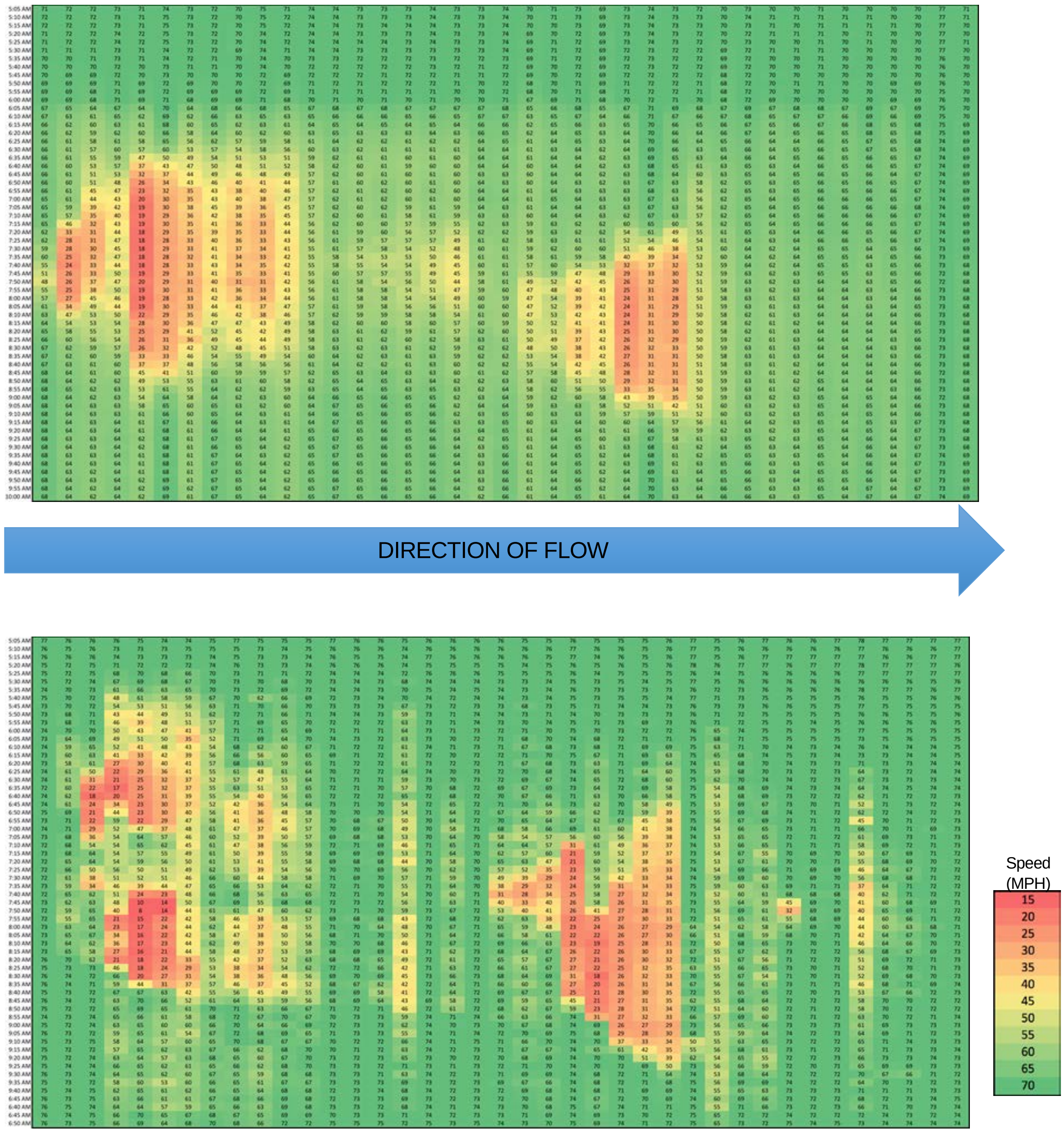

Figure 13. Heatmap. Southbound I-15 AM observed (top) versus modeled (bottom) speed contours – typical day.

(Source: San Diego I-15—Post-Deployment Analysis, Modeling and Simulation (AMS) Reasonableness Assessment and Tool Modification Technical Memorandum—Final, Cambridge Systematics, Texas A&M Transportation Institute, and Southern Methodist University, December 2015, p. 11, unpublished.)

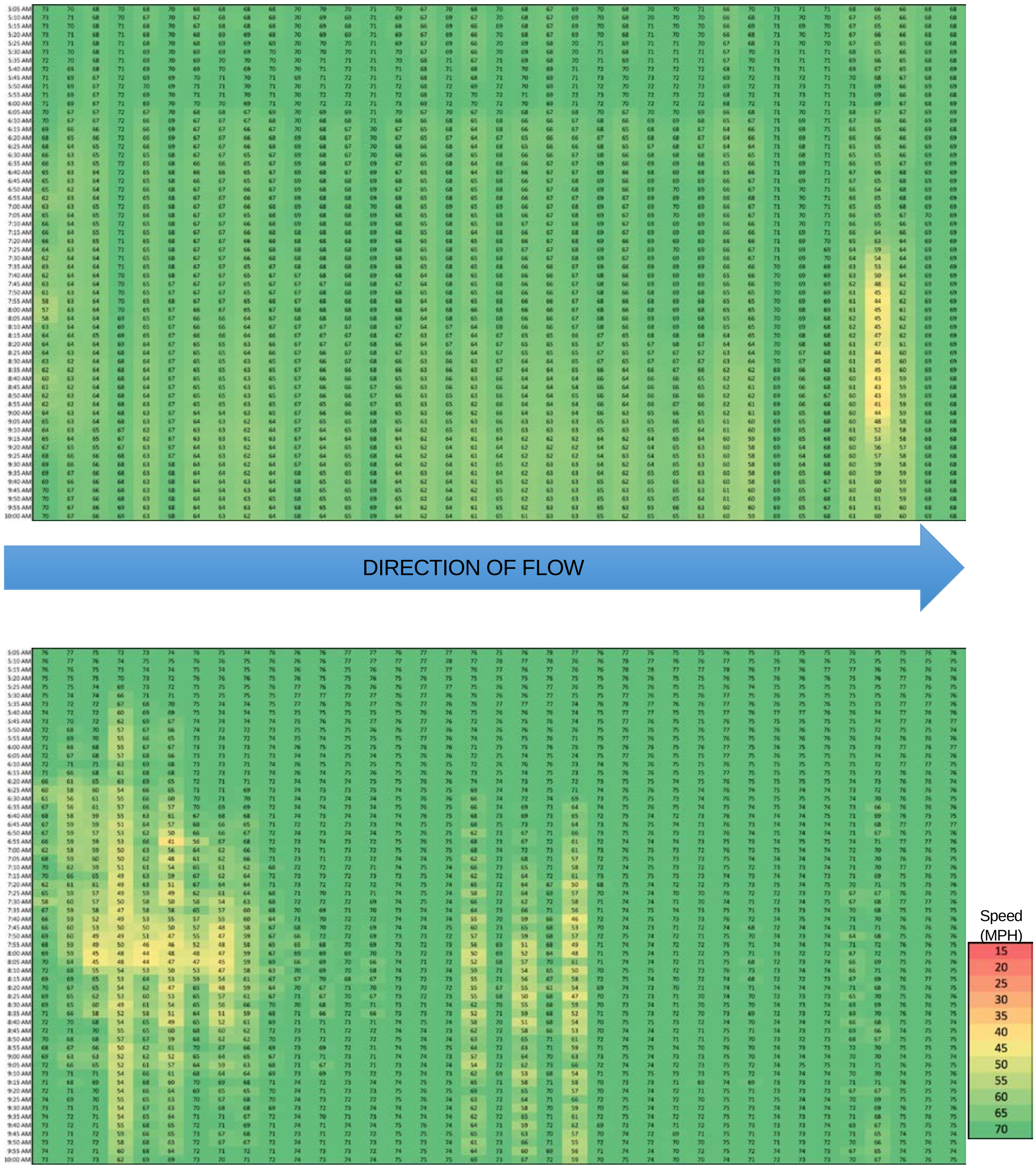

Figure 14. Heatmap. Northbound I-15 AM observed (top) versus modeled (bottom) speed contours – typical day.

(Source: San Diego I-15—Post-Deployment Analysis, Modeling and Simulation (AMS) Reasonableness Assessment and Tool Modification Technical Memorandum—Final, Cambridge Systematics, Texas A&M Transportation Institute, and Southern Methodist University, December 2015, p. 12, unpublished.)

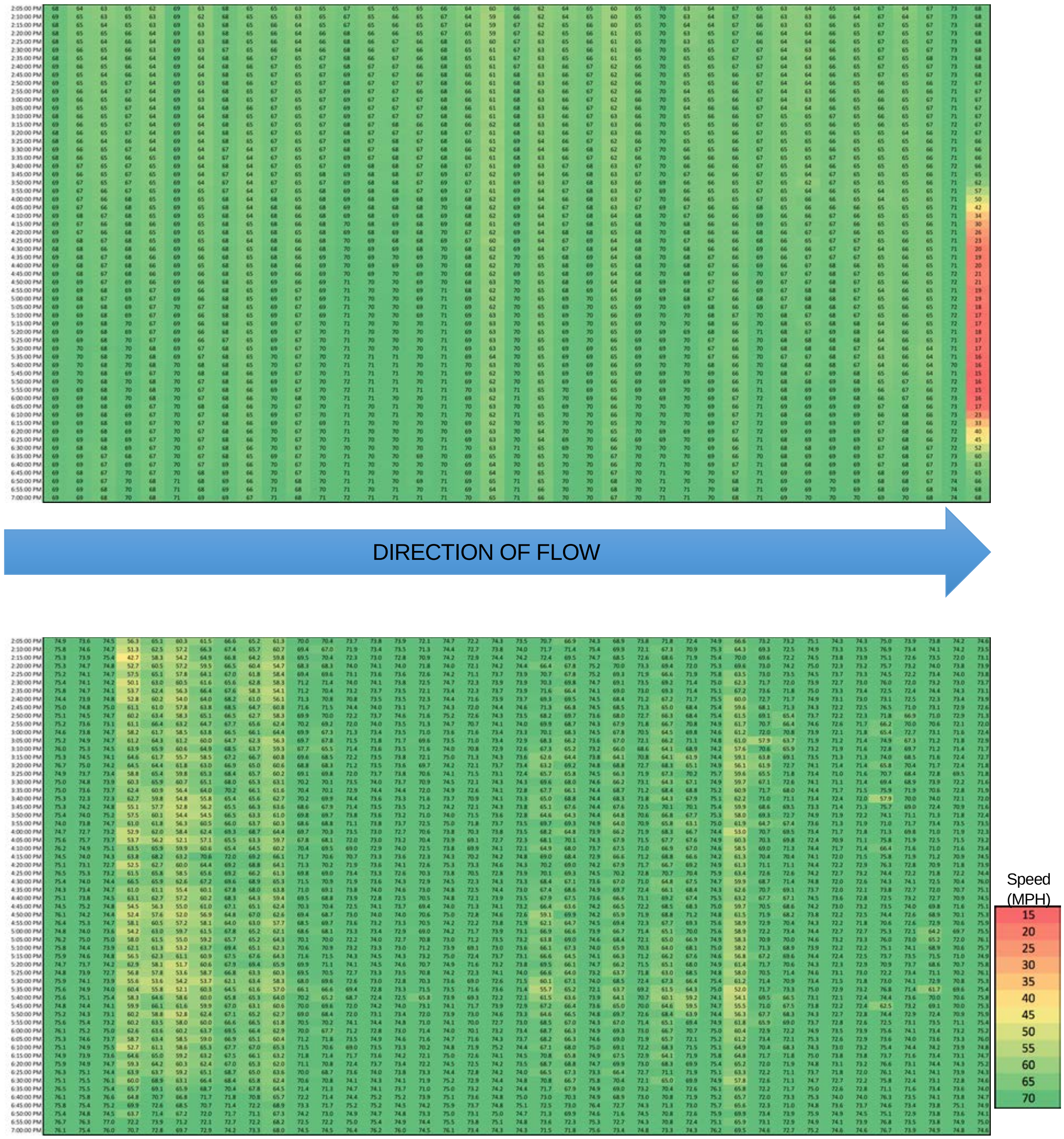

Figure 15. Heatmap. Southbound I-15 PM observed (top) versus modeled (bottom) speed contours – typical day.

(Source: San Diego I-15—Post-Deployment Analysis, Modeling and Simulation (AMS) Reasonableness Assessment and Tool Modification Technical Memorandum—Final, Cambridge Systematics, Texas A&M Transportation Institute, and Southern Methodist University, December 2015, p. 13, unpublished.)

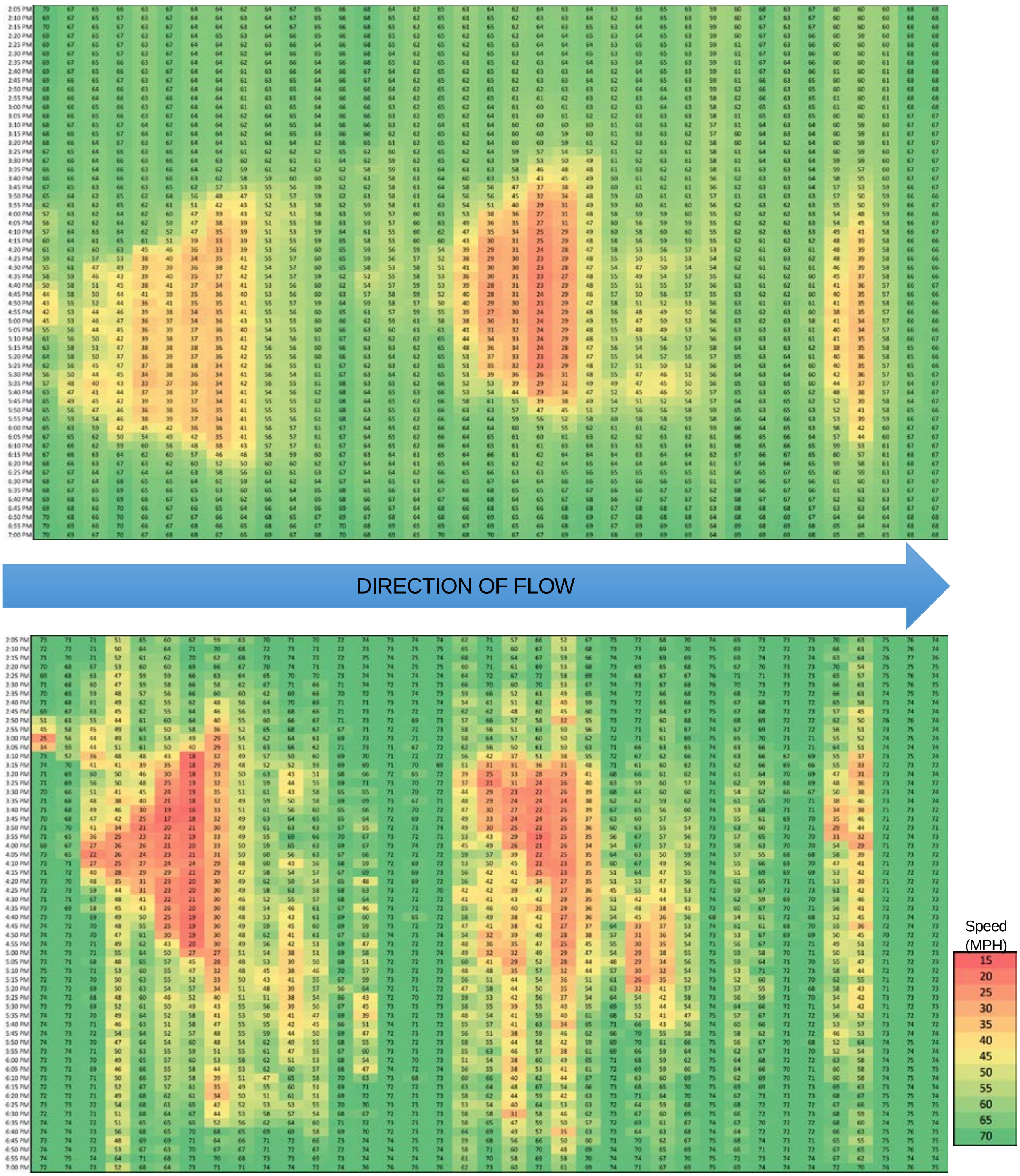

Figure 16. Heatmap. Northbound I-15 PM observed (top) versus modeled (bottom) speed contours – typical day.

(Source: San Diego I-15—Post-Deployment Analysis, Modeling and Simulation (AMS) Reasonableness Assessment and Tool Modification Technical Memorandum—Final, Cambridge Systematics, Texas A&M Transportation Institute, and Southern Methodist University, December 2015, p. 14, unpublished.)

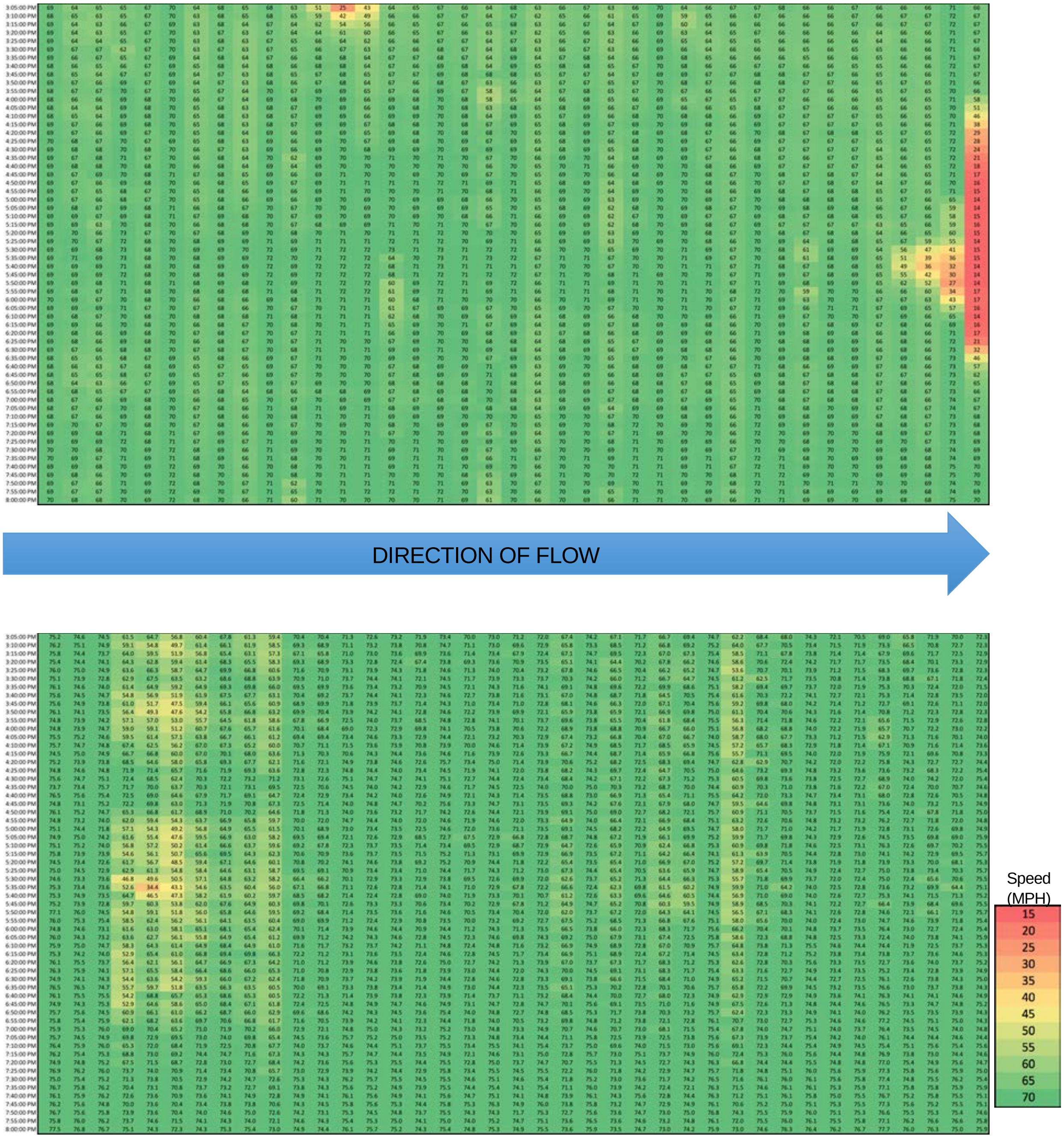

Figure 17. Heatmap. Southbound I-15 PM observed (top) versus modeled (bottom) speed contours – incident condition.

(Source: San Diego I-15—Post-Deployment Analysis, Modeling and Simulation (AMS) Reasonableness Assessment and Tool Modification Technical Memorandum—Final, Cambridge Systematics, Texas A&M Transportation Institute, and Southern Methodist University, December 2015, p. 18, unpublished.)

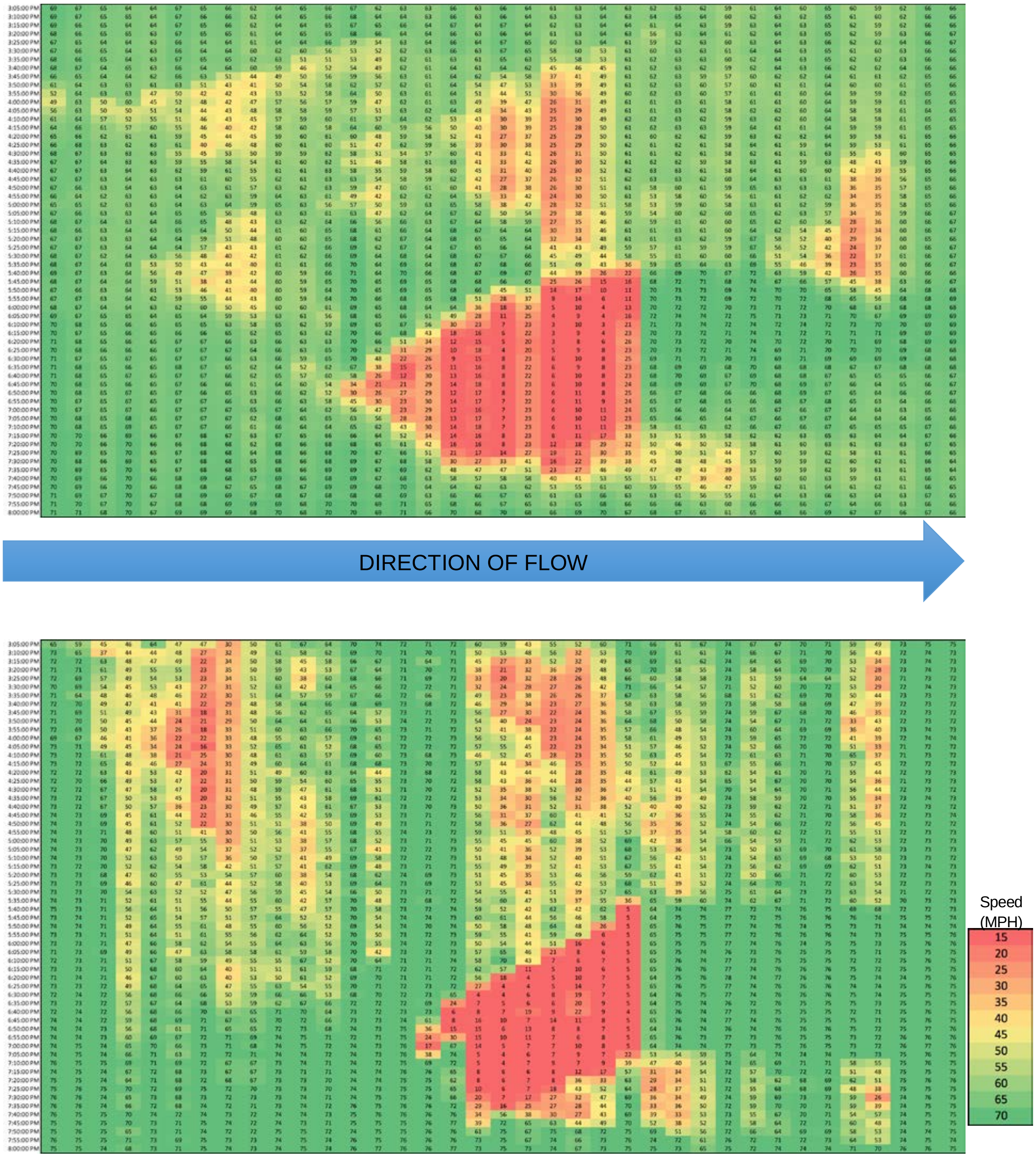

Figure 18. Heatmap. Northbound I-15 PM observed (top) versus modeled (bottom) speed contours – incident condition.

(Source: San Diego I-15—Post-Deployment Analysis, Modeling and Simulation (AMS) Reasonableness Assessment and Tool Modification Technical Memorandum—Final, Cambridge Systematics, Texas A&M Transportation Institute, and Southern Methodist University, December 2015, p. 19, unpublished.)

Overall Conclusion

Verifying that the model accurately represents the current traffic conditions in the field is an important component of the Reasonableness Assessment. This effort helps to ensure that the post-ICM deployment baseline model is capable of accurately representing road geometries, demands, and post-deployment operational conditions in 2014 and 2015. The changes made and the lessons learned through this assessment contribute to the continuous improvement of the AMS approach throughout the various stages of the ICM Initiative.

New and more current field data were collected and several adjustments to the model were completed in order to improve the baseline model. The presence of additional information therefore allowed for a more accurate observed dataset to be compared to the model outputs. For the evaluation of the incident case, the model was fine-tuned to represent the incident by correctly adjusting the number of lanes associated with the closure, the passerby speed at the location of the incident, the incident duration, and the vehicle reactions approaching the incident. The model is a fair representation of the incident.

For a typical day with no incident, the overall comparison of total model link flows against the aggregate field volumes showed that the model met the suggested link count calibration criteria. Plus, the overall results of the speed contour comparisons showed that the model is able to sufficiently represent the bottleneck temporal and spatial extents for both southbound and northbound I-15. For an incident day the model is also able to sufficiently represent the bottleneck temporal and spatial extents during an incident. This is crucial for representing different non-recurring operational conditions that the analysis was based on which increases the accuracy of the estimated corridor benefits.

Therefore, the model was capable of adequately representing the post-deployment corridor operational conditions in the I-15 Corridor.

Further calibration was conducted on the individual clusters used in alternatives analysis, which is described in greater detail in the Analysis Scenarios section of Chapter 8.

Chapter 8. Alternatives Analysis and Results

This section first provides an overview of the analysis, modeling and simulation (AMS) efforts associated with the Post-Deployment Alternatives Analysis. The alternatives analysis serves to assess the performance of various components of the Integrated Corridor Management (ICM) system under different operational conditions (e.g., time of day, direction of traffic, duration until the incident was cleared, etc.). The methodologies, tools, and strategies incorporated into the Post-Deployment Alternatives Analysis are documented in this section, including information regarding the alternative scenarios identified for analysis. This AMS work followed the United States Department of Transportation (US DOT)-approved Post-Deployment AMS Plan.

Several facets of analysis results are presented. The pulse survey results from the Volpe Center reveals the percentage of travelers along the I-15 Corridor who made travel changes based on pre-trip or en-route traveler information. Main findings from mobility, reliability, and variability performance measures are highlighted and compared against estimated travel time benefits from pre-deployment AMS of the "as-planned" ICM system. Lastly, the ICM AMS methodology is reviewed as a whole, with several takeaways summarized for future ICM adopters.

Analysis Scenarios

Once the models were refined using the enhancements presented in the previous chapter, the models were used for additional testing and analysis that served to assess the impacts of the implemented ICM deployment. The potential ICM deployment-related alternatives were identified using cluster analysis that grouped together incidents that occurred under operational conditions (e.g., time of day, direction of traffic, length of time until the incident was cleared, etc.) which were more similar to each other, than to those in other groups (clusters). These clusters were then prioritized based on total delay impact. Field observed incidents that occurred in the year after ICM deployment were matched to high-impact clusters sharing similar operational conditions. Feedback and input from the site coordinators and local agencies were used to select the final eight scenarios included in alternatives analysis, along with an additional hypothetical scenario. (Please note, the contents of this chapter have been based on a set of memos from the Evaluation Contractor to FHWA titled "ICM Evaluation – San Diego Site Cluster Analysis – Daily Incident Probability", dated April 14, 2016 and "ICM Evaluation – San Diego Incident Matching", also dated April 14, 2016.)

The AMS team focused on identifying and then representing the "as deployed" system. This includes linking the assumptions in Chapter 5 about how the "with" and "without" cases are differentiated and modeled with the cluster analysis. Alternatives analysis were performed primarily by Transport Simulation Systems (TSS), contractor to the San Diego ICM Demonstration Site (San Diego Association of Governments) in conjunction with Cambridge Systematics, the AMS contractor for the US DOT.

Analysis Timeframe

Although the ICM deployment on I-15 became operational in March 2013, a major update took place at the beginning of September 2013, and incident/event response capabilities came online in 2015. Wayfinder signs for route guidance on the arterials became active in 2015 – these signs were expected to facilitate routing through alternate arterial routes in response to incident and events. Existing bus rapid transit (BRT) was operating during the peak periods only in 2013; in the summer of 2014 off-peak BRT became operational all day in both directions.

The period after the deployment and testing of Wayfinder signs and additional BRT (mid-2014 to mid-2015) was determined to be the best option for conducting AMS to represent "with ICM" because: 1) the basic ICM system was operational for several months and the system was deemed stable due to early bug fixes; and 2) Wayfinder signs were deployed and alternate routing was in place. The analysis timeframe was consistent with the cluster-representative days shown in Table 8.

Cluster Analysis

In order to group events with similar traffic characteristics during the pre-deployment period along the I-15 corridor, the Evaluation Team conducted a statistical cluster analysis using event occurrences (date and duration), traffic flow rates, average speeds, and travel time data. The San Diego ICM decision support system (DSS) generates response plans based on congestion, and all DSS activations during the evaluation period happened to be incident-related. As such, the objective of the cluster analysis, was to identify the event clusters that fit a certain criteria such as delay impact and occurrence percentage as percent of time period with incidents and percent of total analysis time period. Identified clusters with the most occurrence and impact were used in finding incidents in the post-deployment period that are a close match to those pre-deployment incident types. This was accomplished by measuring the percentage of occurrence of clusters during the pre-deployment period and seeking matches that reflect similar, or ideally, identical incidents in the post-deployment period. The matched incidents and/or events were then used as input parameters in the AMS process.

The archived pre-deployment data were collected between March 1, 2012 and February 28, 2013, and the data sets consisted of the key variables such as the location and type of an event, duration of incidents in minutes, and directional traffic volumes and speeds recorded by the detectors along I-15 in one-hour intervals. The data sets excluded weekend days and Federally-observed holidays; no days of planned special events that would affect traffic conditions significantly were identified for removal. The time periods included in the analyses were AM peak period (6:00 AM – 9:59 AM), Midday (MD) period (10:00 AM – 2:59 PM), and PM peak period (3:00 PM – 6:59 PM). The overnight period from 7:00 PM to 5:59 AM was not of interest for the analyses.

Based on expected impact magnitude, proposed clusters of operational conditions were identified using the following temporal and/or directional variables:

- *Traffic Flow Rate* (vehicles per hour) – The temporal and directional traffic flow rate measured in one-hour intervals at the stations along the I-15 corridor and within the study limits.
- *Day of the Incident* – The day on which the incident occurred.

- *Day-of-Week* – The day of the week on which the incident occurred.
- *Time of the Incident* – The time-of-day on which the incident occurred.
- *Direction of Traffic* – The direction of lanes on which the incident occurred.
- *Duration of Incidents* (minutes) – The reported number of minutes elapsed from the initial occurrence of the traffic incident to the earliest of the time it was closed or that the scene was cleared according to the data.
- *Travel Time* (minutes) – The calculated temporal average directional travel time along the I-15 corridor.

Data sources for the variables listed above include the Regional Integrated Transportation Information System (RITIS), which is maintained by the University of Maryland's Center for Advanced Transportation Technology Laboratory (CATT Lab).

Table 6 presents a summary of identified clusters for the I-15 corridor. After the tabulation of the cluster analysis results, two measures were added to the tables to gain a better understanding of cluster comparisons. These two measures are post-processed values and were not part of the clustering process. The first measure, *single incident delay impact*, is the difference between the average travel time calculated within a particular cluster and the lowest observed (measured) corridor-wide directional travel time regardless of the time period. The observed lowest travel time was recorded as 13.58 minutes for the northbound (December 25, 2012 during the midday peak period) and 14.00 minutes for the southbound direction (November 22, 2012 during the AM peak period). The second measure, *total cluster delay impact* (for each cluster), was calculated as the product of the single incident delay impact and number of days in the cluster.

The "Percent of Analysis Time Period" column shows the percent of days in a year that are represented in each cluster for each direction of travel and directional AM/MD/PM peak period. For the southbound morning peak direction-period, no incidents occur approximately 12.4 percent of the time and for the northbound afternoon peak direction-period, no incidents occur approximately 9.6 percent of the time; the percentages given in this column are by direction-period. For example cluster SB AM 2 represents an occurrence of 37.5 percent for the AM peak period and in the southbound direction only.

Table 6. Summary of all clusters for all time periods and both directions, ordered by total cluster delay impact.

Cluster	**Duration** (min)	**Volume** (vehicle per hour [vph])	**Travel Time** (min)	**Single Incident Delay Impact** (min)	**Incidents Per Period**	**Days in Cluster**	**Total Cluster Delay Impact** (min)	**Percent of Time Period with Incidents**	**Percent of Total Analysis Time Period**	**Total Days with Incidents in Analysis Period**	**Total Days in Analysis**
SB AM 2	42.89	6,348	16.77	2.77	3.7	39	108.03	42.9%	37.5%	91	104
NB PM 3	46.18	9,034	16.35	2.77	5.5	36	99.72	48.6%	34.6%	94	104
NB MID 4	37.31	7,079	15.54	1.96	2.1	42	82.32	51.2%	40.4%	82	104

Table 6. Summary of all clusters for all time periods and both directions, ordered by total cluster delay impact (continuation).

Cluster	Duration (min)	Volume (vehicle per hour [vph])	Travel Time (min)	Single Incident Delay Impact (min)	Incidents Per Period	Days in Cluster	Total Cluster Delay Impact (min)	Percent of Time Period with Incidents	Percent of Total Analysis Time Period	Total Days with Incidents in Analysis Period	Total Days in Analysis
NB PM 4	44.46	8,870	16.11	2.53	2.1	25	63.25	33.8%	24.0%	94	104
SB AM 1	32.64	6,201	15.72	1.72	1.9	29	49.88	31.9%	27.9%	91	104
NB PM 1	35.00	6,416	16.04	2.46	2.5	17	41.82	23.0%	16.3%	94	104
SB PM 1	36.64	4,773	14.95	0.95	2.6	43	40.85	52.4%	41.3%	86	104
SB MID 3	35.46	4,456	15.19	1.19	2.2	33	39.27	36.3%	31.7%	91	104
NB AM 3	29.81	6,721	14.99	1.41	1.9	27	38.07	28.7%	26.0%	74	104
SB AM 3	41.20	6,038	18.33	4.33	5.9	8	34.64	8.8%	7.7%	91	104
SB MID 5	27.38	4,462	15.76	1.76	2.4	19	33.44	20.9%	18.3%	91	104
NB MID 3	32.29	5,992	16.29	2.71	1.6	12	32.52	14.6%	11.5%	82	104
NB AM 1	34.17	4,767	15.02	1.44	1.7	19	27.36	20.2%	18.3%	74	104
SB AM 9	50.40	5,658	21.81	7.81	9.7	3	23.43	3.3%	2.9%	91	104
NB PM 2	32.53	6,955	16.5	2.92	8.8	8	23.36	10.8%	7.7%	94	104
NB AM 4	23.55	5,657	15.94	2.36	3.6	9	21.24	9.6%	8.7%	74	104
SB PM 3	29.97	5,011	15.17	1.17	3.1	18	21.06	22.0%	17.3%	86	104
NB PM 5	34.71	6,836	19.83	6.25	4.7	3	18.75	4.1%	2.9%	94	104
SB MID 1	32.88	4,847	15.41	1.41	3.9	13	18.33	14.3%	12.5%	91	104
SB AM 4	46.01	6,154	16.91	2.91	10.6	5	14.55	5.5%	4.8%	91	104
NB AM 2	35.13	6,937	15.09	1.51	6.0	9	13.59	9.6%	8.7%	74	104
NB MID 6	30.90	5,903	16.24	2.66	7.4	5	13.30	6.1%	4.8%	82	104
NB MID 2	38.14	5,148	15.77	2.19	4.5	6	13.14	7.3%	5.8%	82	104
SB MID 6	51.14	4,354	16.06	2.06	6.2	6	12.36	6.6%	5.8%	91	104
SB PM 2	26.60	5,409	15.08	1.08	3.2	11	11.88	13.4%	10.6%	86	104
NB PM 8	51.29	6,178	24.05	10.47	7.0	1	10.47	1.4%	1.0%	94	104
NB AM 5	68.75	8,146	15.52	1.94	2.0	5	9.70	5.3%	4.8%	74	104
NB MID 7	30.85	7,565	15.5	1.92	5.6	5	9.60	6.1%	4.8%	82	104
NB MID 1	48.53	4,753	15.49	1.91	2.0	5	9.55	6.1%	4.8%	82	104
SB MID 2	36.86	4,177	15.57	1.57	1.8	6	9.42	6.6%	5.8%	91	104
NB PM 6	38.05	9,156	18.02	4.44	13.0	2	8.88	2.7%	1.9%	94	104
SB PM 5	61.17	4,711	16.17	2.17	2.0	4	8.68	4.9%	3.8%	86	104
NB MID 5	38.38	5,888	15.23	1.65	1.3	4	6.60	4.9%	3.8%	82	104
SB MID 4	30.84	4,481	15.74	1.74	11.0	3	5.22	3.3%	2.9%	91	104
SB PM 4	61.68	4,788	15.21	1.21	9.5	4	4.84	4.9%	3.8%	86	104
SB MID 9	22.17	4,999	15.42	1.42	1.3	3	4.26	3.3%	2.9%	91	104
SB PM 6	39.00	4,888	16.13	2.13	8.0	2	4.26	2.4%	1.9%	86	104
NB AM 6	113.38	6,208	15.69	2.11	4.5	2	4.22	2.1%	1.9%	74	104
SB AM 7	35.44	4,774	15.30	1.30	1.7	3	3.90	3.3%	2.9%	91	104

Table 6. Summary of all clusters for all time periods and both directions, ordered by total cluster delay impact (continuation).

Cluster	Duration (min)	Volume (vehicle per hour [vph])	Travel Time (min)	Single Incident Delay Impact (min)	Incidents Per Period	Days in Cluster	Total Cluster Delay Impact (min)	Percent of Time Period with Incidents	Percent of Total Analysis Time Period	Total Days with Incidents in Analysis Period	Total Days in Analysis
NB MID 8	262.83	7,042	15.48	1.90	2.0	2	3.80	2.4%	1.9%	82	104
SB PM 7	693.80	4,662	17.17	3.17	10.0	1	3.17	1.2%	1.0%	86	104
NB AM 7	52.65	4,453	16.62	3.04	17.0	1	3.04	1.1%	1.0%	74	104
SB MID 12	27.73	5,193	15.45	1.45	6.0	2	2.90	2.2%	1.9%	91	104
NB PM 7	733.25	7,778	16.45	2.87	4.0	1	2.87	1.4%	1.0%	94	104
NB MID 9	659.00	6,507	16.33	2.75	4.0	1	2.75	1.2%	1.0%	82	104
SB MID 8	31.00	5,239	14.86	0.86	1.7	3	2.58	3.3%	2.9%	91	104
SB AM 6	229.00	6,350	16.52	2.52	1.0	1	2.52	1.1%	1.0%	91	104
SB PM 9	210.00	5,153	15.24	1.24	1.0	2	2.48	2.4%	1.9%	86	104
NB AM 8	34.75	1,880	15.95	2.37	8.0	1	2.37	1.1%	1.0%	74	104
SB AM 8	32.25	3,417	15.14	1.14	1.5	2	2.28	2.2%	1.9%	91	104
SB MID 10	753.33	4,397	15.88	1.88	3.0	1	1.88	1.1%	1.0%	91	104
SB AM 5	804.00	6,314	15.70	1.70	1.0	1	1.70	1.1%	1.0%	91	104
SB MID 11	203.00	4,651	15.55	1.55	1.0	1	1.55	1.1%	1.0%	91	104
SB MID 7	194.29	4,415	15.43	1.43	7.0	1	1.43	1.1%	1.0%	91	104
NB AM 9	184.00	5,723	14.92	1.34	1.0	1	1.34	1.1%	1.0%	74	104
NB PM 9	189.00	4,620	14.77	1.19	1.0	1	1.19	1.4%	1.0%	94	104
SB PM 8	274.47	5,280	14.95	0.95	15.0	1	0.95	1.2%	1.0%	86	104

(Source: ICM Evaluation – San Diego Site Cluster Analysis – Daily Incident Probability, Battelle, 4/14/16, p. 9-10, unpublished.)

Incident Matching

The focus for incident matching was on clusters for the two peak direction-periods (e.g., southbound-morning and northbound-afternoon). The incident matching process followed the prioritized criteria presented in Table 7 below, which shows how close the values must be to be considered a match. For the purposes of the evaluation, it was desirable that incidents from the baseline and post-deployment periods be matched that include variety, both in the cluster types shown above and type of DSS response plan that was implemented— including combinations of plans with and without traffic signal timing plan changes, ramp metering changes, and advanced traveler information systems (ATIS). As such, incident matching was sometimes performed such that an incident with a unique DSS response was matched to a cluster, while in other incidences unrepresented major clusters were matched to a post-deployment incident.

All incidents with an implementable DSS response were examined for a baseline period match. Some of the top direction-period clusters did not have an incident match with an implementable, actionable DSS response, so incidents with an information only DSS response were examined to identify candidate post-deployment incident direction-periods for the remaining high-impact clusters. The same characteristic matching criteria were used.

Table 7. Incident matching criteria.

Matching Element	Criteria	Priority
Number of Incidents per period	+/- 1	1
Average Peak Hourly Volume	+/- 5%	2
Average Incident Duration	+/- 20%	3

(Source: ICM Evaluation – San Diego Incident Matching, Battelle, 4/14/16, p. 4, unpublished.)

Table 8 shows the results of the incident matching process, which was used as the AMS scenarios in the alternatives analysis. Incident matches with actionable DSS response plans were identified for eight of the nine selected clusters. These incident matches represent a variety of DSS response plan types and clusters. In total, the best matching incident results include five incidents for the northbound afternoon peak direction-period and three for the southbound morning peak direction-period. The sum of all impacts across these top eight clusters represents the majority of impacts associated with the implementation of ICM in the I-15 corridor.

Table 8. Summary of representative days/incidents in the most frequent/impactful clusters during the AM and PM peak periods.

Scenario	Date of Representative Day	DSS Plan Type Implemented	Total Cluster Day Impact (min)	Percent of Total Time Period	DSS Event ID	DSS Response ID
NB PM 1	6/16/15	Ramps, Signals, ATIS	41.8	16.3%	845922	30617
NB PM 2	6/09/15	Ramps, Signals	23.4	7.7%	842085	30451
NB PM 3	5/05/14	Ramps, Signals, ATIS	99.7	34.6%	853963	31039
NB PM 4	7/07/14	Ramps, Signals, ATIS	63.3	24.0%	639956	19536
NB PM 5	2/19/15	Signals, ATIS	18.7	2.9%	760369	28292
SB AM 1	5/27/15	Signals	49.9	27.9%	817649	30332
SB AM 2	2/09/15	Signals, ATIS	108.0	37.5%	754666	27929
SB AM 3	5/07/15	Ramps, Signals, ATIS	34.6	7.7%	804238	30028
Hypothetical	5/26/15	None. Express Lanes opened.	N/A	N/A	N/A	N/A

(Source: ICM Evaluation – San Diego Incident Matching, Battelle, 4/14/16, p. 5, unpublished.)

The purpose of the ninth scenario – Hypothetical – was to model the impacts of a DSS response for a scenario that did not occur during the evaluation period. The Evaluation, AMS and US DOT teams chose to evaluate the effectiveness of opening the Express Lanes to all traffic as part of the DSS response plans. An incident that warranted this response was selected and its duration and number of lanes closed was similar to the average incident that warranted a response.

It should be noted that a scenario which results in a response plan which opens the Express Lanes to all traffic is generally driven by rare conditions such as major incidents that involve significant disruptions to corridor performance. Under such conditions, the value that ICM brings is that it serves/provides coordinated response plans *in advance* of resorting to opening the Express Lanes. Operations and management of the I-15 ICM system is on-going and the I-15 ICM site team continues to examine future enhancements to the system including how to enhance the system business rules based on lessons learned and response plan activations including major incidents that may require resorting to opening Express Lanes to all traffic.

Figure 19 shows where each of the nine AMS scenarios would lie on an operational condition dartboard with two axes: (1) time period (AM peak period or PM peak period), and (2) event type (congestion caused by bottleneck or congestion caused by incident). The size of each circle corresponds to the percent of total analysis time period for that scenario, except for the Hypothetical scenario, which does not have a representative percentage.

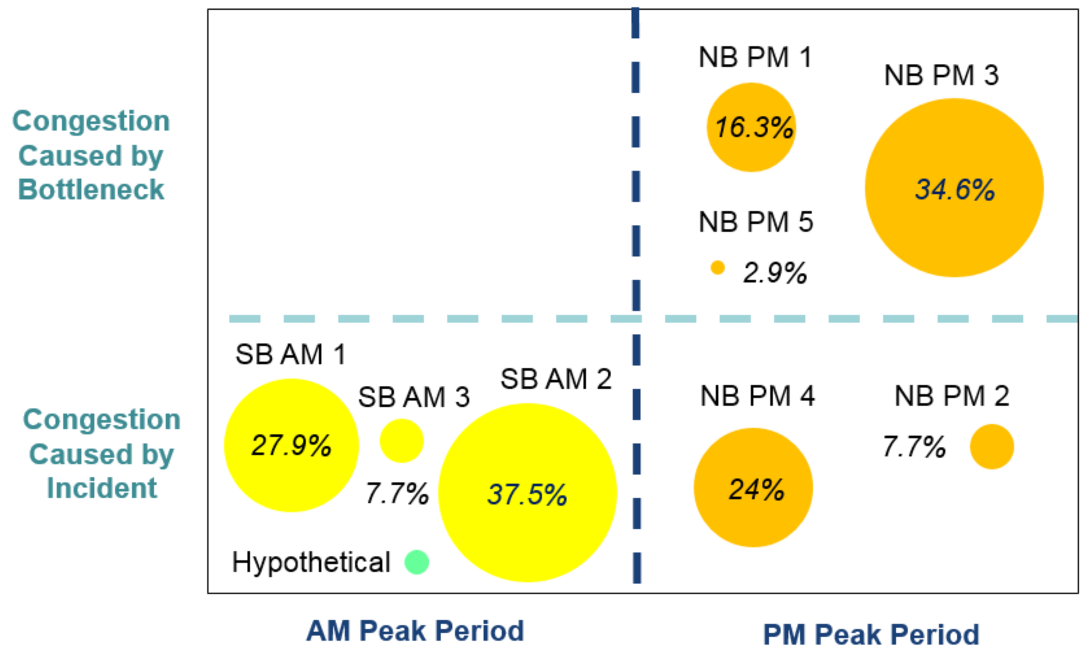

Figure 19. Illustration. Operational condition dartboard categorized by time period and event type.

(Source: Cambridge Systematics, Inc., 2016)

The most impactful clusters of operational conditions were analyzed using the AMS tools, and then compared to the “without ICM” alternatives representing the transportation system without ICM turned on (but with pre-ICM corridor management practices in place). These comparisons facilitated the evaluation of impacts of the ICM system on the I-15 corridor. The identification of specific incidents or other events representing individual clusters were closely coordinated between the AMS, Evaluation and Volpe Center survey teams so as to ensure that event start and end times, impacts (such as number of lanes closed), and other characteristics were in complete agreement between the AMS, Evaluation and Survey team efforts.

Model Calibration for Cluster-Representative Days

An iterative travel demand adjustment process was employed at the start of the analysis of each of the cluster-representative days, so that the model would reasonably represent the travel demand during each particular representative day. This process started by comparing observed versus modeled link volumes in the five links directly upstream of the primary incident during that day. Then the origin-destination (OD) table was iteratively adjusted so that the sum of the modeled volumes in these links comes within 15 percent of the sum of the observed volumes in these links.

Table 9 below shows that the calibration process was able to bring the total percent error calculated for each cluster-representative day below the threshold value of 15 percent for all 36 hourly time periods. Therefore, the San Diego AMS model was deemed capable of representing the travel demand during each particular representative day. The resulting trip table was then used in modeling both the “with ICM” and “without ICM” scenarios.

Table 9. Aggregated percent error of modeled vs. observed volume data for each cluster-representative day.

Cluster	With Incidents and with ICM			
NB PM 1	4-5 PM	5-6 PM	6-7 PM	7-8 PM
	1%	10%	6%	2%
NB PM 2	2-3 PM	3-4 PM	4-5 PM	5-6 PM
	-5%	1%	-12%	4%
NB PM 3	2-3 PM	3-4 PM	4-5 PM	5-6 PM
	-6%	-3%	-5%	2%
NB PM 4	4-5 PM	5-6 PM	6-7 PM	7-8 PM
	1%	3%	4%	-6%
NB PM 5	3-4 PM	4-5 PM	5-6 PM	6-7 PM
	3%	-1%	2%	-4%
SB AM 1	6-7 AM	7-8 AM	8-9 AM	9-10 AM
	-1%	-1%	3%	2%
SB AM 2	6-7 AM	7-8 AM	8-9 AM	9-10 AM
	6%	-7%	6%	3%
SB AM 3	6-7 AM	7-8 AM	8-9 AM	9-10 AM
	0%	-11%	-5%	-13%
Hypothetical (based on SB AM 3 cluster)	6-7 AM	7-8 AM	8-9 AM	9-10 AM
	0%	-11%	-5%	-13%

(Source: Cambridge Systematics, Inc., 2016.)

Traveler Survey Results

The report titled *“Integrated Corridor Management Initiative: Traveler Response Panel Survey – San Diego”* presents findings from the ICM traveler behavior surveys, a set of panel surveys of I-15 corridor users, conducted before and after the deployment of ICM. The purpose of the surveys was to measure the impacts of the ICM initiative on travelers’ use of real-time information (pre-trip and en-route), their travel behavior in the corridor, and their satisfaction with their corridor trips. In addition to surveying drivers about their general behavior in a baseline and endline survey, pulse surveys were administered immediately following incidents in the corridor to obtain a measure travelers’ use of traveler information during incident conditions and its impact on their behavior.   A survey of transit riders was also conducted. Key findings are summarized below. (Please note, the contents of this section have been based on the US DOT report "Integrated Corridor Management Initiative: Traveler Response Panel Survey – San Diego", dated July 2016.)

I-15 Drivers

Awareness and Use of Traveler Information Sources

In both the baseline and endline surveys, respondents were asked about their awareness and use of specific information sources – including websites, apps, alerts, social media, and telephone numbers. For a number of the sources, there is a significant increase in awareness; however this does not translate into increased use. That is, decreases in the percentage who had "never heard of" a source were accompanied by increases in the percentage who had "heard of, but never use" the source. It is worth noting that these shifts may be due, in part, to a learning effect. That is, through the process of being surveyed multiple times, respondents were repeatedly exposed to questions about information sources, and this constituted a form of "learning" about these sources.

In a separate measure that asked respondents to rate how informed they feel (using a seven point scale) about where to check for real time *traffic* information, there is a decrease in the proportion who feel they are uninformed (rating of 1, 2, or 3) – from 30 percent to 20 percent. However, there is no significant increase in the percent who feel informed (rating of 5, 6, or 7); rather more respondents reported being "somewhat" informed. The findings were similar with respect to how informed respondents feel about where to check for real time *transit* information.

The use of specific information sources generally remained stable across the baseline and endline surveys, with the exception of Google Maps (both the website and the app). The percent ever using the Google Maps website increased from 45 percent to 55 percent and similarly for the Google Maps app, the percent using it increased from 46 percent to 56 percent. However, there was no significant change in the frequency with which respondents consulted these or other information sources.

In addition, in the baseline and endline surveys, respondents were asked more generally about the frequency with which they consult real-time travel information for their morning and afternoon peak hour trips in the I-15 corridor– always, nearly always, sometimes, rarely, or never. While there was no change on this measure for morning peak trips, there was a slight increase in the frequency with which respondents consult information for their afternoon trips.

Travel Behavior in the Corridor

In the baseline and endline surveys, traveler behavior changes were captured only very generally. For a list of possible changes (e.g., minor route changes, completely change route, leave for trip earlier, leave for trip later, switch to transit, telecommute) respondents were asked whether they had made the change – as a result of learning about traffic congestion on their route – in the last month, outside of the last month or never. The question was asked separately for travel behavior changes occurring pre-trip versus en-route. Overall, responses on these measures were consistent across the baseline and endline surveys. In response to learning about traffic congestion *prior to leaving for their trip*, respondents were most likely to start their trip earlier or to make route changes; about one-third of respondents reported making each of those changes in the last month. In addition, about one-fifth reported completely changing their route (17 percent) or starting their trip later (17 percent) in the last month. Relatively few respondents made other types of changes. In fact, in both the baseline and endline surveys, three-quarters or more of respondents reported “never” having switched mode (e.g. taking transit or carpooling instead of driving), and two-thirds of respondents had never cancelled their trip or telecommuted instead of traveling. With respect to *en-route* changes in travel due to learning about traffic congestion, respondents were again most likely to change their route. While en-route, large majorities have never switched to transit or cancelled their trip – a finding that is consistent in both the baseline and endline surveys.

When asked about changes made in response to information at the trip level (across all pulse surveys), Table 10 and Figure 20 show a small increase in the morning peak in the proportion who made a minor route change based on pre-trip information (increased from 7 percent pre-ICM to 10 percent post-ICM). In addition, three percent fewer post-ICM travelers did nothing in response to congestion during the morning peak after learning from real-time information sources en-route. Table 11 and Figure 21 highlight travel behavior changes during the afternoon peak period. Two percent fewer post-ICM travelers who did nothing in response to congestion during the afternoon peak period after learning from real-time information sources pre-trip. Travelers surveyed by the Volpe Center stated several reasons for not making changes to their travel plans after learning about the delays, including the fact that alternatives were unlikely to reduce their trip home, incidents did not sound too severe, alternatives were not convenient, or they did not need to arrive at their destination by a particular time (more prevalent for travelers during the afternoon peak period).

I-15 Transit Riders

Use of Communication Devices and Real-Time Traveler Information

Transit riders are most likely to use their smartphones to acquire real-time traffic or transit information, and fewer respondents cited regular use of the radio, television or highway electronic signs. Indeed, in comparison to drivers, transit riders were less likely to regularly use the radio (which tends to focus on road conditions) or electronic highway signs. Like drivers, transit riders tend to consult Google Maps for their traffic information, as this source dominated both website and app use. Nearly half of transit riders consult the Google Maps app once a week or more often, and 10 percent or fewer consult any other app as frequently. Likewise, 39 percent of respondents consult the Google Maps website once a week or more often compared to 19 percent who consult TV and radio station websites and 14 percent who consult SigAlert. Other websites utilized once a week or more by at least 10 percent of respondents included 511 (10 percent) and MTS (10 percent).

Table 10. I-15 pulse survey results – changes in travel plans based on pre-trip information.

Travel Changes	AM Peak	PM Peak	Reverse Peak Trips
Minor route changes			
Pre-ICM	7%	12%	7%
Post-ICM	10%	10%	9%
Left earlier			
Pre-ICM	4%	5%	12%
Post-ICM	5%	6%	11%
Left later			
Pre-ICM	3%	4%	<0.5%
Post-ICM	3%	3%	4%
Completely different route			
Pre-ICM	2%	3%	2%
Post-ICM	3%	2%	3%
Changed stops			
Pre-ICM	<0.5%	<0.5%	6%
Post-ICM	1%	1%	<0.5%
Changed to MTS Express/Rapid			
Pre-ICM	<0.5%	<0.5%	<0.5%
Post-ICM	<0.5%	<0.5%	<0.5%
Changed to other transit			
Pre-ICM	<0.5%	<0.5%	<0.5%
Post-ICM	<0.5%	<0.5%	<0.5%
Carpooled			
Pre-ICM	1%	1%	2%
Post-ICM	<0.5%	1%	2%
Other			
Pre-ICM	1%	<0.5%	<0.5%
Post-ICM	<0.5%	<0.5%	<0.5%
No changes			
Pre-ICM	81%	76%	73%
Post-ICM	79%	78%	73%
Sample Size (Pre-ICM)	**332**	**248**	**145**
Sample Size (Post-ICM)	**311**	**235**	**106**

(Source: Integrated Corridor Management Initiative: Traveler Response Panel Survey San Diego - Draft, Volpe National Transportation Systems Center, July 2016.)

Table 11. I-15 pulse survey results – changes in travel plans based on en-route information.

Travel Change	AM Peak	PM Peak
Minor route changes		
Pre-ICM	11%	16%
Post-ICM	10%	16%
Completely different route		
Pre-ICM	6%	5%
Post-ICM	4%	3%
Changed stops		
Pre-ICM	1%	1%
Post-ICM	<0.5%	<0.5%
Used MTS Express		
Pre-ICM	<0.5%	<0.5%
Post-ICM	<0.5%	<0.5%
Used other transit		
Pre-ICM	<0.5%	<0.5%
Post-ICM	<0.5%	<0.5%
Other		
Pre-ICM	5%	1%
Post-ICM	6%	3%
No changes		
Pre-ICM	77%	78%
Post-ICM	80%	79%
Sample Size (Pre-ICM)	**215**	**127**
Sample Size (Post-ICM)	**178**	**180**

(Source: Integrated Corridor Management Initiative: Traveler Response Panel Survey San Diego - Draft, Volpe National Transportation Systems Center, July 2016.)

About one-in-ten transit respondents said they always (8 percent) check information, and a similar proportion do so nearly always (13 percent) for their transit trips in the corridor; one-third hardly ever do so (34 percent), and another third never check information (32 percent). By comparison, 20 percent of drivers always check information and another 18 percent check nearly always.

Transit riders who reported “never” consulting information were asked why they don’t. From a list potential reasons, respondents indicated that they do not check information because they have to use the same route no matter what (48 percent), they are not interested (42 percent), or they typically do not experience delays (39 percent). No respondents said that information is not available, information is not accurate or up-to-date, or information is not detailed enough.

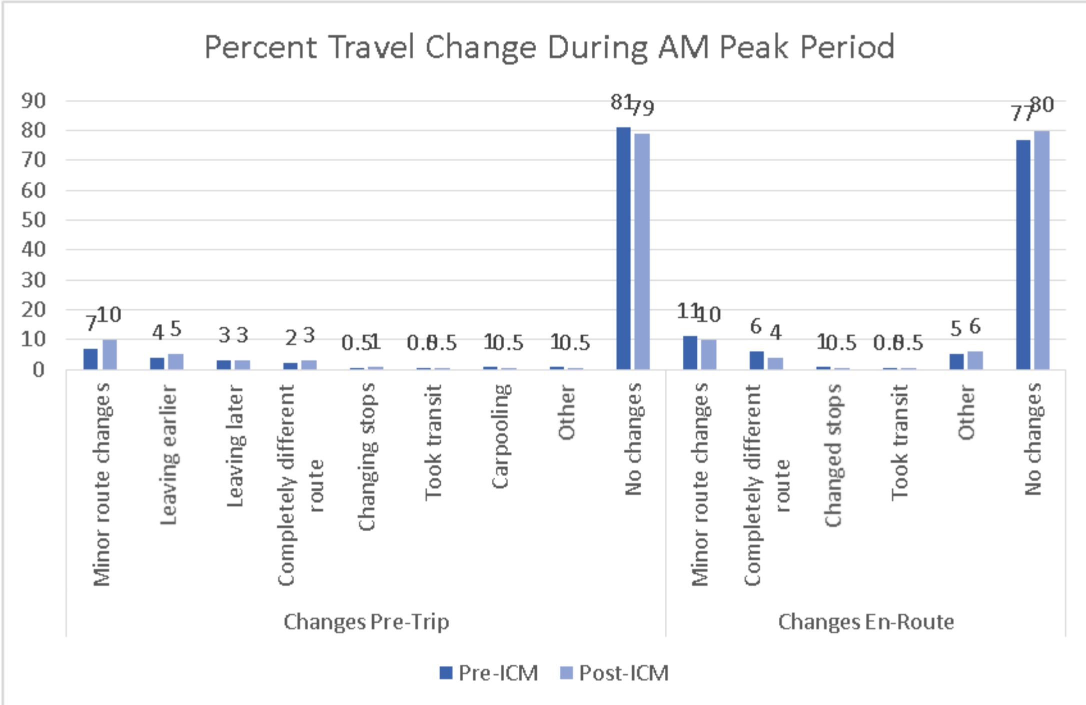

Figure 20. Chart. I-15 pulse survey results – AM peak period travel plan changes.
(Source: Cambridge Systematics, Inc., 2016.)

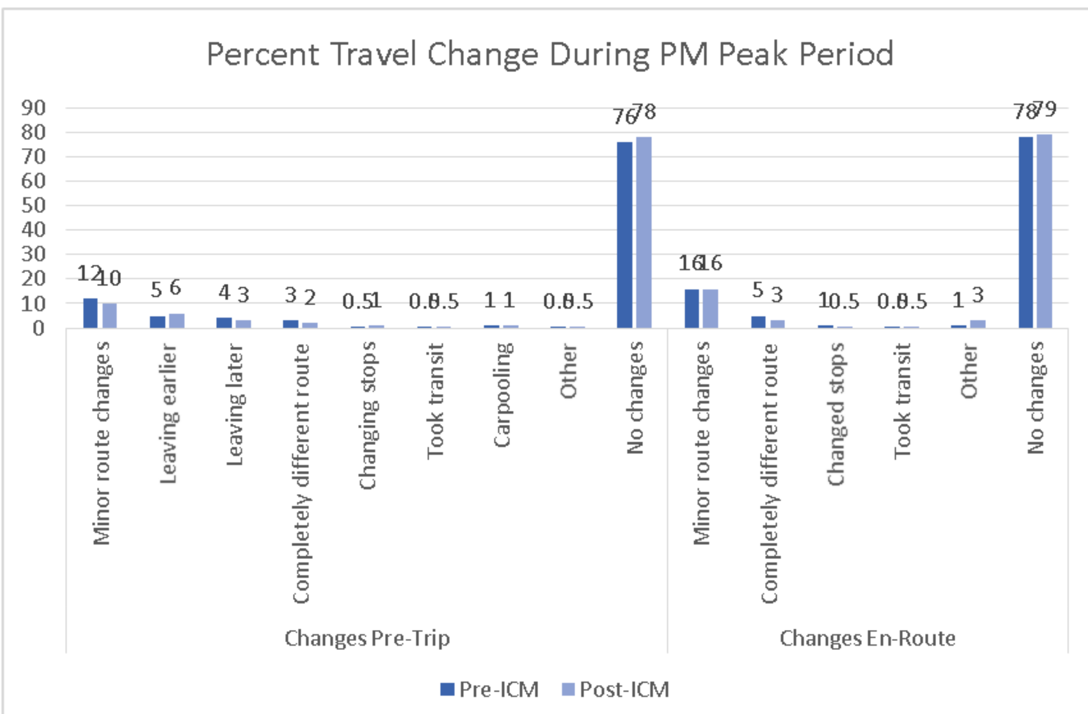

Figure 21. Chart. I-15 pulse survey results – PM peak period travel plan changes.
(Source: Cambridge Systematics, Inc., 2016.)

Impact of Real Time Information on Travel Behavior

Similar to drivers, transit riders were asked a series of questions about the impact of real time traffic and transit information on their travel decisions, both before making a trip as well as during the trip. More specifically, transit riders were asked if they had made any of the following changes – prior to leaving for their trip – as a result of learning about traffic or transit problems:

- Start their trip earlier (29 percent in last month/23 percent not in the last month/46 percent never)
- Choose a different route to get to the transit station (13 percent in last month/19 percent not in the last month/63 percent never)
- Start trip later (20 percent in last month/18 percent not in the last month/58 percent never)
- Choose to drive or carpool instead of taking transit (18 percent in the last month/21 percent not in the last month/57 percent never)
- Choose a different station to get on Metropolitan Transit System (MTS) Rapid/Rapid Express (11 percent in last month/13 percent not in the last month/71 percent never)
- Choose a different station to get off MTS Rapid/Rapid Express (10 percent in last month/15 percent not in the last month/72 percent never)
- Decide to Telecommute (5 percent in last month/13 percent not in the last month/72 percent never)
- Cancel Trip (7 percent in last month/8 percent not in the last month/81 percent never)

For each change, no more than one-third of respondents had made the change in the last month, and a majority of transit riders had "never" made the change (with the exception of starting their trip earlier).

Similarly, respondents were asked if they had ever made any of the following changes while **en-route**, as a result of learning about traffic problems:

- Wait for a later bus due to overcrowding (22 percent in last month/20 percent not in the last month/55 percent never).
- Change route to the transit station (8 percent in last month/16 percent not in the last month/71 percent never).
- Get off MTS Rapid/Rapid Express at a different transit station (5 percent in last month/19 percent not in the last month/73 percent never).
- Use a different station to get on MTS Rapid/Rapid Express (6 percent in last month/13 percent not in the last month/79 percent never).
- Turn around and return to trip start (1 percent in last month/4 percent not in the last month/91 percent never).

While one-fifth of respondents have had to wait for a later train in the last month, relatively few respondents have made any of the other changes. Again, a majority of respondents indicate never having made each change while en-route (with the exception of waiting for a later bus due to overcrowding). Based on the high level of satisfaction with their transit experience, the findings suggest that transit riders generally do not need to alter their trip behavior, as they generally do not face conditions that would require some change.

Analysis Results

One of the main purposes of conducting the traveler response surveys is to determine the effectiveness of providing improved actionable traveler information. Key findings of the survey results are presented, which indicate the actual changes in travel behavior of I-15 drivers and transit riders attributed to the deployed ICM system.

Next, the estimated mobility and reliability performance measures produced through post-deployment AMS are shown. Daily and annual time savings from improved incident management are discussed. Potential travel time benefits for individual corridor users were converted into annual travel time savings and the “as-deployed” ICM system is stacked up against the “as-planned” ICM system.

Performance Measures

In post-deployment AMS, eight scenarios were analyzed with- and without-ICM. Scenarios included both peak period directions. A ninth scenario was analyzed to compare the impact on mobility and reliability between two with-ICM scenarios, one with Express Lanes using dynamic variable pricing (normal operations) and one with Express Lanes open to all traffic during a severe incident. Since a deterministic microscopic model (Aimsun) was used for the simulation, post-processors were used to calculate the impacts on the reliability of travel time. Mobility measures for travel time, delay, and throughput per scenario can be seen in Table 12, Table 14, and Table 15. Reliability measures are presented in Table 15. The values shown in bold typeface represent results where the deployed ICM system had negative impacts on mobility, travel time reliability or variability.

Mobility

Travel Time

Table 12 shows mobility results in terms of daily person hours traveled (PHT). Reductions in PHT and travel time savings are seen in both peak directions (northbound or NB PM and southbound or SB AM). This analysis finding shows a significant travel time benefit resulting from deployment of ICM in the I-15 corridor. The NB PM 3 scenario saved 1,305 person hours traveled (-1.25 percent) in a single four hour window. On the other hand, the Hypothetical scenario shows an *increase* of 1,695 PHT (+2.02 percent) when Express Lanes are open to all traffic. The NB PM 2 and NB PM 5 scenarios also show a slight increase in PHT (+0.04% and +0.25%), which may be attributed to normal variation in the data.

When Express Lanes are under normal operation in the Hypothetical scenario, approximately 300 additional travelers shifted to BRT to avoid additional congestion resulting from the incident and approximately 1,700 additional travelers changed route during the four hour AM peak period to minimize incident impacts. Table 13 breaks down the number of vehicles and travelers that were on the general purpose lanes and Express Lanes both upstream and downstream of the severe incident during the Hypothetical scenario when Express Lanes were under normal operations. Downstream of the event, the I-15 Express Lanes are shown to carry approximately 68 percent more travelers per lane than the general purpose lane (13,735 travelers vs. 8,162 travelers). This results from the combination of higher speeds and higher occupancies in the Express Lanes. So, when the Express Lanes are opened to all traffic during a major incident, this results in higher overall person hours of travel for the entire I-15 corridor which may decrease the appeal for travelers to shift to transit or HOV vehicles in order to take advantage of the travel time savings experienced on the Express Lanes during normal operations.

Table 12. Mobility performance measures – daily Person Hours Traveled.

Scenario	Time Period Reported	Percent of Total Analysis Time Period	Person Hours Traveled			
			with ICM	**without ICM**	**Difference** *(with ICM – without ICM)*	**Percent Change** *[(with ICM – without ICM) / without ICM]*
NB PM 1	4-8 PM	16.3%	78,774	79,320	-546	-0.69%
NB PM 2	2-6 PM	7.7%	91,612	91,576	**36**	**0.04%**
NB PM 3	2-6 PM	34.6%	103,437	104,742	-1,305	-1.25%
NB PM 4	4-8 PM	24.0%	75,942	76,365	-424	-0.55%
NB PM 5	3-7 AM	2.9%	84,570	84,356	**214**	**0.25%**
SB AM 1	6-10 AM	27.9%	78,201	78,451	-250	-0.32%
SB AM 2	6-10 AM	37.5%	75,413	76,189	-776	-1.02%
SB AM 3	6-10 AM	7.7%	86,648	87,658	-1,010	-1.15%
Hypothetical	6-10 AM	N/A	85,762	84,066	**1,695**	**2.02%**

Note for Hypothetical Scenario: Percent change is calculated using *[(with ICM – without ICM) / without ICM]* for all scenarios, except for the Hypothetical scenario, where percent change is calculated using *[(Express Lanes with ICM open to all – Express Lanes with ICM Normal Operations) / Express Lanes with ICM Normal Operations].*
(Source: Cambridge Systematics, Inc., 2016.)

In the Hypothetical scenario when Express Lanes were under normal operations, the average travel time for I-15 southbound travelers in the Express Lanes between Pomerado Road and SR-52 was approximately 2.3 minutes faster compared to travelers in the general purpose lanes (20.5 minutes vs. 22.8 minutes). Table 13 shows that the Express Lanes carried 38 buses, with a total of 1,520 passengers during the 6-10 AM time period of the Hypothetical scenario, resulting in 58.3 person-hours of travel savings attributed to bus occupants alone. Travelers in single-occupancy vehicles saved 28.9 person-hours by opting to use the Express Lanes, while passengers in high-occupancy vehicles saved 965.8 person-hours.

Table 13. Mobility performance measures – traveler breakdown when Express Lanes were under normal operations during hypothetical scenario.

Upstream of Event: Miramar Interchange	General Purpose Lanes		Express Lanes	
	# of Vehicles	# of Travelers	# of Vehicles	# of Travelers
Single-Occupancy Vehicles	38,973	38,973	735	735
High-Occupancy Vehicles	1,394	3,485	9,216	23,040
Buses	-	-	38	1,520
Total	40,367	42,458	9,989	25,295
Average Vehicle Occupancy (AVO)	1.05		2.53	
Number of Lanes	5		2	
Number of Travelers/Lane	8,492		12,648	

Downstream of Event: Split between I-15 and SR-163	General Purpose Lanes		Express Lanes	
	# of Vehicles	# of Travelers	# of Vehicles	# of Travelers
Single-Occupancy Vehicles	39,097	39,097	754	754
High-Occupancy Vehicles	686	1,715	10,078	25,195
Buses	-	-	38	1,520
Total	39,783	40,812	10,870	27,469
Average Vehicle Occupancy (AVO)	1.03		2.53	
Number of Lanes	5		2	
Number of Travelers/Lane	8,162		13,735	

(Source: Cambridge Systematics, Inc., 2016.)

Delay

Delay results, normally represented by person-hours of delay, are reflected in the person hours traveled results shown in Table 12.

Throughput

Table 14 shows mobility results in terms of throughput, using person miles traveled (PMT) as a macroscopic measure of the general mobility of the corridor. The majority of the scenarios in both peak directions show no change, or an increase in PMT, which may be attributed to higher travel speeds resulting from the implementation of ICM. The Hypothetical scenario shows the biggest reduction in PMT – a *decrease* of 9,805 PMT (-0.33%), perhaps linked to the slower travel speeds experienced during the incident during the four hour PM peak period window.

Throughput across an entire period may not show much difference unless latent demand is taken into account. Even if network efficiencies were improved by ICM, it is possible that this did not translate into a significant increase in throughput if there was not much excess demand to begin with. In the case of San Diego I-15 ICM AMS the use of four-hour peak periods contains most of the network congestion (both spatially and temporally) as demonstrated by the model calibration speed contours in Chapter 7 of this report. Adding a reliability threshold or a throughput measure based on peak hourly or 15-minute passenger throughput across a geographic screen-line could potentially be another measure to use in the future to determine the impact on PMT.

Table 14. Mobility performance measures – daily Person Miles Traveled.

Scenario	Time Period Reported	Percent of Total Analysis Time Period	Person Miles Traveled			
			with ICM	without ICM	Difference *(with ICM – without ICM)*	Percent Change *[(with ICM – without ICM) / without ICM]*
NB PM 1	4-8 PM	16.3%	2,905,819	2,905,328	**491**	**0.02%**
NB PM 2	2-6 PM	7.7%	3,446,769	3,445,499	**1,270**	**0.04%**
NB PM 3	2-6 PM	34.6%	3,405,305	3,404,610	**696**	**0.02%**
NB PM 4	4-8 PM	24.0%	2,921,317	2,917,474	**3,843**	**0.13%**
NB PM 5	3-7 AM	2.9%	3,349,013	3,351,511	-2,498	-0.07%
SB AM 1	6-10 AM	27.9%	2,972,239	2,971,470	**769**	**0.03%**
SB AM 2	6-10 AM	37.5%	2,932,909	2,933,015	-106	0.00%
SB AM 3	6-10 AM	7.7%	2,929,091	2,929,228	-137	0.00%
Hypothetical	6-10 AM	N/A	2,923,030	2,932,835	-9,805	-0.33%

Note for Hypothetical Scenario: Percent change is calculated using *[(with ICM – without ICM) / without ICM]* for all scenarios, except for the Hypothetical scenario, where percent change is calculated using *[(Express Lanes with ICM open to all – Express Lanes with ICM Normal Operations) / Express Lanes with ICM Normal Operations].*
(Source: Cambridge Systematics, Inc., 2016.)

Reliability and Variability

The scenarios were aggregated into two categories based on direction and time period to show the trends in mobility and reliability performance measures. Reliability and variability capture the relative predictability of the public's travel time. Unlike mobility, which measures how many people are moving at what rate, the reliability and variability measures focus on how much mobility varies from day to day. Travel time reliability is reported in terms of changes in the Buffer Time and Planning Time Index, while travel time variability is reported in terms of changes in the standard deviation of average travel time. The Planning Time Index is the ratio of the 95th percent peak period travel time to the free flow travel time. The Buffer Time represents the additional time (or time cushion) that travelers must add to their average travel time when planning trips to ensure on-time arrival.

Figure 22 shows the impact that the San Diego ICM deployment is expected to have on travel time reliability in terms of changes to the buffer time. Buffer time is calculated as the difference between the 95th percentile travel time and the median travel time. For both aggregated scenarios (NB PM and SB AM), the figure shows an improvement (decrease) in the median travel time with ICM; this reinforces the findings reported in the mobility performance results earlier in this chapter. An improvement (decrease) in the buffer time needed to ensure on-time arrival 95 percent of the time can also be seen in both aggregated scenarios.

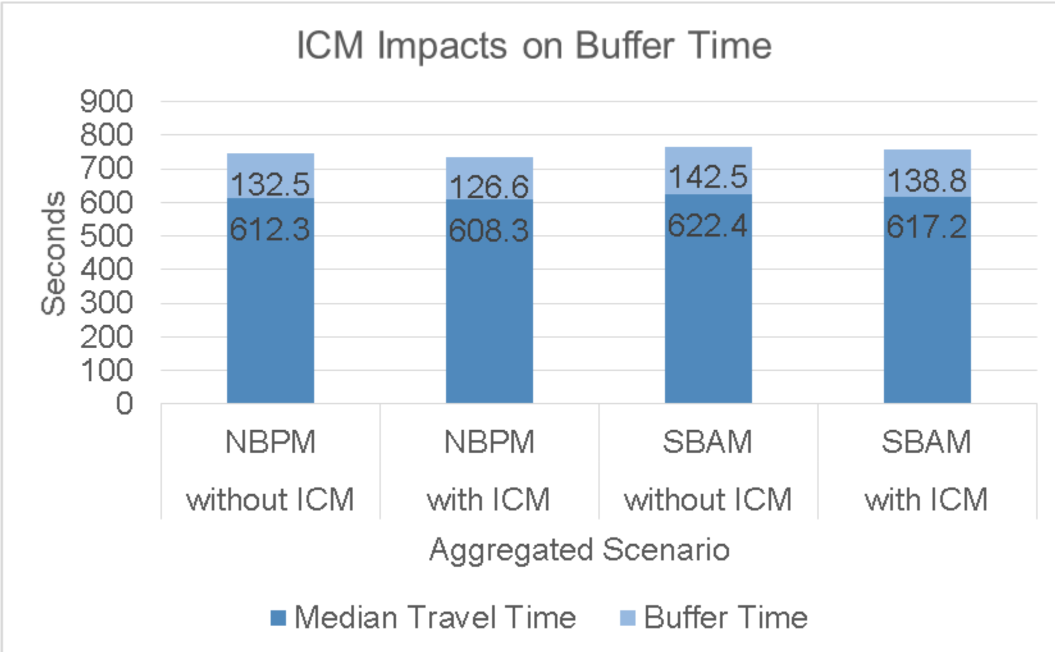

Figure 22. Chart. ICM impacts on travel time reliability – buffer time.
(Source: Cambridge Systematics, Inc., 2016.)

In Table 15, the standard deviation of travel time (linked to travel time variability) also shows an improvement (decrease) for both aggregated scenarios, following the same trend as the buffer time reliability performance measure. The Planning Time Index for the NB PM aggregated scenario shows the opposite trend. The calculation of the Planning Time Index follows the “Travel Time Reliability” equations (11) and (11a) in Appendix B: Performance Measure Calculation Using Simulation. The free flow travel time used in each individual scenario is the minimum travel time for each Origin-Destination (OD) pair. The free flow travel time used for each OD pair in the aggregated scenario is the minimum travel time for that OD pair among all scenarios within each aggregated scenario. All of the travel time values (i.e., median travel time, average travel time, and 95th percentile travel time) are weighted by the number of travelers in each ODTM, meaning travelers going to the same OD, in the same 15 Time frame, using the same Mode.

The calculation of the standard deviation of travel time follows the “Variance in Travel Time” equations (14), (14a) and (14b) also in Appendix B. The calculation for standard deviation of travel time includes only completed trips during the four-hour peak period(s) so as to reduce potential bias caused by outliers. The calculation for Planning Time Index includes all trips completed or partially completed during the four-hour peak period. These differences in the trip population sets used along with complexities in establishing free flow travel times across aggregations of clusters (i.e. free flow travel time will differ across different origins and destinations and will also differ across clusters depending on the response plan activated and alternate routes taken to avoid congestion) influence the diverging trend in this situation. In general, travel time reliability and travel time variability are related but not identical - in situations where the "with ICM" and "without ICM" measures are close to each other, it is possible that the differences in the two measures (Planning Time Index and standard deviation of travel time) go in opposite directions, as they are influenced differently by outliers.

For the NB PM aggregated scenario, it is interesting to see an increase in person miles traveled while person hours traveled decreased. Person miles traveled can increase when vehicles during the four hour PM peak period experience an increase in travel speeds, attributed to reduced congestion.

Table 15. Aggregated mobility, reliability, and variability performance results by direction & time period.

Aggregated Scenario	Mobility		Reliability				Variability	
	Person Miles Traveled	**Person Hours Traveled**	**Median Travel Time** (s)	**Buffer Time** (s)	**95% Travel Time** (s)	**Planning Time Index**	**Average Travel Time** (s)	**Average Travel Time Standard Deviation** (s)
NB PM								
Without ICM	3,180,084	90,164	612.3	132.5	744.8	4.41	635.0	168
With ICM	3,181,446	89,418	608.3	126.6	734.9	4.52	629.0	164
Difference	**1,362**	-745	-4.0	-5.9	-9.9	**0.11**	-6.0	-4
SB AM								
Without ICM	2,948,173	78,236	622.4	142.5	764.9	3.14	636.7	161
With ICM	2,946,781	77,578	617.2	138.8	756.0	3.08	632.2	158
Difference	-1,392	-658	-5.2	-3.7	-8.9	-0.06	-4.5	-3

(Source: Cambridge Systematics, Inc., 2016.)

Response Plan Details for NB PM 3

This section presents the AMS results for one of the representative days (in this case for the NB PM 3 cluster) as an example representing the AMS work that was done for all nine cluster-representative day. NB PM 3 represents congestion caused by a bottleneck during the PM peak period on I-15 at Camino del Norte at Galatyn Parkway, as indicated by the pink segment in Figure 23. The incident matched to this scenario triggered an implementable response plan which intended vehicles to exit at Ted Williams Parkway to Pomerado North and reenter at the Pomerado on-ramp. To aid in this diversion, multiple changeable message signs displayed verbiage indicating “Slowing at Rancho Bernardo. Expect Delays” both before and after the incident and along State Route (SR) 52. Ramp meter rates were adjusted in order to maximize flow on I-15. The arterial traffic signal timing plans were adjusted for 16 signals on Pomerado North to accommodate the increase in traffic demand. As a result, 1,305 person hours of travel were saved overall, compared to a similar incident without an operating ICMS. The majority of travelers along the corridor (51.85 percent) experienced a decrease in travel time.

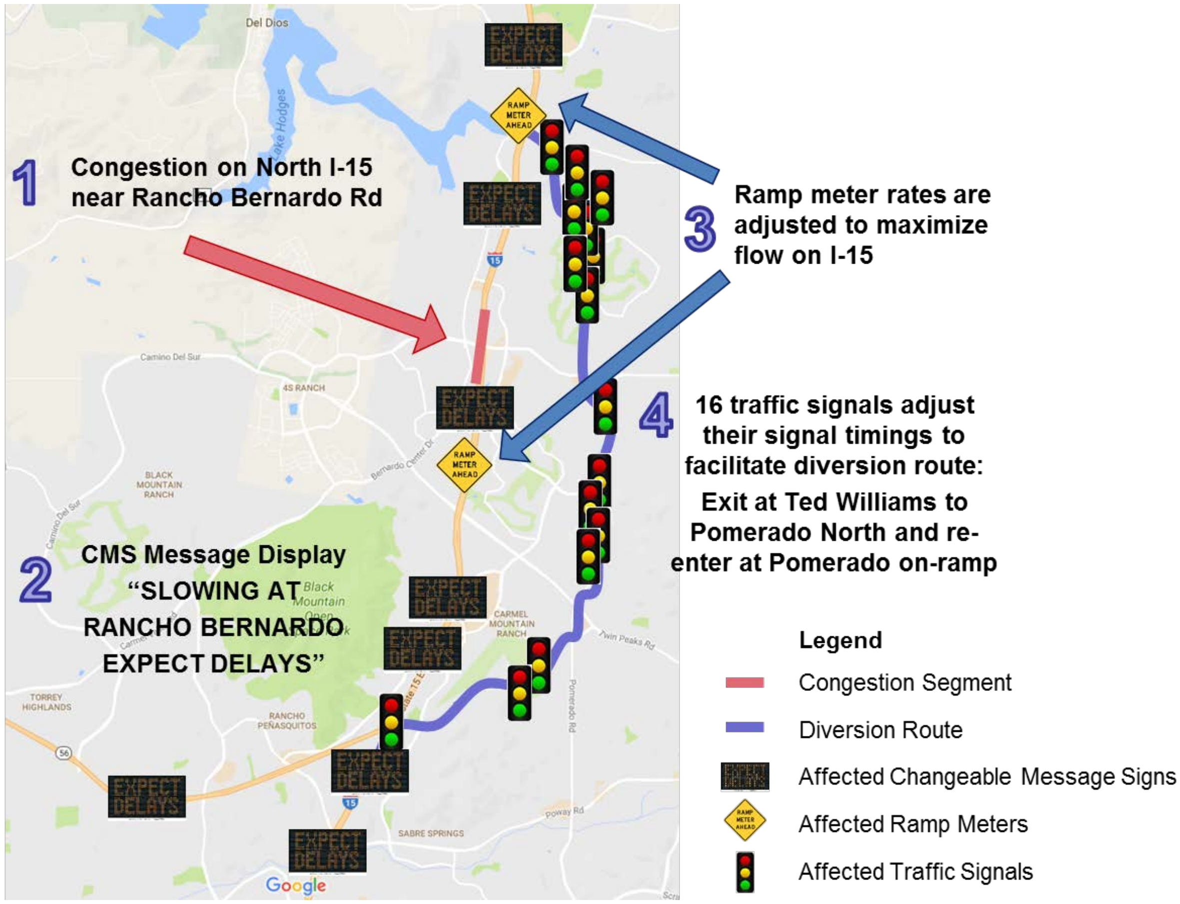

Figure 23. Diagram. Implementable response plan for peak direction scenario NB PM 3.
(Source: Google Maps, Cambridge Systematics, Inc., 2016.)

Summary

By multiplying the difference in PHT in Table 12 by each real scenario's percentage of total analysis time period and assuming 250 workdays in a year, the implementation of ICM is expected to produce savings of **267,850 annual person hours of travel,** a significant benefit that is generally consistent with the estimated travel time savings produced in the pre-deployment AMS analysis.

The scenarios in the northbound peak direction (NB PM 1, NB PM 2, NB PM 3, NB PM 4, and NB PM 5) represent 85.5 percent of the total time period, with a total of 511,762 travelers, while the scenarios in the southbound peak direction (SB AM 1, SB AM 2, and SB AM 3) represent 73.1 percent of the total time period, with a total of 441,733 travelers. This equates to a **cumulative annual travel time variability improvement of 188,816 hours** (also assuming 250 workdays in a year).

Emissions, Fuel Consumption, and Cost Estimation

The I-15 Corridor AMS also produced model outputs for use by the Evaluation Contractor to estimate emissions and fuel consumption, associated with the deployment of ICM strategies. The data provided to the Evaluation Contractor included: a) link lengths, link characterization (freeway, major arterial, minor arterial) and average grade for all network links, and b) average hourly directional link volumes and speeds for the I-15 freeway, Express Lanes, and arterials within the study area. The emissions analysis methodology will incorporate reference values to identify the emissions and fuel consumption rates based on variables, such as facility type, vehicle mix, and travel speed. The emissions and fuel consumption rates will be based on available sources. Emissions will be computed by pollutant, mode, and facility type. Fuel consumption will be computed by fuel type, mode, and facility type.

For the identified ICM strategies and based on input by the Evaluation Contractor, planning-level cost estimates will be prepared for life-cycle costs (capital, operating, and maintenance costs). Within each of the capital, O&M, and annualized cost estimates, the costs are further disaggregated to show the infrastructure and incremental costs. The costs will be estimated for each scenario and a benefit/cost ratio will be assigned to all the individual performance measures. The annualized benefits for each of the measures mentioned above will be calculated using cluster frequencies of occurrence as presented in Table 8.

Travel Time Beneficiaries

Table 16 shows the percentage of travelers along the corridor who are expected to experience improved, worsened or unchanged travel times, as a result of the implemented ICMS. For example, in the NB PM 1 scenario, a DSS plan was implemented which included adaptive freeway ramp metering, arterial traffic signal coordination, and ATIS. As a result, 51.3 percent of travelers experienced a shorter travel time than usual, while 47.41 percent of travelers' travel time increased, and 1.29 percent of travelers saw no change in their travel time. Overall, 3.89 percent of travelers in the NB PM 1 scenario experienced a travel time net gain (overall travel time *reduction*). The table below shows that overall, more travelers experienced travel time benefits in the northbound and southbound peak scenarios (+2.65 percent and +4.01 percent, respectively). This finding is consistent with the finding presented earlier in this chapter showing overall aggregate improvements in travel time as a result of ICM implementation.

Table 16. Travel time-based analysis results.

Scenario	Time Period Reported	Weighted Percent of Total Analysis Time Period	Improved Travel Time	Worsened Travel Time	Unchanged Travel Time	Improved % - Worsened %
NB PM 1	4-8 PM	19.0%	51.30%	47.41%	1.29%	3.89%
NB PM 2	2-6 PM	9.0%	48.94%	49.85%	1.21%	**-0.91%**
NB PM 3	2-6 PM	40.5%	51.85%	46.82%	1.33%	5.03%
NB PM 4	4-8 PM	28.1%	49.39%	49.39%	1.22%	**-0.01%**
NB PM 5	3-7 PM	3.4%	48.65%	49.81%	1.54%	**-1.16%**
NB PM (weighted avg)		100%	50.68%	48.03%	1.29%	2.65%
SB AM 1	6-10 AM	38.2%	50.02%	48.26%	1.72%	1.76%
SB AM 2	6-10 AM	51.3%	51.81%	46.23%	1.96%	5.58%
SB AM 3	6-10 AM	10.5%	51.36%	46.83%	1.81%	4.52%
SB AM (weighted avg)		100%	51.08%	47.07%	1.85%	4.01%
Hypothetical	6-10 AM	N/A	50.40%	47.92%	1.68%	2.48%

(Source: Cambridge Systematics, Inc., 2016.)

"As-Planned" vs. "As-Deployed" AMS Results

The main difference in the scope of the pre- and post-deployment analyses was that the time period of analysis was extended for post-deployment analysis. Instead of focusing only on the AM peak period (6-9 AM), both AM (6-10 AM) and PM (3-7 PM) peak periods were simulated. In pre-deployment AMS in order to estimate annual travel time savings, the AM peak period results were doubled to reflect the PM peak period as well. The ICM strategies remained the same in both pre- and post-deployment analysis. Another difference was that in pre-deployment analysis the TransModeler analysis tool was used, whereas in post-deployment analysis the Aimsun tool was used. Post-deployment AMS used incident details exactly as they occurred, while pre-deployment AMS modeled incidents based on aggregate statistical data on incident frequencies, durations and locations.

Pre-deployment AMS analysis of the "as-planned" ICM system estimated an annual savings of 245,594 vehicle hours of travel (Source: Alexiadis, V. and A. Armstrong, Integrated Corridor Management Modeling Results Report: Dallas, Minneapolis, and San Diego. No. FHWA-JPO-12-037. 2012.). This equates to approximately 282,433 person hours of travel, using an average vehicle occupancy rate of 1.15, while post-deployment AMS analysis of the "as-deployed" ICM system estimated a 267,850 person hour annual savings in the peak directions. The "as-deployed" ICM system was estimated to achieve nearly the same level of travel time savings as the "as-planned" ICM system. While this indicates that AMS is a powerful tool capable of simulating realistic mobility results under a set of ICM strategies, "as-deployed" analysis was more detailed, included several model improvements, and yielded additional insights on when and where benefits are accrued.

Overall Analysis Findings

Overall, the I-15 corridor post-deployment AMS results show consistent travel time improvements in the two peak directions as a result of ICM implementation.

Summary of post-deployment AMS key findings:

- For the two peak directions (southbound AM and northbound PM), the expected daily travel time savings are 1,403 person hours of travel; expected annual savings are 267,850 person hours of travel (approximately 3.3% of delay along the corridor using 35 hours of annual freeway delay per traveler per SANDAG's San Diego Site: I-15 ICM Demonstration Project presentation at the American Public Transportation Association TransITech Conference on March 30, 2011 and an average daily traffic volume of 230,000 per Caltrans District 11 Interstate-15 Transportation Concept Summary published in June 2012).
- The Planning Time Index only improves during the southbound morning peak direction. The Buffer Time improves in both peak directions.
- Travel time variability improves during both peak directions; expected cumulative annual variability improvements is 188,816 hours.
- Overall, more travelers experienced travel time benefits in both peak directions, as well as in the hypothetical severe incident scenario. On average (weighted by percent of total time period of individual clusters), +2.65% of travelers experienced travel time benefits in the northbound PM aggregated scenario and +4.01% experienced travel time benefits in the southbound PM aggregated scenario.

- Overall, in six out of the eight analysis scenarios (excluding the hypothetical scenario), more travelers benefited from ICM, compared to the ones who did not.
- A hypothetical AMS exercise examined the potential benefit of opening the Express Lanes to all traffic during a major incident. No travel time benefits were found in AMS resulting from this potential action for the scenario analyzed.

Benefits of Analysis, Modeling, and Simulation

Whereas the Dallas and San Diego Demonstration Sites followed the same ICM AMS framework, the San Diego I-15 corridor was found to experience approximately 10 times the amount of travel time savings and reliability improvements when compared to the Dallas U.S. 75 corridor. Both sites utilized similar ICM strategies to counteract bottlenecks and/or incidents, such as improved multimodal traveler information, coordinated traffic signal timings, mode shift and route diversion. One of the key differences was how the San Diego ICMS was designed around the concept of real-time adaptive response to changing traffic conditions, unlike the more rigid pre-defined expert rules-based response plans used in Dallas' ICMS. Based on the AMS results from both Demonstration Sites, it is possible that Dallas' fixed playbook system produced limitations which resulted in less significant benefits.

Coordination between and among local and regional agencies promoted data sharing from independently managed systems (transit, freeways, arterials, Express Lanes, incident management), which facilitated a real-time multimodal decision support system. The use of network state prediction in conjunction with real-time simulation and analysis of recommended response plans resulted in an effective decision support system, and was an innovative way to bring performance measures from planning to operations, a fundamental element of Transportation System Management and Operations (TSM&O). The ability of the San Diego ICMS to make automated traffic management decisions (e.g., automatically adjusting signals and ramps when recommended by the simulated evaluations) is the first of its kind in the nation. In the spirit of continuous improvement, 40 alternate route signs were recently installed on surface streets along the I-15 corridor throughout Escondido, Poway, and San Diego, which are used to guide vehicles through surface streets in the event of a major freeway incident.

The AMS methodology and results presented in this report demonstrate the feasibility of reducing congestion using ICM. The observations and benefits of AMS listed below highlight the lessons learned through this initiative.

The AMS process provides an invaluable framework for conducting assessments of the potential impacts and benefits of ICM strategies. The analytical complexity involved in these types of assessment goes far beyond what is typically required for more traditional types of transportation investments. The inclusion of multiple facility types (freeway and arterial) and multiple modes, combined with the potential influence of congestion pricing, complicates the analysis. The focus of the ICM strategies on nontypical operations scenarios (e.g., high demand, incidents, and inclement weather) adds further complexity to the assessment. The AMS procedures provide a pragmatic roadmap to guide practitioners through this complexity while not being too rigid to allow for flexibility in addressing project contingencies.

One major benefit of the ICM AMS methodology for San Diego was that it instigated the use of performance measures to inform and refine the response plans. This allowed AMS to provide insights through measurable results, enabling stakeholders to determine how well the ICM system is working and whether it is accomplishing its goals. This is a major factor that can help agencies determine which transportation investments are worthwhile.

The ICM AMS methodology also builds in continuous improvement through the availability of new data sources. AMS allows agencies to "see around the corner", producing simulations of possible future conditions, allowing agencies to react proactively. AMS offers the flexibility of trying different combinations of traffic mitigation strategies, opening up an envelope of potential benefits, and can also provide more insight to realizing benefits. While models may take effort to set up initially, these models are not only used once. Managers can integrate the methodology with ICM decision support systems to facilitate predictive, real-time, and scenario-based operational decision-making. Overall, this helps agencies create better, more informed products and services.

For the ICM Demonstration Sites (Dallas and San Diego), the costs of developing and conducting AMS accounted for approximately five percent of the overall deployment budget. If the analysis was successful in better structuring the deployment to increase the efficiency of the ICM by a minimum of five percent, or reduced the risk of a deployment cost overrun of five percent or more, the investment in AMS paid for itself. The partners at the Demonstration Sites felt there was significant value in AMS which greatly outweighed the analysis costs. The AMS costs for the Demonstration Sites were likely proportionately higher than they would be in future analysis, due to the need to develop and refine new analysis methods and procedures. Hopefully, the best practices from this development procedure, highlighted in the Traffic Analysis Toolbox Volume XIII "Integrated Corridor Management Analysis, Modeling, and Simulation Guide", can be leveraged by subsequent practitioners to reduce the costs of conducting these activities.

The Demonstration Sites reported that using AMS not only improved their analysis capabilities for the ICM evaluation, but also served to enhance many existing tools and capabilities that can be applied to analysis of other investments. This analytical capital will enhance future analysis and increase confidence in the models. Some of the improvements reported by the Demonstration Sites included new software modules for analysis of multimodal assignment (transit), congestion pricing, Express Lanes, ramp metering, and real-time decision support systems. The Demonstration Sites also cited improved data quality control methods and enhanced model calibration procedures as examples of the continuous improvement benefits of the AMS process.

The ICM AMS approach is neither inexpensive, nor easy to accomplish. However, the value gained outweighs the expense and pays dividends throughout an ICM initiative. The lessons learned during this ICM initiative can be applied to other initiatives as well (e.g., Connected Vehicle Pilot Deployment Program). These closing thoughts highlight the benefits of successful ICM AMS planning and implementation:

- **Invest in the right strategies.** The methodology offers corridor managers a predictive forecasting capability that they lack today to help them determine which combinations of ICM strategies are likely to be most effective under which conditions.
- **Invest with confidence.** AMS allows corridor managers to "see around the corner" and discover optimum combinations of strategies as well as conflicts or unintended consequences inherent in certain combinations of strategies that would otherwise be unknowable before implementation.

- **Improve the effectiveness/success of implementation.** With AMS, corridor managers can understand in advance what questions to ask about their system and potential combinations of strategies to make any implementation more successful.
- AMS provides a long-term capability to corridor managers to **continually improve implementation** of ICM strategies based on experience.

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APPENDIX A. List of Acronyms

AMS	Analysis, Modeling, and Simulation
ATIS	Advanced Traveler Information Systems
ATMS	Advanced Traffic Management System
BRT	Bus Rapid Transit
CATT	Center for Advanced Transportation Technology
CMS	Changeable Message Sign
CHP	California Highway Patrol
CPS	Congestion Pricing System
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CT-RAMP	Coordinated Travel – Regional Activity Based Modeling Platform
DAR	Direct Access Ramps
DSS	Decision Support System
FHWA	Federal Highway Administration
GPS	Global Positioning System
HC	Hydrocarbon
HOV	High-Occupancy Vehicle
I-15	Interstate 15
ICM	Integrated Corridor Management
ICMS	Integrated Corridor Management System
IMTMS	Intermodal Transportation Management System
ITS	Intelligent Transportation Systems
MD	Mid-Day
MTS	Metropolitan Transit System
NB	Northbound
NCTD	North County Transit District
NO_x	Nitrogen Oxides
OD	Origin-Destination
PeMS	Performance Measures System
PHT	Person Hours Traveled
PM	Particulate Matter
PMT	Person Miles Traveled
RAMS	Regional Arterial Management System
RITIS	Regional Integrated Transportation Information System
RMIS	Ramp Metering Information System
SANDAG	San Diego Association of Governments
SB	Southbound
SO_2	Sulfur Dioxide
SR	State Route
SOV	Single-Occupancy Vehicle
SUE	Stochastic User Equilibrium
TDM	Travel Demand Model
TSM&O	Transportation System Management and Operations
TSS	Transport Simulation Systems
UE	User Equilibrium
US DOT	U.S. Department of Transportation

V/C	Volume/Capacity
VHT	Vehicle Hours Traveled
VMT	Vehicle Miles Traveled
VOC	Volatile Organic Compound

APPENDIX B. Performance Measure Calculation Using Simulation

This appendix describes the methodology used in calculating various performance measures for the ICM AMS as summarized in this report.

Calculation Procedures for Key Integrated Corridor Performance Measures from Simulation Outputs

A core element of the Integrated Corridor Management (ICM) initiative is the identification and refinement of a set of key performance measures. These measures represent both the bottom-line for ICM strategy evaluation and define what "good" looks like among key corridor stakeholders. To date, the emphasis on performance-driven corridor management among the participating Pioneer sites has been on measures derived from observed data. In the Analysis, Modeling, and Simulation (AMS) phase of the effort, however, attention has turned to producing comparable measures derived from simulation outputs. This document provides a detailed process by which a set of key national measures of corridor performance can be calculated. It is the intent of the ICM program, and this document, that these processes will be implemented consistently in the three participating AMS sites applying the ICM AMS methodology.

This document provides a detailed description of how measures of ***delay***, ***travel time reliability*** and ***throughput*** are calculated from simulation outputs. A brief discussion of travel time variance is also provided given that travel time variance measures are used in ICM-related benefit-cost calculations. The algorithmic approaches defined here are software independent, that is, this process can be implemented with outputs from any of the time-variant simulation tools utilized in the three participating ICM AMS sites. The document begins with a discussion of the calculation of travel time, which informs both a calculation of delay as well as travel time reliability. Next, we provide a discussion of how corridor throughput is defined and measured. The document concludes with a discussion of how these measures are used to make comparisons between system performance in the pre-ICM case and in one or more distinct post-ICM cases.

Travel Time

Our basic unit of observation in calculating ICM-related performance measures is a trip i made between an origin o, finishing at a destination d, starting within a particular time interval τ using mode m.

We record travel time from a single run of the simulation under operational conditions k for this unit of observation as $t_i^k = t_{o,d,\tau',m}^k$. In the case where multiple random seeds are varied, but the operational conditions are identical, this travel time represents an average for a single trip across the multiple runs. Also, note that this discussion of measures assumes that we are calculating measures for a single case (e.g., pre-ICM); later we will address comparisons between cases.

Operational conditions here refer to a specific set of simulation settings reflecting a specific travel demand pattern and collection of incidents derived from a cluster analysis of observed traffic count data and incident data. An example of an operational condition would be an AM peak analysis with 5 percent higher than normal demand and a major arterial incident. Let k be a specific operational condition and the set of all conditions K. Note that each condition has a probability of occurrence p_k and $\sum_k p_k = 1$.

First, for this particular run(s) representing a specific operational condition, we calculate an average travel time for trips between the same o-d pair that begin in a particular time window. Let τ represent this interval, e.g., an interval between 6:30 AM and 6:45 AM and $\mathbf{I}^k_{o,d,\tau,m}$ the set of $n^k_{o,d,\tau,m}$ trips from o to d starting in interval τ under operational condition k using mode m. Note that $\mathbf{I}^k_{o,d,\tau,m}$ is a collection of trips and $n^k_{o,d,\tau,m}$ the scalar value indicating the number of trips contained in $\mathbf{I}^k_{o,d,\tau,m}$. The set of all τ of interest is the set T. For example, we may be interested in consistently calculating performance measures over all trips that begin in the 12 quarter-hour intervals between 6:00 AM and 9:00 AM.

The classification of travel mode may be determined independently at each site, but the breakdown should capture the combination of all modes utilized in making the trip. For example, one may choose to classify non-high-occupancy (HOV)-auto trips as a mode separately from non-HOV-auto/HOV/walk trips to track the performance of travelers utilizing park-and-ride facilities. However, any classification of modes must be mutually exclusive and collectively exhaustive, that is, $\bigcup_m \mathbf{I}^k_{o,d,\tau,m} = \mathbf{I}^k_{o,d,\tau}$ and $\sum_m n^k_{o,d,\tau,m} = n^k_{o,d,\tau}$.

The average travel time of trips with origin and destination by mode staring in this time interval is:

$$T^k_{o,d,\tau,m} = \frac{\sum_{i \in \mathbf{I}^k_{o,d,\tau}} t^k_i}{n^k_{o,d,\tau,m}} \tag{1}$$

where $n^k_{o,d,\tau,m} > 0$. Let $T^k_{o,d,\tau,m} = 0$ when $n^k_{o,d,\tau,m} = 0$.

The calculation of Equation 1 must also include some estimated travel time for trips that cannot reach their destinations by the end of the simulation period. Later in this document, we will discuss the method for estimating travel times for these trips still underway when the simulation ends.

Next, we calculate the average travel time for this same set of trips across all operational conditions, that is, $\forall k \in K$. Note that it is possible that we may have trips for some o, d, τ, m under some conditions and no trips for the same o, d, τ, m under other conditions. Let $K'_{o,d,\tau,m}$, $K'_{o,d,\tau,m} \subseteq K$ be the subset of conditions where $n^k_{o,d,\tau,m} > 0$.

Equation 2 finds the average travel time by mode for all trips from o to d starting in interval τ over all conditions where at least one trip is made, $k \in K'_{o,d,\tau,m}$:

$$T_{o,d,\tau,m} = \frac{\sum_{k \in K'_{o,d,\tau,m}} T^k_{o,d,\tau,m} p_k}{\sum_{k \in K'_{o,d,\tau,m}} p_k} \tag{2}$$

The average number of trips by mode from o to d starting in interval τ over all conditions $k \in K$:

$$n_{o,d,\tau,m} = \sum_{k \in K} n^k_{o,d,\tau,m} p_k \tag{2a}$$

Combining across modes, the average travel time of trips from o to d starting in interval τ under operational condition k:

$$T^k_{o,d,\tau} = \frac{\sum_m T^k_{o,d,\tau,m} n^k_{o,d,\tau,m}}{n^k_{o,d,\tau}} \tag{3}$$

where $n^k_{o,d,\tau} > 0$. Let $T^k_{o,d,\tau} = 0$ when $n^k_{o,d,\tau} = 0$.

The average travel time for all trips from o to d starting in interval τ under $K'_{o,d,\tau}$ the subset of conditions where $n^k_{o,d,\tau} > 0$, $K'_{o,d,\tau} \subseteq K$:

$$T_{o,d,\tau} = \frac{\sum_{k \in K'_{o,d,\tau}} T^k_{o,d,\tau} p_k}{\sum_{k \in K'_{o,d,\tau}} p_k} \tag{4}$$

The average number of trips from o to d starting in interval τ over all conditions $k \in K$:

$$n_{o,d,\tau} = \sum_{k \in K} n^k_{o,d,\tau} p_k \tag{4a}$$

Equation 5 defines the trip-weighted average travel time of the system across all o, d, τ:

$$\overline{T} = \frac{\sum_{\forall o,d,\tau} T_{o,d,\tau} n_{o,d,\tau}}{\sum_{\forall o,d,\tau} n_{o,d,\tau}} \tag{5}$$

Delay

Delay can be broadly defined as travel time in excess of some *subjective minimum* travel time threshold. Often, discussions of delay focus solely on roadway-only travel focus on either travel time at posted speeds or 85th percentile speeds. Delay for ICM must be defined differently since ICM explicitly includes multimodal corridor performance. Instead, we directly identify delay at the o, d, m

level by deriving a zero-delay threshold $T^0_{o,d,m}$, considering travel times observed across all operating conditions $\forall k \in K$ and all time intervals $\forall \tau \in T$.
The zero-delay threshold for each o-d pair by mode is calculated looking across all operating conditions and all time intervals:

$$T^0_{o,d,m} = \min_{k \in K, \tau \in T} \left\{ T^k_{o,d,\tau,m} \right. \tag{6}$$

In some cases, the cluster analysis will group low-demand, nonincident conditions into a large, high-probability operational condition. In this case, it is possible that a notionally "low" demand pattern will still produce significant congestion in the corridor, particularly in a peak period analysis.

For this reason, the minimum threshold may also be calculated as the travel time derived in the pre-ICM case under a substantially reduced demand pattern with no incidents or weather impacts. The reduced demand pattern should produce enough trips to generate travel time statistics by mode for every set of trips from o to d starting in interval τ (i.e., $n^0_{o,d,\tau,m} > 0 \ \forall\ o, d, \tau, m$). At the same time, the reduced demand should generate no volume-related congestion in the network.

Alternatively, $T^0_{o,d,m}$ may be estimated directly from model inputs. For consistency, however, the travel time associated with these thresholds should include expected transfer time between modes and unsaturated signal delay as in the case where a low-demand pattern is used to drive a zero-delay model run.

From our previous calculation of travel time in Equation 1, recall the average travel time of all trips traversing the network from origin o to destination d starting in time interval τ using mode m under operational condition k, $T^k_{o,d,\tau,m}$
Using zero-delay thresholds $T^0_{o,d,\tau,m}$, calculate average trip delay under condition k for each o, d, τ, m:

$$D^k_{o,d,\tau,m} = max\left[T^k_{o,d,\tau,m} - T^0_{o,d,\tau,m}, 0\right] \tag{7}$$

Combining across all operational conditions, calculate the average delay for each o, d, τ, m over $K'_{o,d,\tau,m}$, the subset of conditions where $n^k_{o,d,\tau,m} > 0$.

$$D_{o,d,\tau,m} = \frac{\sum_{k \in K'_{o,d,\tau,m}} D^k_{o,d,\tau,m} p_k}{\sum_{k \in K'_{o,d,\tau,m}} p_k} \tag{7a}$$

Combining across modes, the average delay for trips from o to d starting in interval τ :

$$D_{o,d,\tau} = \frac{\sum_m D_{o,d,\tau,m}\, n_{o,d,\tau,m}}{n_{o,d,\tau}} \tag{8}$$

where $n_{o,d,\tau} > 0$. Let $D_{o,d,\tau} = 0$ when $n_{o,d,\tau} = 0$.

Systemwide average trip delay (Equation 9):

$$D = \frac{\sum_{\forall o,d,\tau} D_{o,d,\tau} n_{o,d,\tau}}{\sum_{\forall o,d,\tau} n_{o,d,\tau}} \tag{9}$$

Aggregating this average delay over all trips produces total system delay (Equation 10):

$$\hat{D} = \sum_{\forall o,d,\tau} D_{o,d,\tau} n_{o,d,\tau} \tag{10}$$

Travel Time Reliability

Corridor reliability measures are inherently measures of outlier travel times experienced by a traveler making the same (or similar) trip over many days and operational conditions. We have already defined and organized travel time measures from the simulation with respect to trips from o to d starting in interval τ over using mode m for all conditions $k \in K$. Just as in the case of the subjective notion of delay as travel time in excess of some minimum threshold, the notion of what reliable travel is depends on a *relative maximum* acceptable travel time threshold. For the ICM AMS effort, as in many studies with a travel reliability measure, a threshold based on the 95th percentile travel time is selected. Note that this percentile is calculated considering travel times for similar trips (i.e., o, d, τ, m) with respect to travel time variation induced by changes in operational conditions $k \in K$.

To identify the 95th percentile travel time, first we generate an ordered list of travel times for each o, d, τ, m across all operating conditions:

$$\mathrm{T}_{o,d,\tau,m} = \left[T^1_{o,d,\tau,m}, T^2_{o,d,\tau,m}, \cdots, T^J_{o,d,\tau,m}\right] \text{ where } T^j_{o,d,\tau,m} \le T^{j+1}_{o,d,\tau,m} \text{ for all } j = 1 \cdots J. \tag{11}$$

The 95th percentile travel time from this list is identified using the probabilities associated with each operational condition.

$$T^{[95]}_{o,d,\tau,m} = T^j_{o,d,\tau,m} \text{ where } \sum_{k=1}^{j} p_k = 0.95 \tag{11a}$$

Note the array of travel times $\mathbf{T}_{o,d,\tau,m}$ represents levels on a linear step-function. This implies that if 17.4 minutes is the travel time associated with an operational condition occupying the 92nd through 98th travel time percentile, we simply use the 17.4-minute travel time as the 95th percentile value. Also note that the specific operational conditions under which the 95th percentile travel time is found will vary among o, d, τ, m. For example, a major freeway incident creates congestion and high travel times for trips that originate upstream of the incident location, but creates free flowing and uncongested conditions for trips that originate downstream of the incident location.

Equation 12 defines planning time index for each o, d, τ, m, the ratio of the 95th percentile travel time to the zero-delay travel time for trips from o to d starting in interval τ using mode m over all conditions $k \in K$:

$$\rho_{o,d,\tau,m} = \frac{T^{[95]}_{o,d,\tau,m}}{T^{0}_{o,d,\tau,m}} \tag{12}$$

Equation 12a defines planning time index by o,d,τ across all modes:

$$\rho_{o,d,\tau} = \frac{\sum_m \rho_{o,d,\tau,m}\, n_{o,d,\tau,m}}{n_{o,d,\tau}} \tag{12a}$$

Average systemwide planning time index considers all o,d,τ , weighted average by trip volume:

$$\rho = \frac{\sum_{\forall o,d,\tau} \rho_{o,d,\tau}\, n_{o,d,\tau}}{\sum_{\forall o,d,\tau} n_{o,d,\tau}} \tag{13}$$

We may also be interested in trip-weighted planning time index within a mode across all o,d,τ :

$$\rho_m = \frac{\sum_{\forall o,d,\tau} \rho_{o,d,\tau}\, n_{o,d,\tau,m}}{\sum_{\forall o,d,\tau} n_{o,d,\tau}} \tag{13a}$$

Variance in Travel Time

Variance in travel time can be calculated in a variety of ways. The key here is that some care must be taken to isolate the specific variation of interest. Additionally, as variance is strongly influenced by outliers, in order to eliminate any potential bias introduced into the variance of travel times resulting from the estimation of a fulfilled travel time for incomplete travelers at the end of the simulation period, the variance calculation should be restricted to completed travelers defined as set $\ddot{\mathbf{I}}^k_{o,d,\tau}$ consisting of $\ddot{n}^k_{o,d,\tau}$ trips. While the inclusion of the fulfilled incomplete travelers' travel times in the other performance measures may be influenced by the same bias, the nature of the variance calculation magnifies the effects of that potential bias. This effect may be more significant in larger models where the calibration and validation efforts must be focused on the primary corridor or study area.

Given this, the variance in travel time among members of the same origin, destination, and time interval in a single run is:

$$V^k_{o,d,\tau} = \frac{\sum_{i \in \ddot{\mathbf{I}}^k_{o,d,\tau}} \left(\ddot{t}^k_i - \ddot{T}^k_{o,d,\tau}\right)^2}{\ddot{n}^k_{o,d,\tau} - 1} \tag{14}$$

Recall $K'_{o,d,\tau}$, $K'_{o,d,\tau} \subseteq K$ as the subset of conditions where $\ddot{n}^k_{o,d,\tau} > 0$. The variance of travel time for each o,d,τ under all operation conditions is then defined as:

$$V_{o,d,\tau} = \frac{\sum_{k \in K'_{o,d,\tau}} V^k_{o,d,\tau}\, p_k}{\sum_{k \in K'_{o,d,\tau}} p_k} \tag{14a}$$

The average variance among all o, d, τ is a weighted average of the variances:

$$V = \frac{\sum_{\forall o,d,\tau} V_{o,d,\tau}\, \ddot{n}_{o,d,\tau}}{\sum_{\forall o,d,\tau} \ddot{n}_{o,d,\tau}} \tag{14b}$$

Throughput

The role of a throughput measure in ICM is to capture the primary product of the transportation system: travel. Particularly in peak periods, the capability of the transportation infrastructure to operate at a high level of efficiency is reduced. One of the goals of ICM is to manage the various networks (freeway, arterial, transit) cooperatively to deliver a higher level of realized system capacity in peak periods. While throughput (e.g., vehicles per lane per hour) is a well-established traffic engineering point measure (that is, in a single location), there is no consensus on a systemwide analog measure. In the ICM AMS effort, we use the term *corridor throughput* to describe a class of measures used to characterize the capability of the integrated transportation system to efficiently and effectively transport travelers. We do not consider freight throughput in these calculations, although this could be revisited at a later date.

In order to support throughput measures, additional trip data need to be generated as simulation outputs. For each trip i made between an origin o, finishing at a destination d, starting at a particular time τ' we obtain from the simulation the travel time $t^k_{o,d,\tau'}$ and a distance traveled $s^k_{o,d,\tau'}$. In some cases, trip-level outputs from the simulation are only available at a vehicle level, so some trips may have multiple passengers associated with that trip (e.g., in the case of carpool travel). Let $x^k_{o,d,\tau'}$ represent the number of travelers associated with a particular trip record.

Passenger-miles traveled (PMT) are accumulated using a process similar to travel time. First, we convert individual trip PMT into an average PMT for trips from origin o to destination d with a trip start in time interval τ.

$$X^k_{o,d,\tau} = \frac{\sum_{i \in \boldsymbol{I}^k_{o,d,\tau}} s^k_i x^k_i}{n^k_{o,d,\tau}} \tag{15}$$

For trips that cannot be completed before the end of the simulation, see the following section for the estimation of total trip distance.

Equation 16 finds the average PMT for all trips from o to d starting in interval τ over all operational conditions $k \in K$:

$$X_{o,d,\tau} = \sum_{k \in K} X^k_{o,d,\tau} p_k \tag{16}$$

Equation 17 defines the aggregate PMT across all o, d, τ:

$$X = \sum_{\forall o,d,\tau} X_{o,d,\tau}\, n_{o,d,\tau} \tag{17}$$

Restricting the calculation of measures to selected cohorts is also relevant to the calculation of delay and travel time reliability measures. Although peak periods vary among the AMS sites in terms of the onset and duration of congestion, a consistent set of trips that contribute to measure calculation (others simply run interference) should be identified. As in the case of the throughput time cut-off point, US DOT may wish to prescribe specific times in the future.

Estimation of Travel Times and Travel Distance for Incomplete Trips

Trips that cannot complete their trips by the time that the simulation ends are still included in the calculation of all delay and travel time calculations. Our approach is to estimate total travel time including any additional time that would be required to complete the trip given the average speed of travel.

First, let $\ddot{\mathbf{I}}^{0}_{o,d,\tau}$ be the set of $\ddot{n}^{0}_{o,d,\tau}$ trips from origin o, destination d starting a trip in time interval τ that can be completed under the low-demand operational condition used to identify the zero-delay travel times.

The average distance traveled over these trips is:

$$\ddot{X}^{0}_{o,d,\tau} = \frac{\sum_{i \in \ddot{\mathbf{I}}^{0}_{o,d,\tau}} s_i}{\ddot{n}^{0}_{o,d,\tau}} \tag{24}$$

Note: If $\ddot{n}^{0}_{o,d,\tau} = 0$ then $\ddot{X}^{0}_{o,d,\tau}$ is indeterminate. In this case, find τ', the closest time interval such that $\underset{\tau'}{\arg\min} \left|\tau' - \tau\right|$ where $n^{0}_{o,d,\tau'} > 0$. Approximate $\ddot{X}^{0}_{o,d,\tau}$ using $\ddot{X}^{0}_{o,d,\tau'}$.

Next, let $\overleftarrow{\mathbf{I}}^{k}_{o,d,\tau}$ be the set trips from origin o, destination d starting a trip in time interval τ that *cannot* be completed under operational condition k. For all $i \in \overleftarrow{\mathbf{I}}^{k}_{o,d,\tau}$, let $\overleftarrow{x}^{k}_{i}$ be the distance traveled on the trip i up to the point where the simulation ends, and let $\overleftarrow{t}^{k}_{i}$ the travel time on trip i up to the point where the simulation ends. Average travel speed for a trip that cannot be completed is expressed in Equation 25:

$$\overleftarrow{v}^{k}_{i} = \frac{\overleftarrow{x}^{k}_{i}}{\overleftarrow{t}^{k}_{i}} \tag{25}$$

Estimated total trip travel time for a trip that cannot be completed before the simulation ends is the accumulated travel time plus the time to travel the remaining distance at average trip speed:

$$t^{k}_{i} = \overleftarrow{t}^{k}_{i} + max\left\{\frac{\left(\ddot{X}^{0}_{o,d,\tau} - \overleftarrow{x}^{k}_{i}\right)}{\overleftarrow{v}^{k}_{i}}, 0\right\} \tag{26}$$

$$x^{k}_{i} = \max\left\{\ddot{X}^{0}_{o,d,\tau}, \overleftarrow{x}^{k}_{i}\right\} \tag{27}$$

Comparing Pre-ICM and Post-ICM Cases

All of the travel time and throughput measure calculation procedures defined above are conducted under a single set of simulation settings reflecting a specific set of corridor management policies, technologies and strategies (here referred to as a *case*, but often called an *alternative*). The complete suite of delay, travel time reliability and throughput measures are calculated independently for each case (e.g., Pre-ICM or Post-ICM). Comparisons of the resulting measures are then made to characterize corridor performance under each case.

Comparing Observed and Simulated Performance Measures

These few key measures have been defined in detail for national consistency across all AMS sites. Sites have also identified measures. This document has dealt in detail with the calculation of measures from simulation outputs. However, the calculation of comparable measures using observed data demands an equivalent level of detailed attention. These observed measures will be critical in the AMS effort to validate modeling accuracy and in performance measurement in the demonstration phase. Because of the nature of the simulation output, the modeling analyst is able to resolve and track performance at a level of detail that is not available to an analyst working with field counts, speeds and transit passenger-counter outputs. However, it is the responsibility of the site and the AMS contractor to ensure that these measures are similar in intent, if not in precise calculation. In many cases, the simulation tools or their basic outputs can be manipulated to produce measures quite comparable with field data. An example of this is in throughput calculation, where a site may wish to pursue a screenline passenger throughput measure from field data. In addition to the system-level throughput measures detailed above, the simulation model can be configured to produce passenger-weighted counts across the same screenline to match the field throughput measure.

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

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

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