PARTNERS FOR ADVANCED TRANSPORTATION TECHNOLOGY
INSTITUTE OF TRANSPORTATION STUDIES
UNIVERSITY OF CALIFORNIA, BERKELEY

I-210 Connected Corridors Pilot

Analysis, Modeling, and Simulation: Report for Phase 1 Version 2

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Partners for Advanced Transportation Technology works with researchers, practitioners, and industry to implement transportation research and innovation, including products and services that improve the efficiency, safety, and security of the transportation system.

Primary Author

Anthony D Patire, PhD
Research and Development Engineer
California PATH
University of California, Berkeley

Contributing Authors

Joe Butler
Project Manager
California PATH
University of California, Berkeley

Ethan Xuan, PhD
Research Engineer
California PATH
University of California, Berkeley

Thomas Schreiter, PhD
Research Engineer
California PATH
University of California, Berkeley

Gabriel Gomes, PhD
Research Engineer
California PATH
University of California, Berkeley

Francois Dion, PhD, PE (Michigan)
Senior Development Engineer
California PATH
University of California, Berkeley

Paul Gabet, MS
Graduate Student Researcher
California PATH
University of California, Berkeley

Fred Winik
Technical Writer
California PATH
University of California, Berkeley

EXECUTIVE SUMMARY

Analysis, modeling, and simulation (AMS) is an evaluation process used to understand traffic operations along a corridor, identify key transportation challenges, and explore potential management strategies to be used to improve corridor operational performance. AMS is a crucial part of the systems engineering methodology tasked with insuring that solutions are chosen correctly, funds are spent effectively, and performance is measured quantitatively. AMS supports the Connected Corridors effort for the I-210 Pilot Project, and proceeds in phases along with the planning, implementation, deployment, and evaluation of the I-210 Pilot Project itself.

The first component of AMS is *analysis*, which means developing as thorough an understanding of the corridor as possible through detailed investigation of available information about the corridor.

The second component of AMS is *modeling*, which means developing and calibrating a model that captures existing traffic conditions. Model building is an iterative process that begins with the best data and best understood parts of the corridor, and continues as additional data are analyzed and the extent of the model is expanded.

The third component of AMS is *simulation*, which means using the developed model to improve understanding of traffic behavior on the corridor, and to define and select the best management strategies and control interventions to address its key challenges.

A PHASED APPROACH

The AMS effort unfolds in phases:

- Phase 1: Corridor analysis, funding support, and model development
- Phase 2: Corridor model completion and selection of management strategies
- Phase 3: Evaluation of I-210 Pilot

This report describes the work of AMS **Phase 1**. This phase focused on collecting, organizing, and analyzing corridor data, using the data to support funding requests, and converting the data into a useful form for modeling and simulation.

At the beginning, there was no single place where all corridor information was assembled; data were fragmented into multiple databases, across jurisdictions and facilities, stored in different formats, and organized separately. One success of Phase 1 is the extensive amount of data collected about the I-210 corridor, the identification of data gaps, and additional studies performed to fill those gaps. Synthesis of these data reveal a broad, detailed, and holistic picture of the I-210 corridor characteristics, operational challenges, capabilities, and user needs.

Areas with good data availability were identified. One such area, in Arcadia along the I-210 corridor between Michillinda and Huntington Dr., was selected as the Phase 1 test area. During Phase 1, the test area was used in the development and demonstration of an AMS methodology, described below. This methodology will be used in Phase 2 for defining and selecting ICM strategies for the I-210 Pilot Project.

This Phase 1 test area was then modeled and simulated, providing a venue to assess each step of the methodology itself. This process generated confidence in model choices, algorithm performance, and scalability. In addition, areas such as cost/benefit analysis were identified for further refinement.

AMS METHODOLOGY

The key steps in the methodology are:

1. Assess existing corridor operations.
    - Select the study area.
    - Collect and organize existing traffic data.
    - Assess data quality and data gaps.
    - Perform additional studies to fill data gaps.
    - Synthesize holistic view of corridor characteristics, challenges, capabilities, and needs.
2. Select a modeling approach and create a model to capture existing corridor operations.
3. Select scenarios that are representative of relevant transportation challenges. (Based on project scope, the current AMS effort focuses on incidents and incident management.)
4. Select feasible management strategies and control interventions to address the scenarios, using ramp meters, intersection signals, and the managed routing of travelers.
5. Run simulations to calculate performance metrics and measure effects of scenarios and interventions identified in steps 3 and 4.
6. Assess the infrastructure costs (capital, operations and maintenance) of implementing the selected strategies.
7. Evaluate the benefits gained from the various strategies against the costs of implementing them.

In practice, the execution of AMS is not a linear process. Many of the key steps are performed in parallel. For example, model calibration is an iterative process composed of several steps: Run the simulation as per step 5, compare with data obtained in step 1, reassess the trustworthiness of the data, make adjustments to the model in step 2, and repeat.

ANALYSIS

The analysis effort of Phase 1 has achieved a comprehensive inventory of the I-210 corridor, a detailed assessment of I-210 freeway data quality, and a categorization of corridor incidents. After initial data were gathered, the most glaring gaps in traffic demand information and in infrastructure capabilities were identified. Stakeholders and partners responded immediately to procure additional data. In addition, two funding applications were written to address infrastructure deficiencies:

- PSR/PR—Project Study Report / Project Report to Request Programming in the 2014 SHOPP and Provide Project Approval (07-LA-210 PM R24.7/R44.92): $20 million approved and in process.
- LACFP—Los Angeles County Metropolitan Transportation Authority (Metro) 2015 Call for Projects: $6 million awaiting approval.

Data is the lifeblood of traffic analysis and management, and the importance of high-quality data—including its timeliness, accuracy, and coverage—cannot be overstated. The AMS team conducted an in-depth assessment of data quality from loop detectors on the I-210 freeway and identified VDS (vehicle detection stations) that are working but do not capture an entire cross section of flow. Detectors are also categorized by issue type such as configuration error, location uncertainty, or counting error. Addressing these issues is crucial for real-time situational awareness and model calibration. Inadequate, incomplete, or contradictory data increases risk to the Pilot deployment, and may lead operators to make inaccurate assessments about corridor operational needs.

The AMS team performed a cluster analysis on the I-210 freeway to determine the distribution of incidents: their frequency, location, severity, and duration. In Phase 1, this information was then used to select a common incident type to simulate on the Phase 1 test area, and to carry through each step of the AMS methodology. In Phase 2, the cluster analysis will be used to build a family of scenarios that together are representative of corridor operations.

A large-scale Synchro model of the I-210 corridor was assembled that includes all intersection signal plans active at 5:00 pm, as well as approach flows and turning volumes from all area traffic studies between 2006 and 2014. There are over 500 intersections coded into the Synchro model, including about 450 signalized intersections, 63 stop controlled intersections, and 110 intersections with observed traffic counts. Stakeholders have requested the Synchro model and the data used to populate it in order to enhance their operational capabilities. This Synchro model is the AMS team's repository for "static" arterial data in a single, electronic format. In addition, the team now has software tools to extract this data and provide it to the macroscopic model.

MODELING AND SIMULATION

The Connected Corridors team is working to build new simulation tools using a macroscopic approach. The advantages of this model include its conceptual simplicity, appropriateness for the control and management strategies outlined in the Concept of Operations, and the fact that all parameters of the model are directly observable from field data.

The model was calibrated on the Phase 1 test area that included a westbound portion of the I-210 and a parallel arterial. A representative incident was simulated on the freeway during the PM in which one lane is blocked for 30 minutes. An intervention was simulated consisting of signal synchronization, downstream ramp meter adjustment to allow traffic to re-enter the freeway downstream of the incident, and a hypothetical change in traveler routing.

Based on simulations, this report describes how benefits may be assessed within the test area. The assessment is not intended to be an evaluation of the benefits of ICM, but rather an illustrative example of the proposed methodology. This work lays the foundation for the next phase of AMS, which will complete a model of the corridor, and define and select intervention strategies.

ASSESSMENT OF COSTS AND BENEFITS

In Phase 1, the team focused on identifying infrastructure upgrades such as sensing capabilities and improved information dissemination to travelers. As part of the ongoing systems engineering process, infrastructure requirements will continue to be identified, including control functions, communications connectivity, and decision support.

The benefits of reductions in delay, vehicle operating costs, emissions, and travel time reliability were computed with the help of Cal-B/C v5.0 Corridor[8], developed by Caltrans and System Metrics Group. Relative benefits with and without the intervention were calculated for the simulated incident.

Due to the tentative nature of the results and ongoing discussions with stakeholders on cost assumptions, this Phase 1 report does not present a direct benefit/cost comparison. This report is not to be interpreted as an evaluation of the benefits of ICM, but rather as an illustrative example of the methodology to be carried forward into Phase 2.

CONCLUSION

Phase 1 of AMS has achieved a comprehensive inventory of the I-210 corridor, a detailed assessment of I-210 freeway data quality, and a categorization of corridor incidents. Essential sections of funding applications were supported by the successful corridor analysis. A new model was developed over the Phase 1 test area. The model, including both freeway and arterial roads was successfully calibrated. A common incident type with and without intervention was simulated and evaluated. A costs and benefits methodology was demonstrated. All of these accomplishments are now ready to be applied in AMS Phase 2.

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1. INTRODUCTION AND BACKGROUND

Analysis, modeling, and simulation (AMS) is an evaluation process used to understand traffic operations along a corridor, identify key transportation challenges, and explore potential management strategies to improve corridor operational performance. AMS is a crucial part of the systems engineering methodology tasked with insuring that solutions are chosen correctly, funds are spent effectively, and performance is measured quantitatively. AMS supports the Connected Corridors effort for the I-210 Pilot Project, and proceeds in phases along with the planning, implementation, deployment, and evaluation of the I-210 Pilot Project itself.

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The second component of AMS is *modeling*, which means developing and calibrating a model that captures existing traffic conditions. Model building is an iterative process that begins with the best data and best understood parts of the corridor, and continues as additional data are analyzed and the extent of the model is expanded.

The third component of AMS is *simulation*, which means using the developed model to improve understanding of traffic behavior on the corridor, and to define and select the best management strategies and control interventions to address its key challenges.

The extensive amount of data collected about the I-210 corridor provides a broad and detailed picture of its characteristics, operational challenges, capabilities, and user needs. This information then raises key questions for the ICM project:

- How could ICM improve corridor performance?
- What are the most important scenarios that can be addressed by the project (recurrent congestion, incidents, weather, planned events, etc.)?
- What response strategies should be considered?
- How should the effectiveness of response strategies be measured?
- How should benefits and costs be assessed?

These questions are explored through analysis, modeling, and simulation.

1.1. ADVANTAGES OF AMS

Beyond the major advantage of being able to try out and analyze interventions in a simulated environment before deploying a system, AMS makes it possible to:

- Assess existing operating conditions
- Identify the most feasible and effective control strategies
- Reveal data and infrastructure gaps that might otherwise go unnoticed
- Identify unexpected challenges

- Significantly reduce project risk
- Quantify benefits and costs
- Provide justification for repairing and upgrading sensing and control elements
- Target infrastructure investments that will have the greatest impact
- Help stakeholders understand and visualize system dynamics at the corridor level
- Provide scenarios and response strategies for systems engineering documents
- Enhance common understanding among stakeholders

1.2. AMS OBJECTIVES FOR THE I-210 PILOT

The initial scope of the I-210 Pilot, determined through discussions with corridor stakeholders, will focus on managing incidents and events with freeway-arterial integration, gradually expanding to incorporate transit, parking, and demand management:

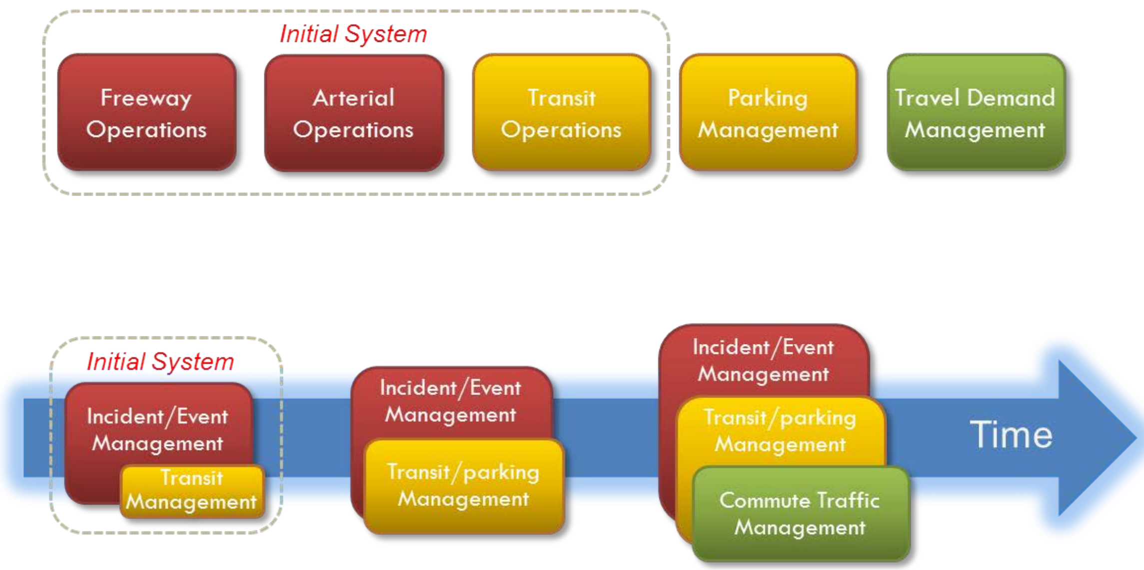

Figure 1-1: Project scope for the I-210 pilot

Based on this project scope, the AMS effort focuses on incidents and incident management and aims to:

1. Understand key challenges in providing efficient traffic operations along the corridor during incidents
2. Demonstrate integrated freeway and arterial simulation capabilities that capture “on the ground” conditions
3. Generate corridor-level metrics to characterize operations
4. Simulate the effects of incidents and management options that improve operations, using control strategies based on ramp meters, signal lights, and the managed routing of travelers (roads, transit, etc.)

1.3. PHASES OF AMS

The AMS effort will unfold in phases:

- **Phase 1: Corridor analysis, funding support, and model development**
  - Create analysis methodologies and procedures
  - Assess data availability and quality
  - Evaluate preliminary model results

- **Phase 2: Corridor model completion and selection of management strategies**
  - Extend model across the corridor
  - Calibrate corridor model
  - Develop, evaluate, and select management strategies

- **Phase 3: Evaluation of I-210 Pilot**
  - Utilize before and after studies to quantify corridor improvements

This report describes the work of AMS **Phase 1**. This phase focused on collecting, organizing, and analyzing corridor data, using the data to support funding requests, and converting the data into a useful form for modeling and simulation.

When AMS work began, there was no single place where all corridor information was assembled; data were fragmented into multiple databases, across jurisdictions and facilities, stored in different formats, and organized separately. One success of Phase 1 is the extensive amount of data collected about the I-210 corridor, the identification of data gaps, and additional studies performed to fill those gaps. Synthesis of these data reveal a broad, detailed, and holistic picture of the I-210 corridor characteristics, operational challenges, capabilities, and user needs.

Areas with good data availability were identified. One such area, in Arcadia along the I-210 corridor between Michillinda and Huntington Dr., was selected as the Phase 1 test area. During Phase 1, the test area was used in the development and demonstration of an AMS methodology, described in section 1.4. This methodology will be used in Phase 2 for defining and selecting ICM strategies for the I-210 Pilot Project.

This Phase 1 test area was then modeled and simulated, providing a venue to assess each step of the methodology itself. This process generated confidence in model choices, algorithm performance, and scalability. In addition, areas such as cost/benefit analysis were identified for further refinement.

1.4. OVERVIEW OF THE AMS PROCESS

The overall methodology for analysis, modeling, and simulation of the I-210 corridor is illustrated in Figure 1-2:

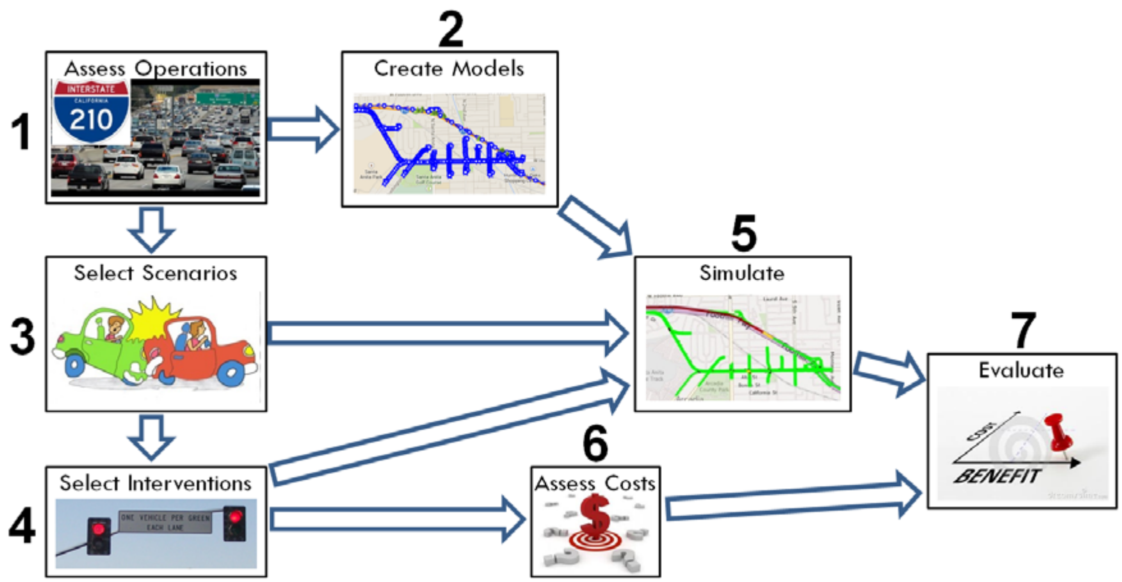

Figure 1-2: Overall AMS methodology

As the figure shows, the key steps are:

1. Assess existing corridor operations.
   a. Select the study area.
   b. Collect and organize traffic data.
   c. Assess data quality and data gaps.
   d. Perform additional studies to fill data gaps.
   e. Synthesize holistic view of corridor characteristics, challenges, capabilities, and needs.
2. Select a modeling approach and create a model to capture existing corridor operations.
3. Select scenarios that are representative of relevant transportation challenges. (Based on project scope, the current AMS effort focuses on incidents and incident management.)
4. Select feasible management strategies and control interventions to address the scenarios, using ramp meters, intersection signals, and the managed routing of travelers.
5. Run simulations to calculate performance metrics and measure effects of scenarios and interventions identified in steps 3 and 4.
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In practice, the execution of AMS is not a linear process. Many of the key steps are performed in parallel. For example, model calibration is an iterative process composed of several steps: Run the simulation as per step 5, compare with data obtained in step 1, reassess the trustworthiness of the data, make adjustments to the model in step 2, and repeat.

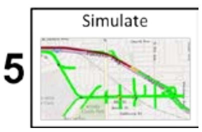
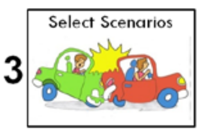
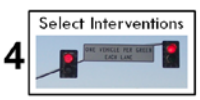
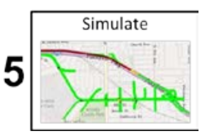
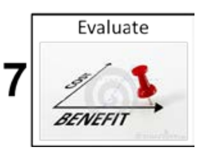
Although each of the steps in the methodology, from 1 through 7, was visited during Phase 1, the majority of the effort and time was spent on collecting and analyzing data, and converting it into a useful format to facilitate subsequent steps.

Essential terms used in this report

- **Scenario**: The operational challenge or problem to be addressed; in this report, an incident that affects traffic flow, such as a crash blocking one lane of the freeway for 30 minutes during a weekday afternoon peak period
- **Intervention**: The action taken to address the problem, such as changing signal plans or adjusting ramp meters to facilitate the flow of traffic off the freeway, onto arterials, and back onto the freeway downstream of the incident
- **Simulation**: A virtual representation that captures both the scenario and the intervention and measures their effects on traffic conditions

1.5. STRUCTURE OF THIS REPORT

This report is organized to illustrate the steps in the AMS methodology shown in Figure 1-2.

This chapter	Does this	And illustrates this step
Chapter 2: Corridor boundaries	Describes the corridor's boundaries and how the geographical limits are defined in the AMS effort	1 
Chapter 3: Assessing corridor operations and data	Presents an assessment of corridor operations and data, providing a context for more detailed analysis in subsequent chapters	
Chapter 4: Model development and calibration	Describes construction, calibration, and validation of the cell transmission model (CTM) chosen for this AMS effort. This process involves iteration among steps 1, 2, and 5 to obtain a baseline model.	1  2  5 
Chapter 5: Analysis process and simulation results	Presents: • the cluster analysis to identify a representative incident scenario • an intervention to mitigate congestion caused by the incident • the simulations to assess the intervention's effectiveness • the modeling and simulation results for a network spanning a section of I-210 and one parallel arterial	3  4  5 
Chapter 6: Assessing costs and benefits	Reviews the existing infrastructure along the I-210 corridor, estimates costs of upgrades to implement ICM management strategies, and illustrates a method for evaluating the benefits of doing so	6  7 
Chapter 7: Conclusion for AMS Phase 1	Summarizes the AMS Phase 1 effort and outcomes	
Chapter 8: Planning for AMS Phase 2	Explains next steps planned for AMS Phase 2	
Appendices	Presents additional information on data quality, the simulation model, and cost/benefit analysis	

2. CORRIDOR BOUNDARIES

This chapter describes the geographical boundaries of the I-210 corridor at several levels of granularity. These boundaries are based on discussions with stakeholders, as well as the evolving needs of the project.

2.1. MANAGED ROADWAYS FOR THE I-210 PILOT

The map in Figure 2-1 is drawn from the I-210 Concept of Operations (ConOps). This map includes all managed roadway sections in the first phase of the project area. The corridor section extends from the SR-134 interchange in the west to the I-605 interchange in the east and includes the major arterials from Huntington Drive and Duarte Road in the south to Orange Grove and Foothill Blvd. in the north, passing through the cities of Pasadena, Arcadia, Monrovia, and Duarte.

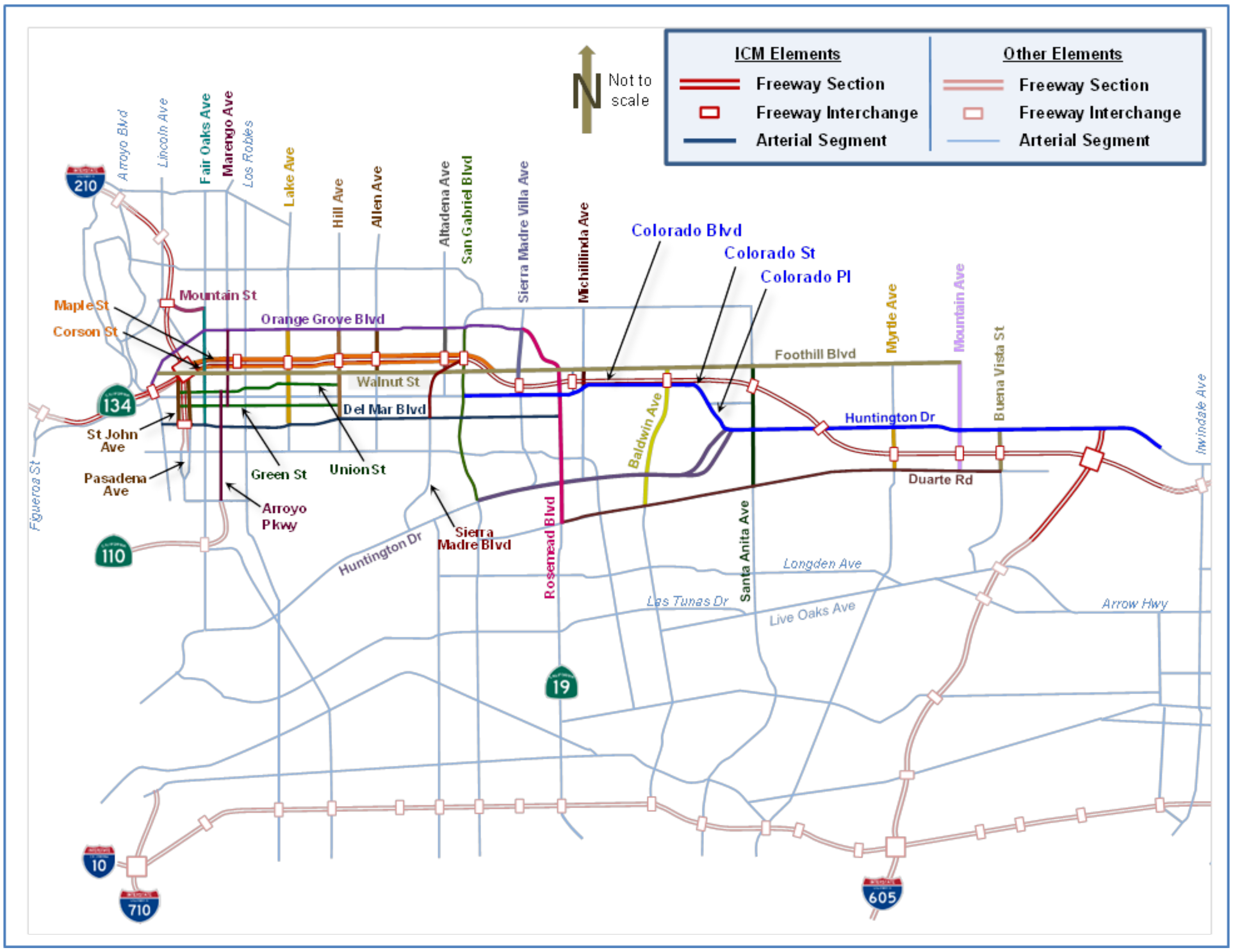


Figure 2-1: ConOps map of managed roadway sections

The following arterials, or combination of arterials, provide alternate routes parallel to the I-210 freeway:

- Orange Grove Boulevard
- Walnut Street / Foothill Boulevard
- Maple Street and Corson Street
- Colorado Boulevard / Colorado Street / Colorado Place
- Green Street and Union Street one-way couplet
- Del Mar Boulevard
- Huntington Drive
- Huntington Drive / Foothill Boulevard
- Duarte Road

To reach these parallel routes from the I-210 or I-10 freeway, drivers can take the following north-south arterials (in addition to the I-605 and SR-57 freeways):

- Mountain Street
- Saint John Avenue and Pasadena Avenue
- Fair Oaks Avenue
- Arroyo Parkway / Marengo Avenue
- Lake Avenue
- Hill Avenue
- Allen Avenue
- Sierra Madre Boulevard
- San Gabriel Boulevard
- Rosemead Boulevard (SR-19)
- Baldwin Avenue
- Santa Anita Avenue
- Myrtle Avenue
- Buena Vista Street

2.2. AREA STUDY MAP FOR AMS

To carry out the AMS effort for the project, it was necessary to identify the specific roadways that would be most important for modeling and simulation. Through ongoing discussions with corridor stakeholders, the Connected Corridors team was able to define the AMS study area shown in Figure 2-2. More detailed than the ConOps map, Figure 2-2 is intended to include all roads that are potentially relevant for simulation purposes. In addition to managed roadway sections, the area study map also includes roads that may experience secondary effects as a result of traffic response plans that are deployed on nearby managed roadway sections.

The map shows a base network of roads in purple. These purple roads have been selected based on the presence of signalized intersections and on their importance in discussions with stakeholders. This network extends to the east past Irwindale (not shown).

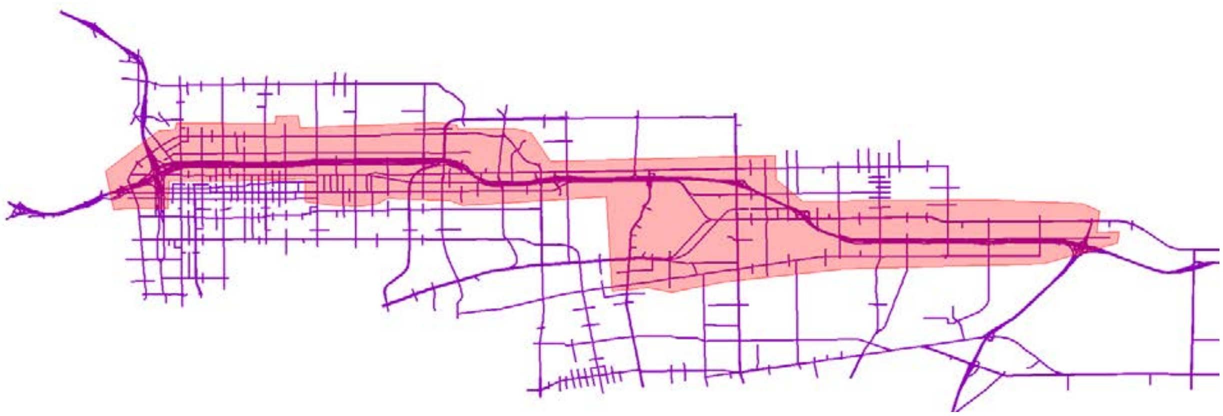


Figure 2-2: Area study map

The arterial streets inside the pink shaded region of Figure 2-2 have been scrutinized in detail. Geometries, lane counts, turn bays, etc. have been manually verified against satellite imagery. These arterials will be added to the model in AMS Phase 2.

This pink region includes the closest eastbound and westbound arterials on both the north and south sides of the I-210 freeway. The area inside Pasadena includes the access roads, Corson and Maple, in addition to Orange Grove Blvd. to the north and Walnut St. to the south. In Arcadia and eastward, the shaded region includes Foothill Blvd. and Duarte Road via Santa Anita Ave., as well as Colorado Blvd. and Huntington Drive.

2.3. AMS PHASE 1 MAP

The map in Figure 2-3 represents the region modeled and simulated in AMS Phase 1. The results in this version of the AMS report are based on this 2014 network. Additional roads will be added to the simulation model in AMS Phase 2.

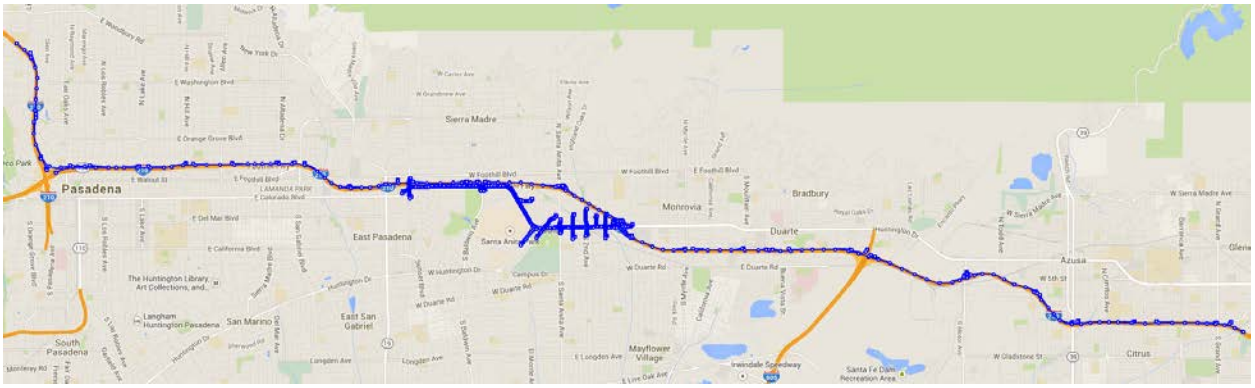


Figure 2-3: 2014 AMS Phase 1 test area network

The model includes about 18.5 miles of the I-210 freeway in the westbound direction. In addition, it includes a parallel route along Huntington and Colorado through Arcadia and part of Monrovia. The arterial is modeled in both eastbound and westbound directions, including all signalized intersections and their cross streets.

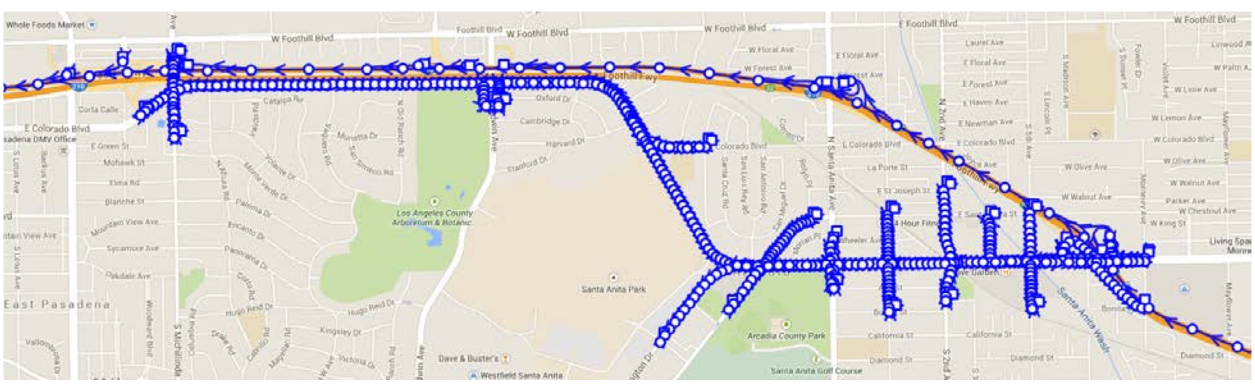


Figure 2-4: 2014 AMS Phase 1 test area detail

3. ASSESSING CORRIDOR OPERATIONS AND DATA

The assessment of corridor operations, the first step in the AMS methodology, identifies the corridor's main characteristics and transportation challenges and provides the context for subsequent steps in the AMS process. In the current AMS effort, the assessment was crucial in shaping such decisions as the extent of the freeway to be modeled and identifying key data gaps for additional traffic studies. Drawn from the Corridor Description and System Inventory [1], the assessment in this version of the AMS report focuses on:

- Freeway bottlenecks
- Freeway incidents
- Freeway data quality
- Arterial operations
- Arterial incidents
- Arterial data

3.1. FREEWAY BOTTLENECKS

Figure 3-1 and Figure 3-2 identify the main recurring bottlenecks associated with the AM and PM peak travel periods along the I-210 freeway. These bottlenecks were identified and verified during the winter of 2007 and spring of 2008 by the team that developed the I-210 Corridor System Management Plan (CSMP). The bottlenecks were identified based on data from Caltrans' 2006 State Highway Congestion Monitoring Program (HICOMP) Annual Data Compilation report, probe vehicle runs, Caltrans freeway detector data, aerial photos, field reviews, and other data sources.

As the figures show, most of the bottlenecks along the freeway are in locations with significant weaving traffic or traffic entering or exiting the freeway, in some cases compounded by roadway geometry factors such as sharp curves or lane drops.

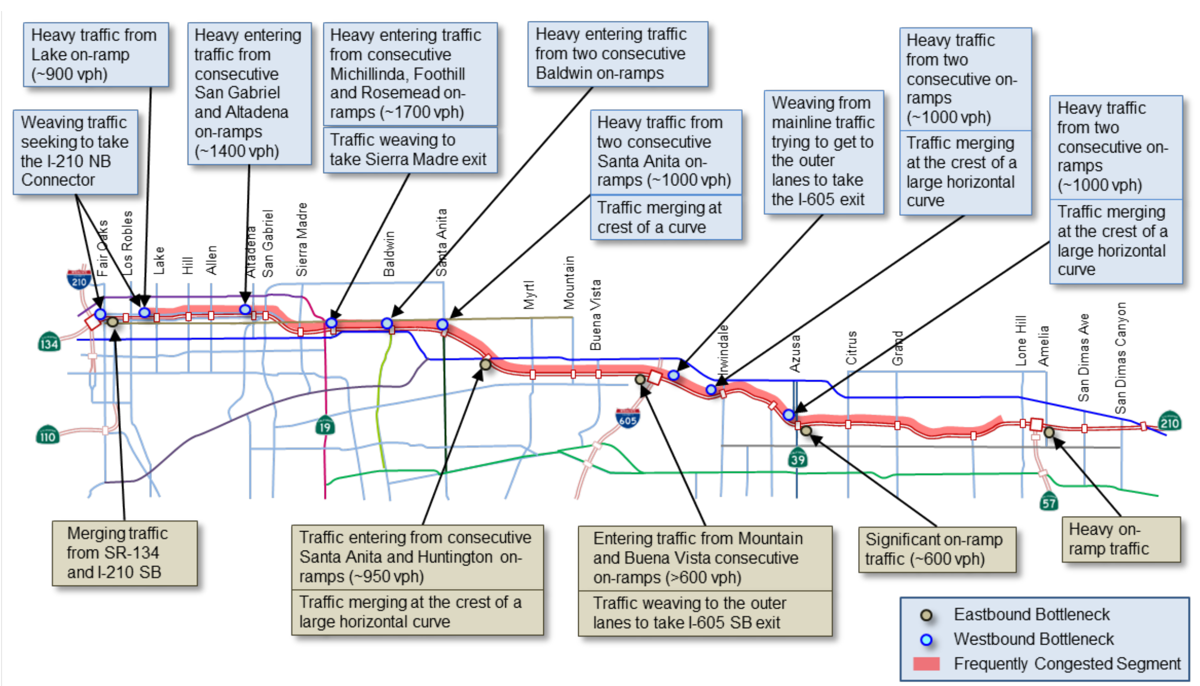


Figure 3-1: Major 2008 bottlenecks – AM peak

In each direction, the bottlenecks on the HOV lane typically occur at the same location as the bottlenecks on the freeway mainline. This is primarily due to the close proximity of the HOV lane to the mainline traffic lanes. Along the I-210, the HOV lane is separated from the mainline lanes by a simple double yellow-and-white stripe separation about two feet in width. The HOV lane also has little to no inside shoulder. When stop-and-go traffic occurs on the mainline, traffic on the HOV lane also slows down, mainly out of caution, thus resulting in a flow breakdown, particularly near the HOV lane ingress/egress locations and at roadway curves.

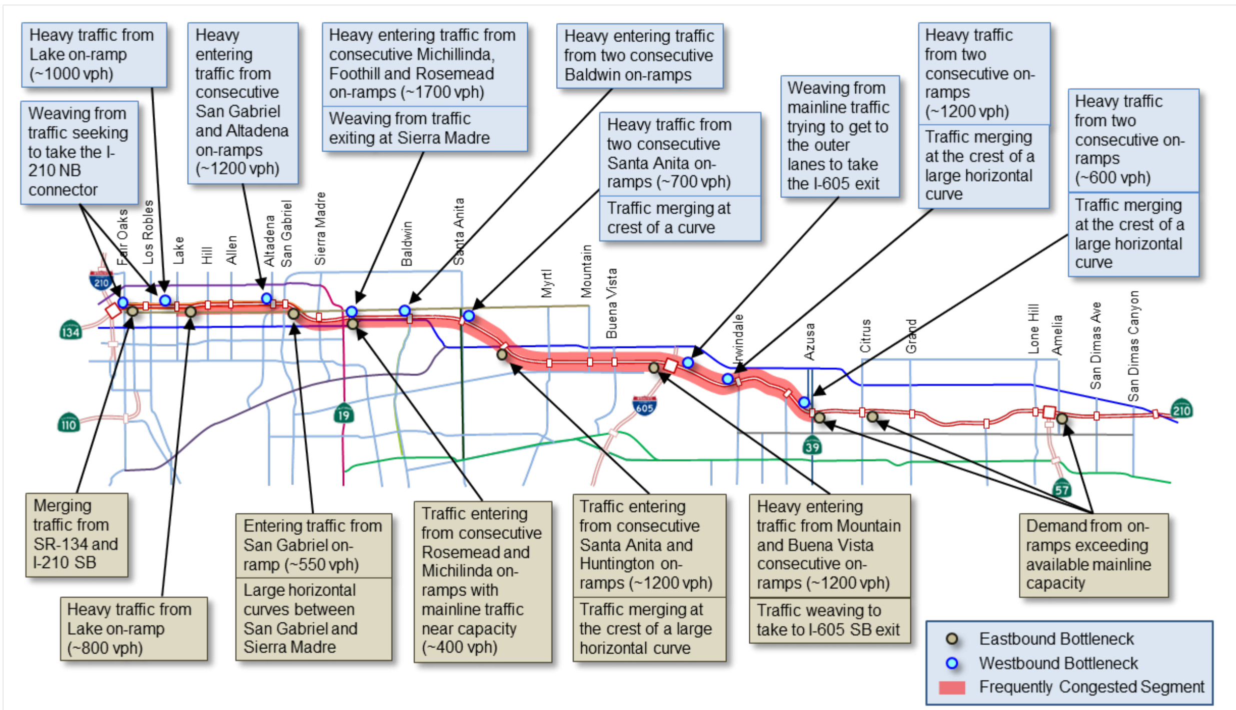


Figure 3-2: Major 2008 bottlenecks – PM peak

The extent of the I-210 freeway that must be modeled is heavily influenced by the 2008 bottleneck assessment. In order to simulate actual traffic conditions, it is crucial to include bottlenecks that might spill back into the area being modeled. The freeway model must therefore extend beyond the weaving sections of the 134-210 interchange in the west and beyond the bottleneck near Azusa Ave. in the east.

The interaction between the HOV lane and the general purpose lanes is also an important factor in selecting a modeling approach. For this section of the I-210 freeway, HOV bottlenecks occur in the same locations as those on the mainline. Due to the proximity of the HOV lane and the mainline, the flow breakdown process is coupled. For these reasons, the team chose to simply model the HOV and mainline together as a single pipe in the AMS Phase 1 model.

3.2. FREEWAY INCIDENTS

The following analysis summarizes data collected on freeway incidents along the corridor, and includes their frequency, types, causes, and locations. The eastbound and westbound sections of I-210 between Rosemead and I-605 have among the highest rates of incidents per million VMT on weekdays. The preliminary model for Phase 1 focuses within this area.

3.2.1. INCIDENT FREQUENCY

Table 3-1 shows statistics on incidents logged by the CHP along various sections of I-210 in Los Angeles County throughout 2011 (the most recent year with a complete set of incident records), based on information available in PeMS. The statistics cover both injury and non-injury data (excluding fatal incidents) and incidents ranging in duration from less than one minute to several hours. The top part of the table presents average statistics for normal weekdays; the bottom shows statistics for weekend days and weekdays falling on a holiday.

The data in Table 3-1 indicate that over 40 incidents were logged on average every weekday, and 22 daily on weekends and holidays. When considering only the section extending from SR-134 to SR-57, approximately 24 incidents were logged daily on average during weekdays, and 12 incidents during weekends or holidays. These frequencies indicate that days without incidents are rare.

Table 3-1: Frequency and rate of incidents on I-210 in 2011

Corridor Section			I-210 W				I-210 E			
Segment	Mileposts	Length	Number of Incidents	Vehicle-miles traveled (VMT)	Incidents/ Day	Incidents/ million VMT	Number of Incidents	Vehicle-miles traveled (VMT)	Incidents/ day	Incidents/ million VMT
Weekdays										
I-5 to SR-134	0.0 – 25.0	25.0	1,835	339,578,943	7.3	5.4	1,762	324,338,666	7.0	5.4
SR-134 to Rosemead	25.0 – 30.0	5.0	729	166,269,804	2.9	4.4	637	175,010,107	2.6	3.6
Rosemead to I-605	30.0 – 36.6	6.6	1,076	166,158,455	4.3	6.5	961	167,657,426	3.8	5.7
I-605 to SR-57	36.6 – 45.0	8.4	1,385	218,635,400	5.5	6.3	1,294	231,871,070	5.2	5.6
SR-57 to Foothill	45.0 – 47.3	2.3	93	43,758,903	0.4	2.1	110	25,030,549	0.4	4.4
Foothill to County Line	47.3 – 52.5	5.2	223	91,213,575	0.9	2.5	325	120,708,649	1.3	2.7
Freeway	***0.0 – 52.5***	***52.3***	***5,349***	***1,025,615,08***	**21.4**	***5.2***	***5,089***	***1,044,616,470***	**20.4**	***4.9***
Weekends and Holidays										
I-5 to SR-134	0.0 – 25.0	25.0	689	118,633,140	4.6	5.8	629	116,207,283	4.2	5.4
SR-134 to Rosemead	25.0 – 30.0	5.0	248	66,396,295	1.7	3.7	173	70,969,312	1.2	2.4
Rosemead to I-605	30.0 – 36.6	6.6	300	70,636,813	2.0	4.2	313	69,956,648	2.1	4.5
I-605 to SR-57	36.6 – 45.0	8.4	412	93,418,639	2.8	4.4	379	98,754,346	2.5	3.8
SR-57 to Foothill	45.0 – 47.3	2.3	21	19,902,723	0.1	1.0	42	11,295,046	0.3	3.7
Foothill to County Line	47.3 – 52.5	5.2	76	40,664,034	0.5	1.9	148	53,017,030	1.0	2.8
Freeway	***0.0 – 52.5***	***52.5***	***1,746***	***409,651,646***	**11.6**	***4.3***	***1,684***	***420,199,667***	**11.2**	***4.0***

Source: All Non-injury and injury accidents reported by PeMS from CHP incidents data

For the rate of incidents relative to traffic demand, the table indicates that, for the entire section of I-210 within Los Angeles County, 4.9 incidents per million miles traveled were logged on average during weekdays, and that 4.0 incidents per million miles traveled were logged on average over weekend days and holidays. When looking at the data on a section-by-section basis, the portion of I-210 between Rosemead Boulevard and the I-605 freeway shows the highest incident rates, with rates varying between 5.7 and 6.5 incidents per million miles traveled, compared to rates of 2.5 to 5.4 incidents on surrounding sections. This is not surprising given that this section features high traffic demand and several bottlenecks. On a directional basis, a higher incident rate also appears to be associated with the westbound traffic between the SR-134 and SR-57 interchanges.

3.2.2. INCIDENT TYPES AND CAUSES

Figure 3-3 and Figure 3-4 show the collision types and primary causes for all incidents along I-210 between milepost 25.21 (Pasadena) and milepost 52.12 (county border) throughout 2011. This analysis is based on information from Caltrans' Traffic Accident Surveillance and Analysis System (TASAS) and covers 597 incidents.

Figure 3-3 indicates that 53% of incidents were rear-end collisions, i.e., collisions strongly related to the presence of congestion. If incidents associated with lane-changing behavior are added to the statistics, such as sideswipe and broadside collisions, nearly 80% of all recorded incidents could be linked to either congestion or traffic behavior. Figure 3-4 shows that a large majority of incidents were caused by driver-related factors, such as speeding (55%), unsafe lane change (17%), and improper turn movements (11%). These statistics suggest that a strong potential exists along I-210 to reduce incident occurrences through improvements to congestion, lane-changing maneuvers, or other unsafe behavior.

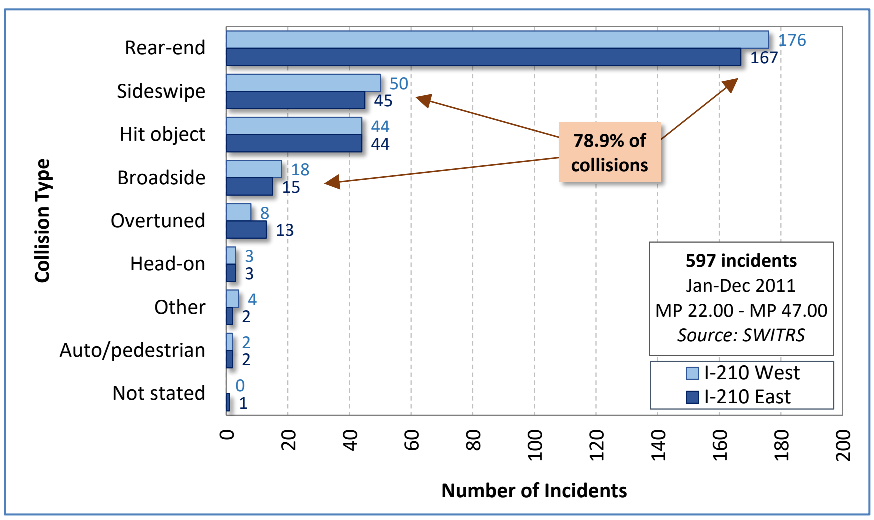


Figure 3-3: Types of collisions along I-210 in 2011

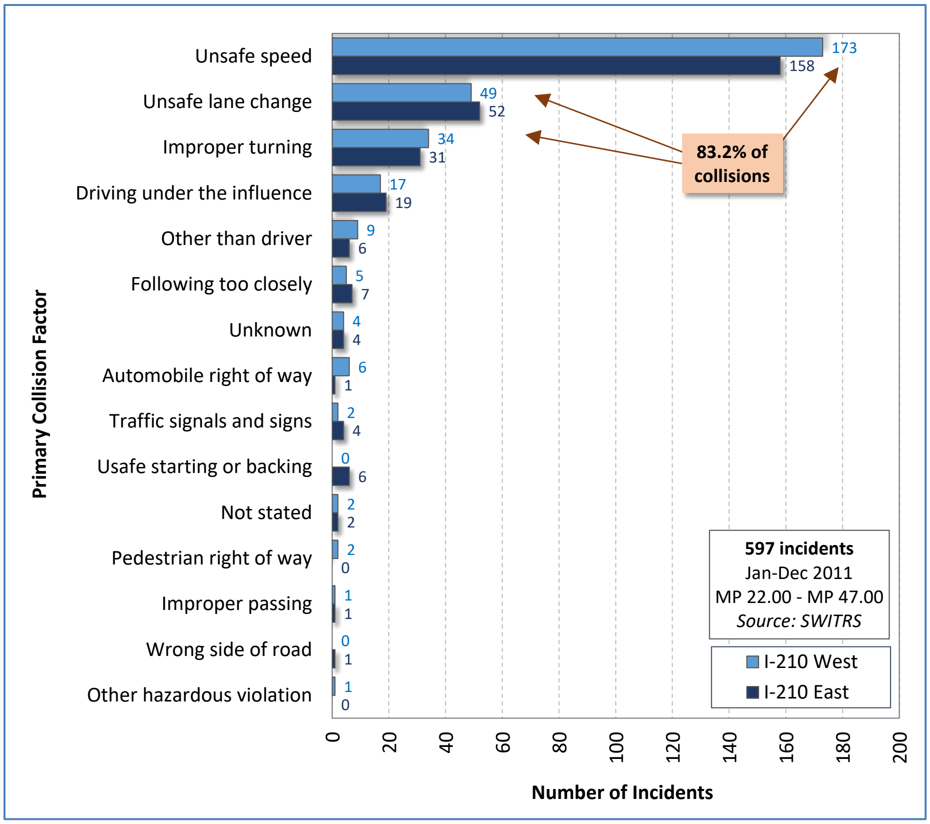


Figure 3-4: Primary causes of collisions along I-210 in 2011

3.2.3. INCIDENT LOCATIONS

Figure 3-5 and Figure 3-6 show the location of collisions logged by the CHP along I-210 for the years 2010 and 2011, drawn from the Statewide Integrated Traffic Records System (SWITRS) database. The illustrations show AM and PM peak periods in both directions on the freeway, from Arroyo Blvd. on the west end to the Route 66/Foothill interchange on the east end. The AM peak period includes 316 incidents, the PM peak period 328.

The figures indicate that collisions are distributed across the freeway and that rear-end collisions appear to correlate with peak period congestion. Although there appear to be clumps of accidents near Lake Ave. and Huntington ramps, for example, there does not exist a prevalent hotspot. With few exceptions, incidents have happened on every half-mile segment of I-210 between the 134 and 605 interchanges for the years 2010 and 2011.

These patterns suggest that efforts to mitigate congestion during incidents along this corridor may be worthwhile. Further investigation of collisions, including severity, is explored in section 5.1.2.

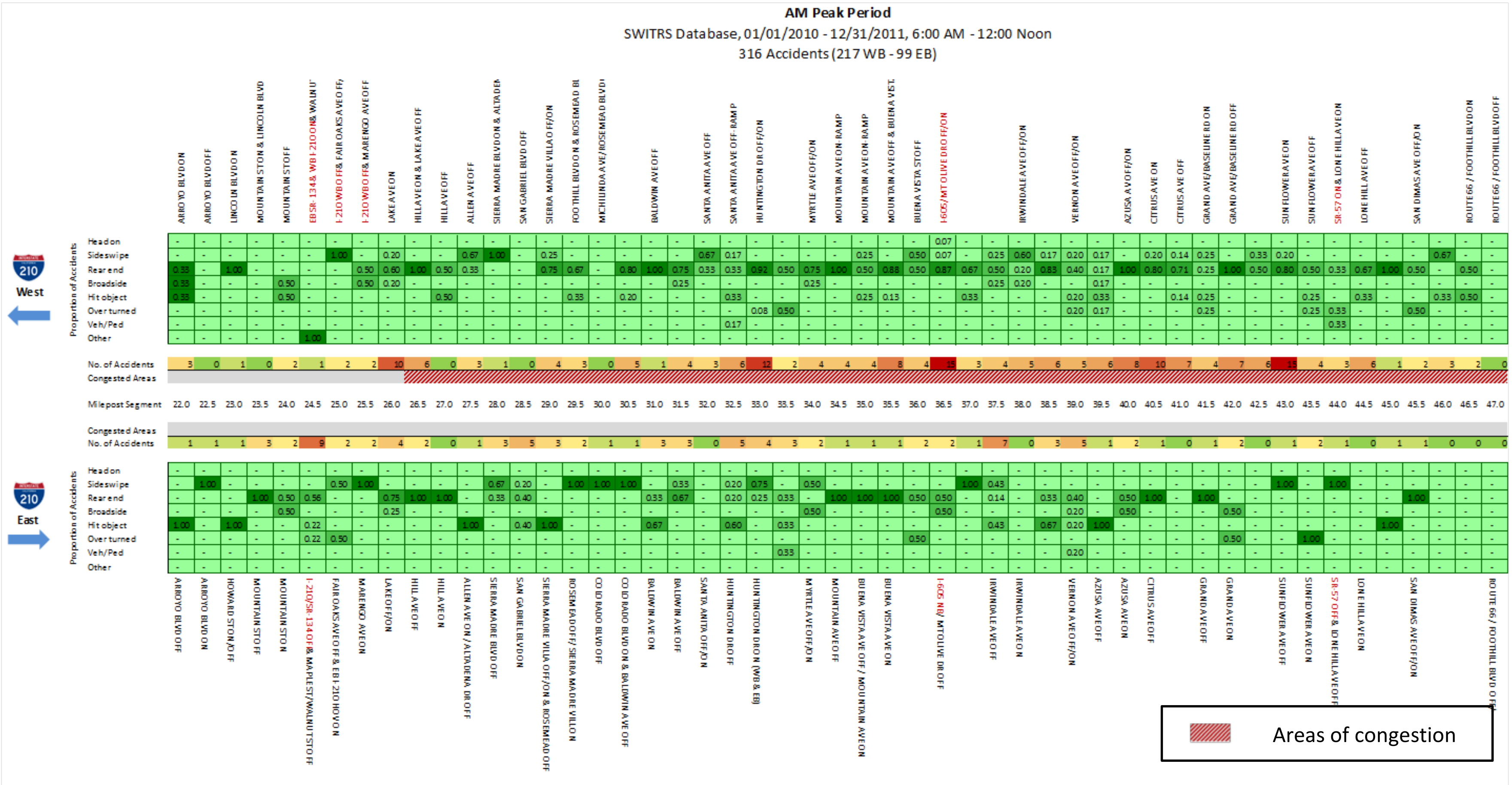


Figure 3-5: AM collisions involving CHP, by type (2010-2011)

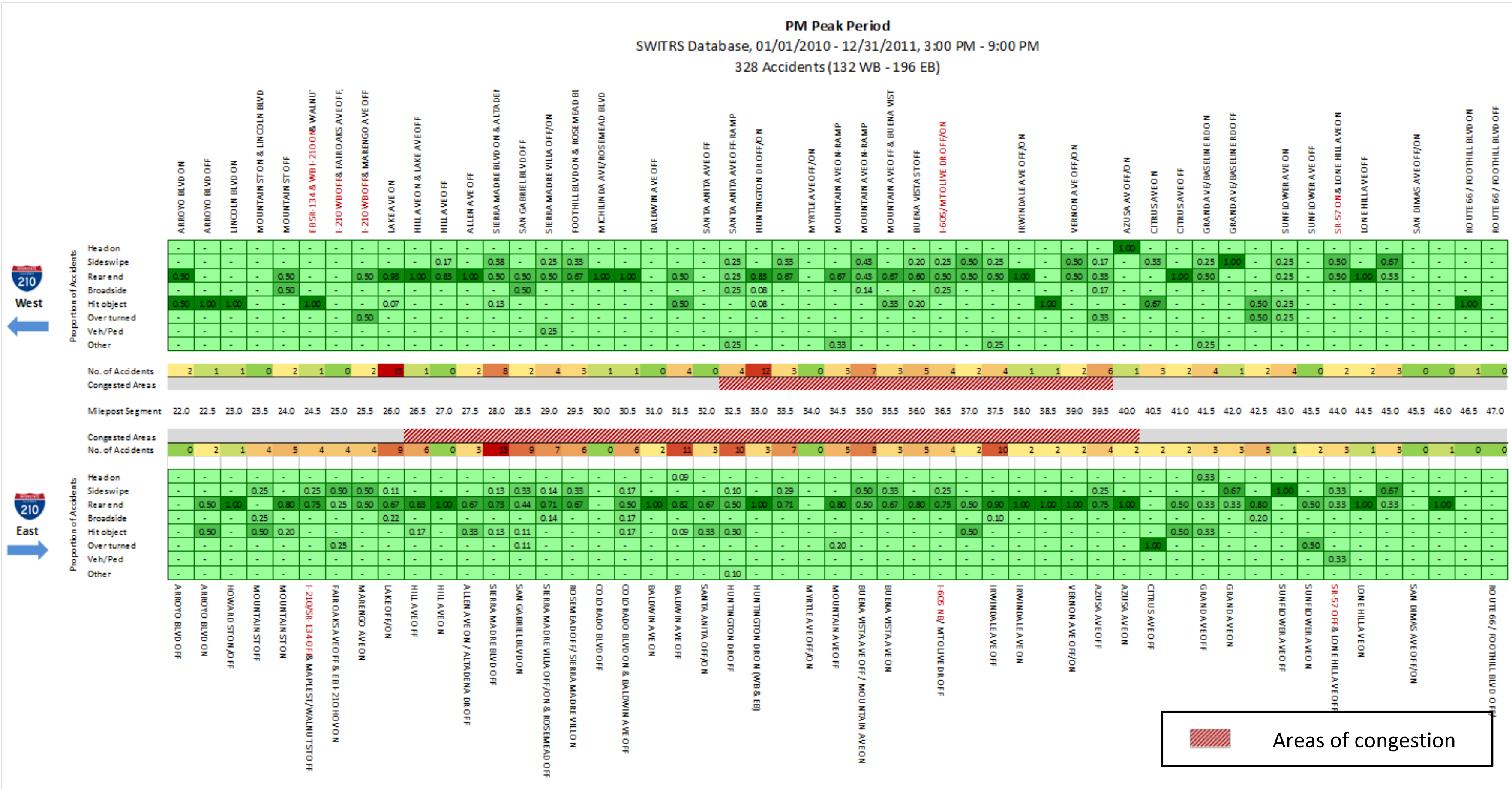


Figure 3-6: PM collisions involving CHP, by type (2010-2011)

3.3. FREEWAY LOOP DETECTOR DATA

As part of examining corridor operations, the AMS team performed a detailed assessment of data quality from loop detectors on the I-210 freeway. While the overall coverage and detector health is very good, this analysis pinpoints key areas for improvement. These improvements are crucial for model calibration, for real-time situational awareness during the pilot deployment, and for future evaluation of the I-210 pilot.

For a complete description of the methodology used in this assessment, see Chapter 8 (Appendix A). The methodology itself is appropriate for continuous data quality monitoring, and supplements detector health monitoring already in place by PeMS. It is anticipated that methods such as these will be incorporated by agencies to support corridor management practices.

This assessment focuses on the stretch of eastbound and westbound freeway from SR-134 near Figueroa to I-210 at Grand Avenue. Results are summarized below. There are six error categories:

1. Ramps for which no VDS is listed in PeMS
2. Stations which appear in PeMS to be in a constant failure mode
3. Stations that are working but do not capture an entire cross section of flow
4. PeMS configuration errors
5. Configuration uncertainty, where the exact location of sensors is not clear from PeMS
6. Stations suspected of having counting errors

1. Ramps for which no VDS is listed in PeMS

These are ramps that were identified in aerial photographs but which do not show up in the PeMS VDS inventory. They either lack detection or their detector stations have not been registered with PeMS.

Fwy	Street	Type	Lat	Lng
210E	Corson St.	off-ramp	34° 9'0.24"N	118° 9'13.30"W
210E	Fair Oaks	on-ramp	34° 9'6.52"N	118° 9'0.14"W
210E	Buena Vista	off-ramp	34° 8'6.81"N	117°59'8.04"W
210E	Mount Olive	off-ramp	34° 8'5.14"N	117°57'36.67"W
210W	Near Buena Vista	off-ramp	34° 8'8.37"N	117°58'46.26"W
210W	Vernon	off-ramp	34° 7'28.24"N	117°54'49.95"W

2. Stations which appear in PeMS to be in a constant failure mode

The following stations remained in one of the PeMS failure modes during the entire inspection period, from October to December 2014.

VDS	Type	Fwy	Abs PM	Street
716563	on-ramp	134E	11.52	Figueroa
763908	off-ramp	210E	28.28	Sierra Madre V1
716562	on-ramp	134W	11.47	Figueroa
716566	on-ramp	134W	12.76	Orange Grove
769301	freeway-freeway	134W	12.88	210E
769302	freeway-freeway	134W	12.89	710
761363	HOV	210W	34.9	Mountain Ave
761366	on-ramp	210W	34.9	Mountain Ave
718210	mainline	210W	34.9	Mountain Ave
761329	HOV	210W	30.78	Baldwin
717662	off-ramp	210W	30.78	Baldwin SB
717668	off-ramp	210W	32.02	Santa Anita
717656	off-ramp	210W	30.0	Rosemead 2
774037	off-ramp	134W	11.62	Colorado
769706	freeway-freeway	605N	36.09	605N to 210W
769704	HOV	210W	36.09	Highland

3. Stations that are working but do not capture an entire cross section of flow

The loops of these stations do not cover all lanes. This category includes seven cases in which an auxiliary lane is not represented in the PeMS database, even though aerial photographs suggest that it is measured. See Section 8.3.7.3 for an example.

VDS	Type	Fwy	Abs PM	Street	Problem
769774	freeway-freeway	210E	36.89	605 NB	VDS does not cover all lanes
717691	off-ramp	210E	41.98	Grand Ave	VDS does not capture all flow
761177	mainline	210E	35.65	Buena Vista	Aux lane
772857	mainline	210E	37.39	San Gabriel River	Aux lane
772872	mainline	210E	37.79	Irwindale	Aux lane
717686	mainline	210W	41.79	Grand 1	Aux lane
717678	mainline	210W	39.81	Azusa 1	Aux lane
772873	mainline	210W	37.79	Irwindale	Aux lane
772858	mainline	210W	37.39	San Gabriel River	Aux lane

4. PeMS configuration errors

Mainline/HOV station pair (772903,772905) appears listed in PeMS to be on I210E at absolute postmile 40.2. PeMS also shows station pair (772902,772904) as being adjacent to (772903,772905) on the westbound side. However, the analysis strongly suggests that these should be reversed: (772903,772905) is on 210W and (772902,772904) is on 210E.

5. Configuration uncertainty, where the exact location of sensors is not clear from PeMS

The 134/210 interchange is a complex, multi-level freeway junction. The exact location of detector stations cannot be inferred from the configuration data provided by PeMS. A more careful study of the detection diagrams for this area is needed.

6. Stations suspected of having counting errors

The flow balance tests performed during the assessment suggest that the following stations may be miscounting vehicles.

VDS	Type	Fwy	Abs PM	Street
717601,763608	mainline, HOV	210E	12.45	San Rafael
717631,763614	mainline, HOV	210E	25.12	Fair Oaks 1
768916	freeway-freeway	210E	25.12	NB 710 to EB 210
761167	off-ramp	210E	35.41	Mountain
769703	HOV	210E	36.09	Highland
769705	freeway-freeway	210E	36.09	EB 210 to SB 605
761191,761188	mainline, HOV	210E	36.62	Mount Olive Dr.
772872,772874	mainline, HOV	210E	37.79	Irwindale
761242	HOV	210E	41.98	Grand Ave
761329,717663	mainline, HOV	210W	30.78	Baldwin 1
717644,717645	mainline, HOV	210W	28.27	San Gabriel

3.4. ARTERIAL OPERATIONS

In order to model arterial traffic dynamics, information such as signal plans, approach flows, and turning counts are required. Signal timing sheets were collected from each jurisdiction for each of the signalized intersections in the corridor. Additional information was culled from analyses performed by various consulting firms over the past nine years for various groups of intersections as part of traffic signal retiming projects or traffic impact studies.

Demand information such as approach flows and turning counts were extracted from these analyses where possible. In addition, an assessment of available traffic capacity at individual signalized intersections was performed to understand recurrent traffic conditions. Volume-to-capacity (v/c) ratios are presented in Figure 3-7 and Figure 3-8 for the AM Peak and PM Peak periods, respectively. The dates in each figure are the dates of the studies the information is drawn from for each section of the corridor. Since the studies are spread across time, with the oldest analyses from 2006, the numbers shown in Figure 3-7 and Figure 3-8 should be viewed as only a rough assessment of available traffic capacity at individual intersections.

The need for newer or additional traffic studies to obtain approach flows and turning counts at signalized intersections for modeling purposes was determined based on a number of factors:

- The date of the most recent traffic study
- Road size—size of intersecting streets (major arterial vs. minor arterial vs. small street)
- Distance—distance to freeways and incident scenarios of interest
- Coverage—spatial data coverage
- ADT—average daily traffic volumes
- Locations of arterial incident hot spots

In general, data from 2011 or later was considered adequate. For high-priority intersections based on their role, functionality, and importance within the corridor, new studies were requested. The results of these new studies were entered into a Synchro model of the corridor arterial system.

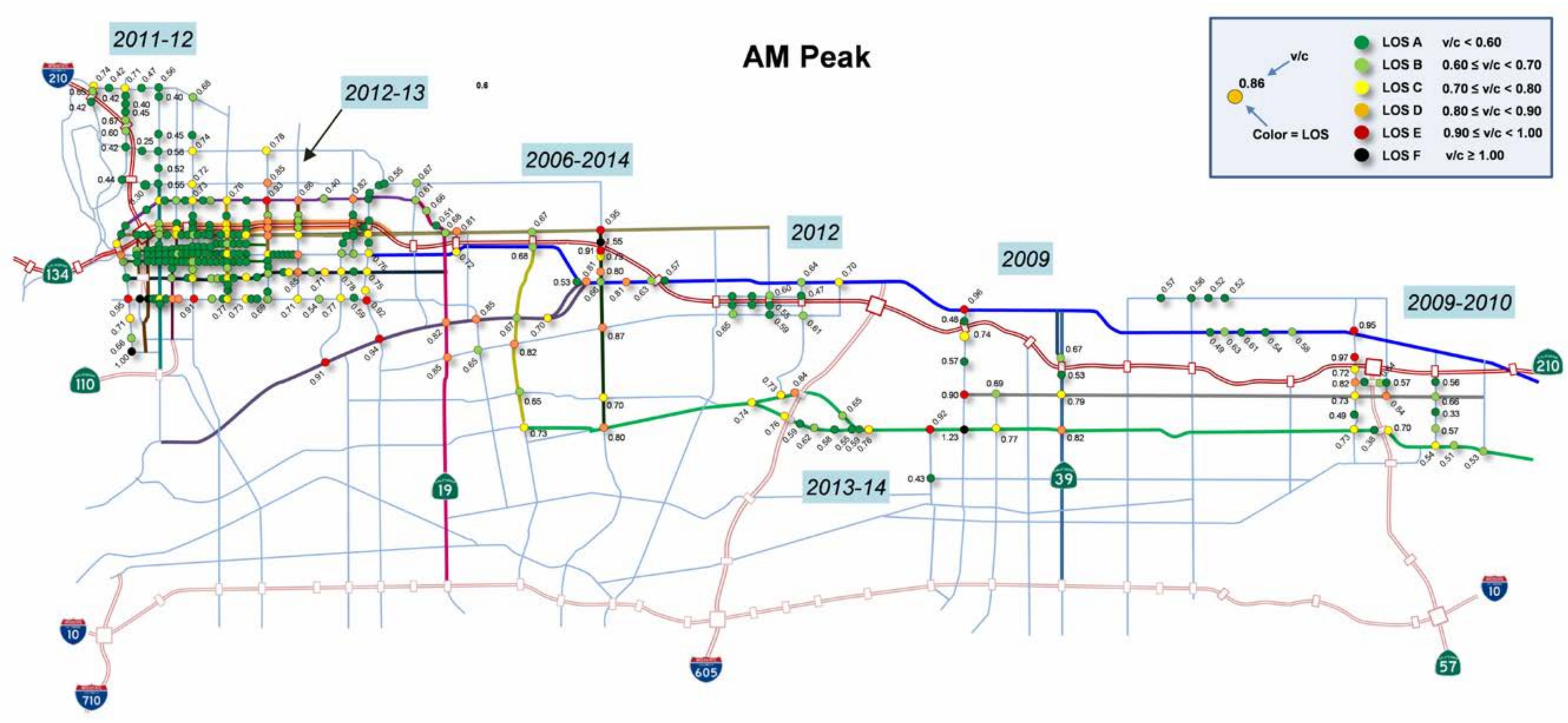


Figure 3-7: Volume-to-capacity ratio at signalized intersections – AM peak

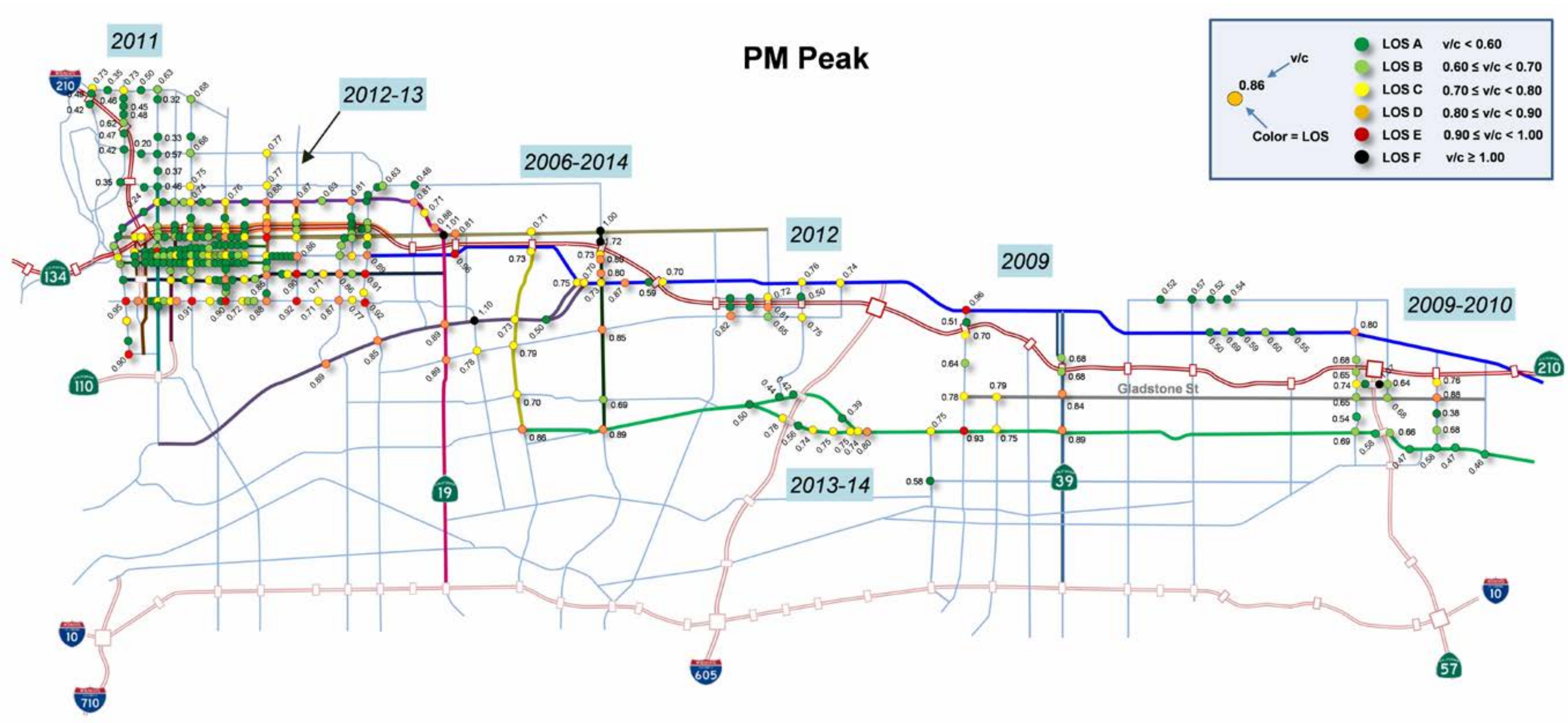


Figure 3-8: Volume-to-capacity ratio at signalized intersections – PM peak

3.5. ARTERIAL INCIDENTS

To understand arterial incidents along the corridor, the AMS team collected a range of data characterizing their locations, frequency, types, and causes.

Figure 3-9 maps the number of incidents that have been recorded near key signalized intersections within the western half of the I-210 corridor throughout 2012 and 2013. This assessment is based on data from the SWITRS database and the City of Pasadena. Approximately only 1,900 incidents of the reported 5,587 incidents are mapped. Incidents that occurred at minor intersections or between two intersections are not shown. While incidents are shown to occur throughout the corridor, a few intersections present significantly higher frequencies of incidents. These are highlighted with red callouts in Figure 3-9 and identified in Table 3-2. Most of them are intersections carrying relatively high traffic.

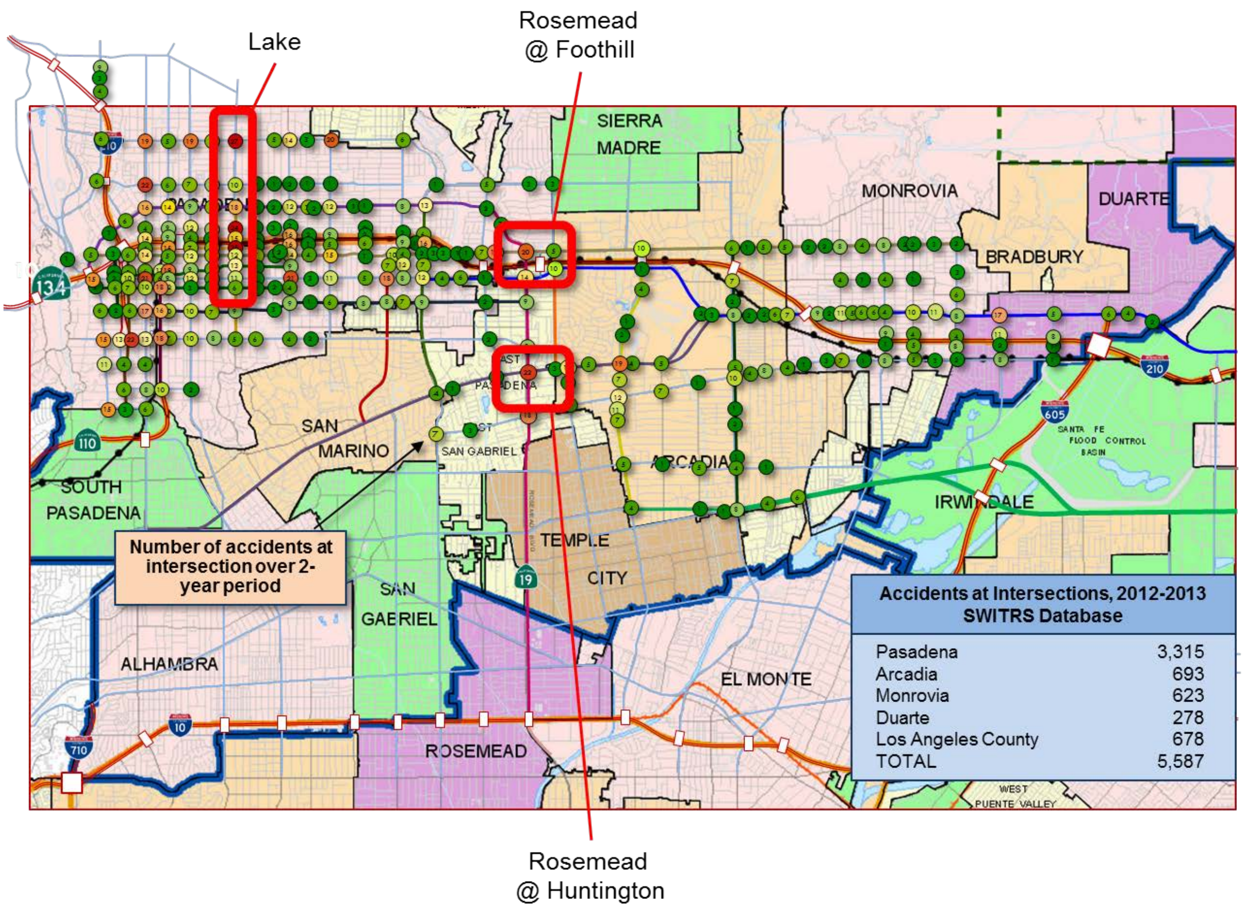


Figure 3-9: Arterial incidents (2012-2013)

Table 3-2: Signalized intersections with highest number of incidents in 2012-2013

Jurisdiction	Intersection	Number of Incidents
Pasadena	Washington Boulevard / Lake Avenue	25
Pasadena	Corson Street / Lake Avenue	25
Pasadena	Villa Street / Lake Avenue	24
LA County	Huntington Drive / Rosemead Boulevard	22
Pasadena	Colorado Boulevard / Fair Oaks Ave	21
Pasadena	Colorado Boulevard / Hill Avenue	21
Pasadena	Mountain Street / Fair Oaks Avenue	21
Pasadena	Foothill Boulevard / Rosemead Boulevard	20
Pasadena	Washington Boulevard / Allen Avenue	20
Pasadena	Union Street / Marengo Avenue	19
Pasadena	Foothill Boulevard / Sierra Madre Ville Avenue	19
Arcadia	Huntington Drive / Baldwin Ave	19
Pasadena	Washington Boulevard / Fair Oaks Avenue	19
Pasadena	Washington Boulevard / Los Robles Avenue	19
Pasadena	Green Street / Arroyo Parkway	18
Pasadena	Colorado Boulevard / Sierra Madre Boulevard	18
Pasadena	Orange Grove Boulevard / Lake Ave	18
Pasadena	Del Mar Boulevard / Fair Oaks Avenue	17
Duarte	Huntington Drive / Buena Vista Ave	17
Pasadena	Del Mar Boulevard / Arroyo Parkway	16
Pasadena	Maple Street / Hill Ave	16
Pasadena	Corson Street / Hill Ave	16
Pasadena	Orange Grove Boulevard / Fair Oaks Avenue	16

Figure 3-10 and Figure 3-11 show the collision types and primary causes associated with all the incidents that occurred in 2012 and 2013 in the cities of Pasadena, Arcadia, Duarte, and Monrovia, as well as the surrounding unincorporated county areas. This analysis is based on the same data that was used to develop the map in Figure 3-9 and includes all 5,587 recorded incidents for the period.

Figure 3-10 indicates that 28% of incidents that occurred around signalized intersections were rear-end collisions, i.e., collisions strongly related to the presence of congestion. If incidents associated with lane-changing behavior are added to the statistics, such as sideswipe and broadside collisions, nearly 78% of all recorded incidents could be linked to either congestion or traffic behavior. Figure 3-11 further indicates that a large majority of incidents were caused by vehicles being driven at unsafe speed (22% of incidents) or by drivers failing to respect right-of-way (16%), making improper turns (15%), or failing to respect traffic signs and signals (12%). These four factors account for nearly 64% of all recorded incidents. These statistics suggest that a strong potential exists along the I-210 to reduce incident occurrences through improvements to congestion, lane-changing maneuvers, or other unsafe behavior.

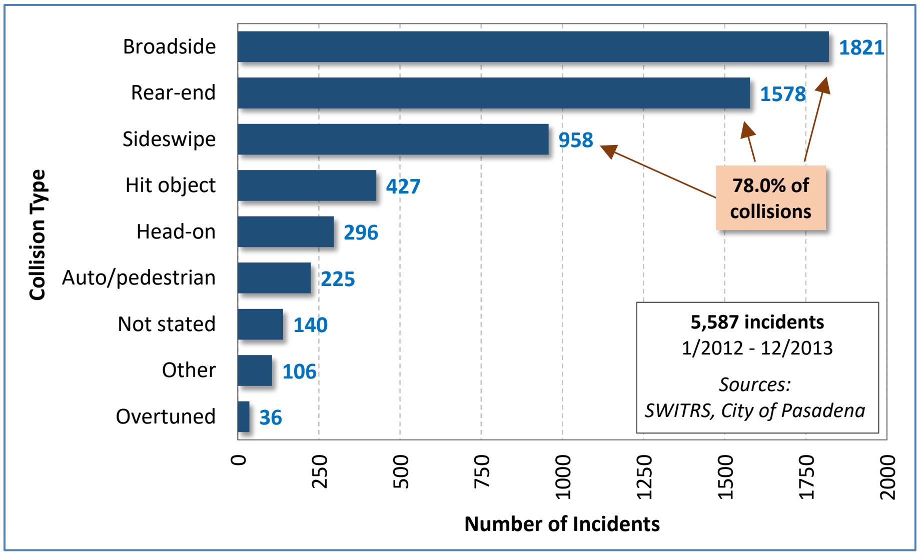


Figure 3-10 –Collision types along corridor arterials in 2012-2013

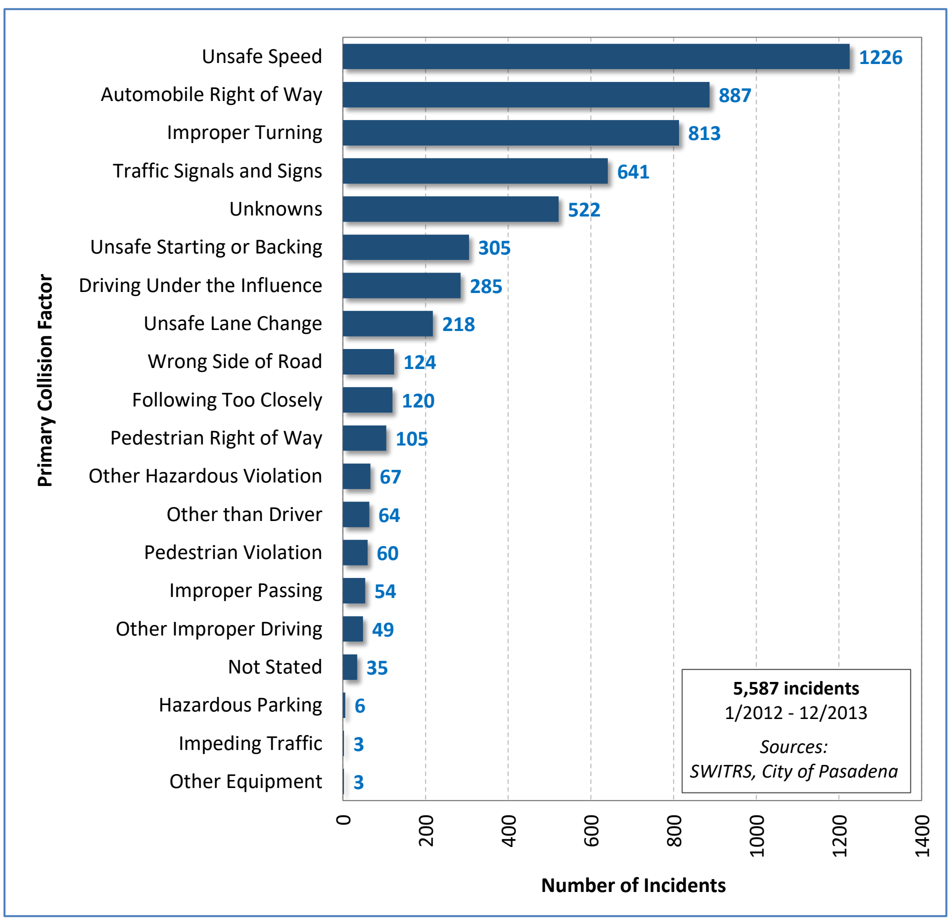


Figure 3-11 – Primary causes of collisions along corridor arterials in 2012-2013

3.6. ARTERIAL DATA

One of the challenges in working with diverse information about arterials was to make it accessible and usable. One milestone in the analysis was to assemble a spreadsheet in which to summarize information on each of the key arterial intersections in the corridor. This spreadsheet [9] was used to capture aspects of intersection geometry, available data, and prioritization, as well as control and sensing infrastructure.

In addition, the AMS team assembled a large-scale Synchro model of the I-210 corridor. This Synchro model is the repository for “static” arterial data in one place in a single, electronic format. The current model contains all intersection signal plans active at 5:00 pm, as well as approach flows and turning volumes from all area traffic studies between 2006 and 2014. There are over 500 intersections coded into the model, including about 450 signalized intersections, 63 stop-controlled intersections, and 110 intersections with observed traffic counts.

Figure 3-12 shows a screenshot of the model to illustrate the geographical region covered:

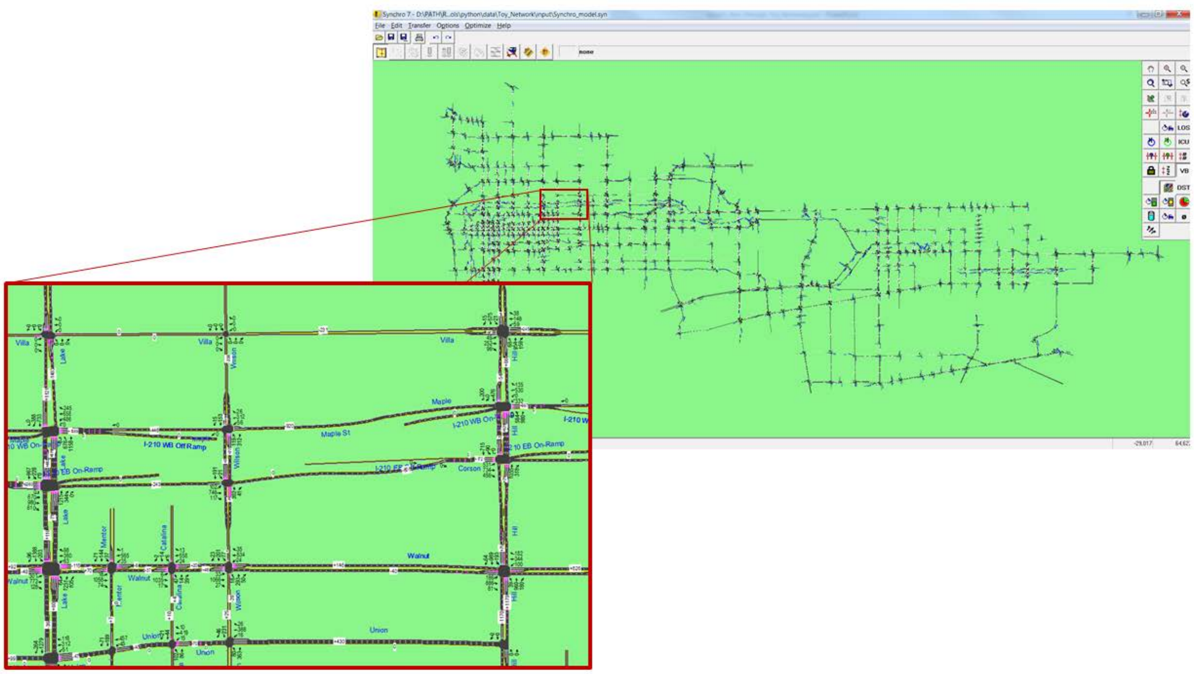


Figure 3-12: Screenshot of corridor area Synchro model

4. MODEL DEVELOPMENT AND CALIBRATION

Modeling traffic conditions in the I-210 corridor is central to the AMS effort. This chapter presents an overview of the process of model development and calibration, focusing on the methodologies employed through 2014. It includes:

- Snapshot of the model-building process
- Modeling approach and analysis tools for assessing ICM strategies
- Cell Transmission Model (CTM) framework
- Data requirements for CTM
- Model construction, calibration, and validation

4.1. SNAPSHOT OF THE MODEL-BUILDING PROCESS

The overall model-building process is illustrated in Figure 4-1:

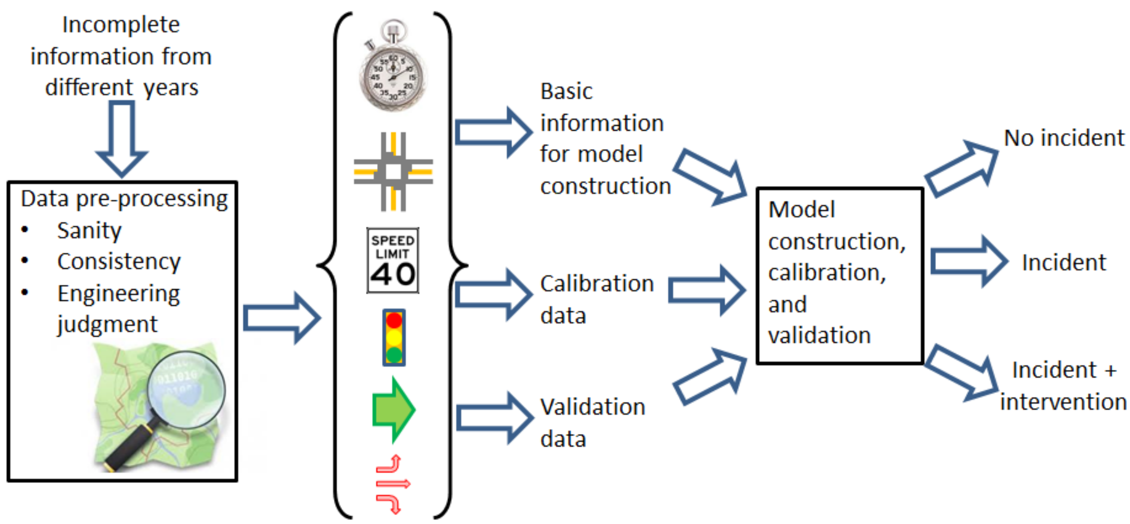


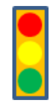
Figure 4-1: Model-building process

As the figure shows:

1. Information about the corridor comes from various sources and different years and needs to be checked in a pre-processing step. Does it look reasonable (i.e., not garbled or fragmentary)? Is it fairly consistent? Does it seem usable for the intended purpose?

2. After the initial checks, the data is processed to produce the information needed for modeling and simulation, including:


Travel times


Signal timing


Network geometry


Flows

Speed limits


Turning ratios

3. Some of the processed data is used to construct the model, some to calibrate the model, and some to validate the model's simulation results against observed traffic conditions.

4. The completed model can be used to simulate traffic conditions along the corridor under various operational conditions, such as no incident, an incident with no intervention, and an incident with intervention.

4.2. MODELING APPROACH

Choosing a modeling approach is, of course, fundamental to conducting modeling and simulation on a corridor. Several analysis tools are available for analyzing ICM operating strategies. For the purposes of this evaluation, existing analysis tools were split into these general categories:

- Travel demand models
- Simulation models, including macroscopic, microscopic, and mesoscopic models

4.2.1. TRAVEL DEMAND MODELS

Travel demand models predict future demand in a roadway network based on analytical relationships of trip generation, destination choice, mode choice, time-of-day travel choice, and route choice. These models are typically used to predict the impacts of major highway improvements in metropolitan areas, e.g., a new highway facility. Today, travel demand models are used in more wide-ranging tasks, including development of transportation master plans, evaluation of proposed land-use changes, initial design of transportation facilities, and evaluation of air quality impacts. However, these tools were not designed to evaluate travel management strategies, such as ITS, ICM, and operational strategies. Travel demand models have only limited capabilities to accurately estimate changes in traffic performance (such as speed, delay, and queuing), resulting from implementation of these operational strategies, because of the poor representation of the dynamic nature of traffic in travel demand models. Examples of travel demand modeling tools available in the I-210 corridor models include the SCAG Regional model (implemented in TRANSCAD) and the local Pasadena model (implemented in VISUM).

4.2.2. SIMULATION MODELS

Simulation models model traffic flow movement and interaction in time and space. There are several types of simulation models depending on the representation of traffic flow:

- **Macroscopic simulation models:** Macroscopic simulation models are based on the deterministic relationships of the flow, speed, and density of the traffic stream. The simulation in a macroscopic model takes place on a section-by-section basis, treating traffic flow as a fluid rather than by tracking individual vehicles. Macroscopic models have considerably fewer data and computer requirements than microscopic models. They can simulate certain control strategies in large networks. However, they cannot model transportation improvements that affect the operational performance of individual vehicles (e.g., geometric improvements on intersections and ramps). Examples of operational macroscopic models for I-210 include the FREQ model and the TOPL model, based on cell transmission (CTM). Figure 4-2 shows typical output of the TOPL model for a 14-mile section of the I-210 freeway:

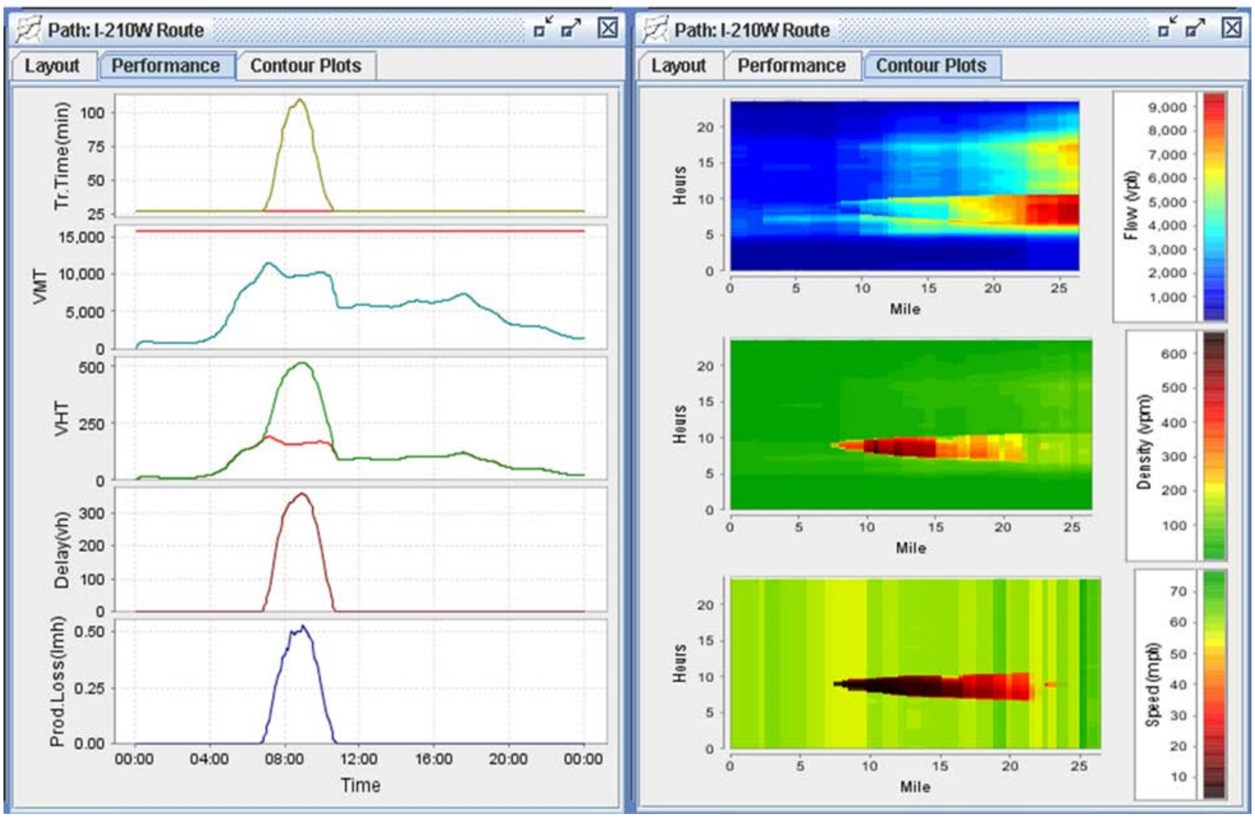


Figure 4-2: TOPL model output of I-210 freeway

- **Microscopic simulation models:** These models simulate the movement and interactions of individual vehicles based on car-following, lane-changing, and queue discharge algorithms. Typically, vehicles enter a transportation network using a statistical distribution of arrivals (a stochastic process) and are tracked through the network each second (or fraction of a second). Typically, upon entry, each vehicle is assigned a destination, a vehicle type, and a driver type. In many microscopic simulation models, the vehicle operating characteristics are influenced by design features (e.g., vertical grade, horizontal curvature, and superelevation), based on relationships developed in prior research. The primary means of calibrating and validating microscopic simulation models is through the adjustment of driver sensitivity factors. Computer time and storage requirements for microscopic models are fairly large, usually limiting the network size, the number of vehicles to be simulated, and the number of simulation runs that could be performed. Because of the detailed representation of the traffic network found in these models and because of their ability to model traffic control strategies (such as ramp metering or traffic signal pre-emption), these tools are well suited for modeling ICM strategies such as accommodating/promoting cross-network diversions. The Aimsun product of TSS includes microscopic simulation capabilities. Examples of microscopic simulation models in the I-210 corridor are the VISSIM model of the I-210 freeway and the VISSIM Pasadena model consisting of the I-210 freeway in the Pasadena area and 190 signalized intersections.

- **Mesoscopic simulation models:** Mesoscopic models combine the properties of both microscopic and macroscopic simulation models. They track individual vehicles, but their movement is based on the deterministic speed-flow relationships as in the macroscopic models. Mesoscopic models are appropriate for assessing traveler information and guidance strategies because they consider the queue formation and dissipation on the network links. As such, they include dynamic assignment algorithms (DTA) and can evaluate dynamic traveler diversions in large-scale networks. Examples of mesoscopic simulation models include the Aimsun product of TSS, as well as Dynasmart-P, Dynasim, and Dynameq. There are no operational mesoscopic models for the I-210 corridor.

4.2.3. MODEL SELECTED FOR I-210 PILOT

The macroscopic modeling approach (specifically, the Cell Transmission Model or CTM) was selected in this study for the following reasons:

- **Simulation and development of control strategies**: The CTM model can simulate existing control and management strategies as outlined in the Concept of Operations document for the I-210 corridor. Existing strategies include ramp metering strategies (fixed time, traffic-responsive demand-capacity, ALINEA, SWARM), incident management strategies (diversion), and signal control (progression of fixed time signals along arterials). The model can be also used in the development of new strategies (model-based control or MBC).

- **Simplicity in model development and calibration**: Model inputs include link geometrics (number of lanes, length) which can be automatically imported from digital maps. The calibration of the model parameters (fundamental diagram) can be accomplished from the data provided by the loop detectors located at each cell. Furthermore, algorithms are available for data checking and verification, and imputation of missing data.

- **Empirical observation**: It is important to recognize that the model parameters (e.g., free-flow speed, capacity) can be readily observed in the field, as opposed to microscopic models where model capacity is based on driver-vehicle characteristics that cannot be observed. Multiple model runs have to be performed for microscopic models to come up with a set of parameters that result in observed capacities. This is a complicated process taking into consideration that microscopic models are stochastic, i.e., multiple repetitions are required for each model run.

- **Model execution**: The model can be simulated quickly, which makes it a preferred tool in a decision support system framework as envisioned in the I-210 test corridor. Several scenarios and interventions can be simulated in real time and the best intervention can be recommended to the operator.

The CTM model consists of homogeneous road segments (cells or links) and nodes (location of on- or off-ramps or changes in the link characteristics). Traffic (in terms of flow/unit of time) moves across links subject to the demand, capacity of the cell, and available space at the next cell. Model parameters include free-flow speed, capacity, jam density, and congestion speed, i.e., the basic parameters of the fundamental diagram of traffic flow. A more detailed description of the CTM model, including theoretical details, input data requirements, and output options, is presented in the following sections.

4.2.4. MODEL LIMITATIONS

It should be noted that a macro model like CTM cannot model in detail certain strategies for the freeway and arterial. These include dynamic mobility applications (DMA) that are based on vehicle connectivity (cooperative adaptive cruise control, speed harmonization, queue warning), adaptive signal control on arterials, and alternative intersection designs. Most of these treatments require the detail and realism of microscopic simulation models. Furthermore, the CTM model cannot directly model traveler information services to individual vehicles to multiple destinations. This is typically modeled through mesoscopic models.

4.3. CELL TRANSMISSION MODEL (CTM) FRAMEWORK

The Cell Transmission Model framework, in this AMS effort, is used to model traffic conditions for both the freeway and arterials. At its most basic, it starts with a unidirectional roadway with one entrance and one exit. The road is divided into cells, or links (note that "cell" and "link" are used interchangeably), representing roadway segments. The cell length is chosen so it is reasonable for the speed limit and the desired time granularity of the results:

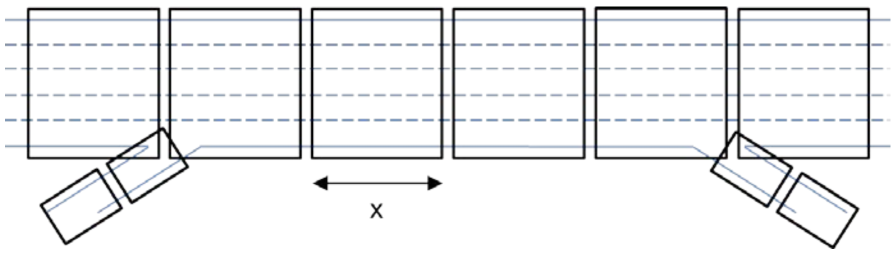


Figure 4-3: Roadway divided into cells

At each point in time, the traffic state consists of the number of vehicles located in each cell. The change in the number of vehicles in a cell (the evolution of the traffic state) is a function of the number of vehicles entering and leaving the cell:

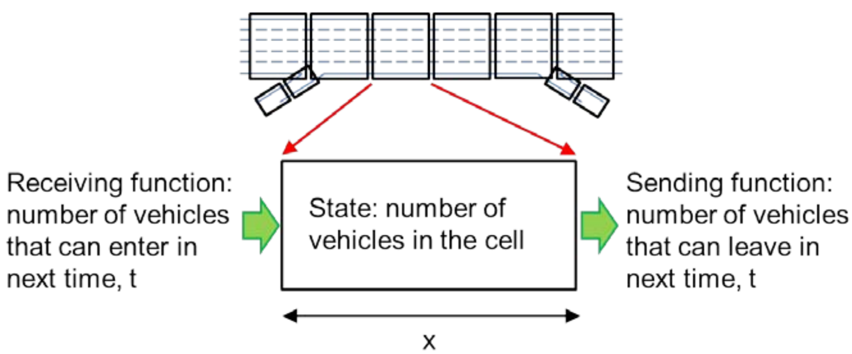


Figure 4-4: Evolution of traffic state

The empirical relationship between the number of vehicles occupying a cell of length **x** (a.k.a. density) and the number of vehicles entering or leaving the cell over time **t** (a.k.a. flow) is represented by the cell's fundamental diagram. This AMS study uses the triangular fundamental diagram:

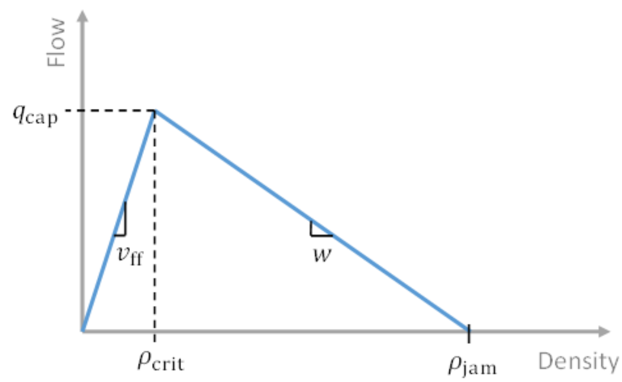


Figure 4-5: Fundamental diagram

As more vehicles flow into the cell (i.e., as the flow increases), density in the cell also increases, up to a critical point (the peak of the triangle in Figure 4-5). Up to this critical point, the cell can receive additional vehicles at a rate up to its capacity, q_{cap}. If density continues to increase beyond that point, the cell can only receive additional vehicles at a reduced rate—the flow corresponding to its current density according to its fundamental diagram. Traffic slows, congestion develops, and a congestion wave may propagate backward into the upstream cells.

For more technical information

A high-level technical description of the cell transmission model can be found in section 9, including:

- The fundamental diagram
- The Godunov Scheme for a chain of links
- The node model
- Signalized intersections
- Ramp meters
- Performance measures

For a complete description of the model, see [6].

4.4. DATA REQUIREMENTS FOR CTM

To model a corridor using a CTM, the following information is needed:

- **Supply**—a network of roads
- **Demand**—turning ratios and boundary flows
- **Control**—signal plans
- **Parameters**—fundamental diagrams
- **Scenario information**—in the current AMS effort, incidents affecting traffic flow

These elements are outlined in Table 4-1:

Table 4-1: Data requirements for CTM

SUPPLY	
	**Network of roads represented as links (cells) and nodes**. The network is created by selecting links and nodes from a base map, as shown in Figure 4-6. The base map is the I-210 "universe" to be modeled in CTM:  **Figure 4-6: Base map for network**

DEMAND

Turning movements (split ratios) at each node. These are the fractions of vehicles that take each available downstream link at each diverge opportunity in the network, as illustrated in Figure 4-7. They can be obtained by:

- measurements from sensors
- counts from traffic studies
- results from other models such as
  - SCAG TDM model (TransCAD)
  - Pasadena DTA (VISUM/VISSIM

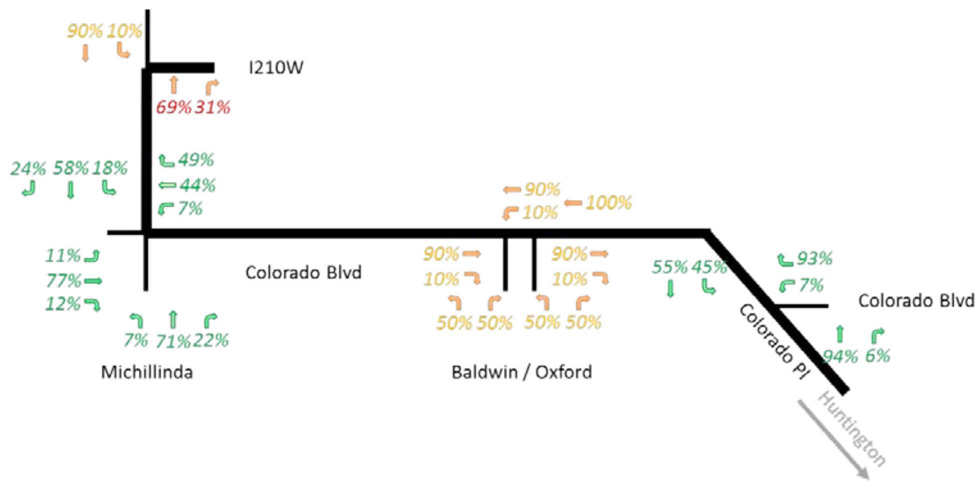
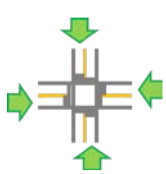


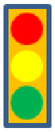
Figure 4-7: Turning movements (split ratios)



Boundary flows (demands) at all entrances of the network. They can be obtained by using:

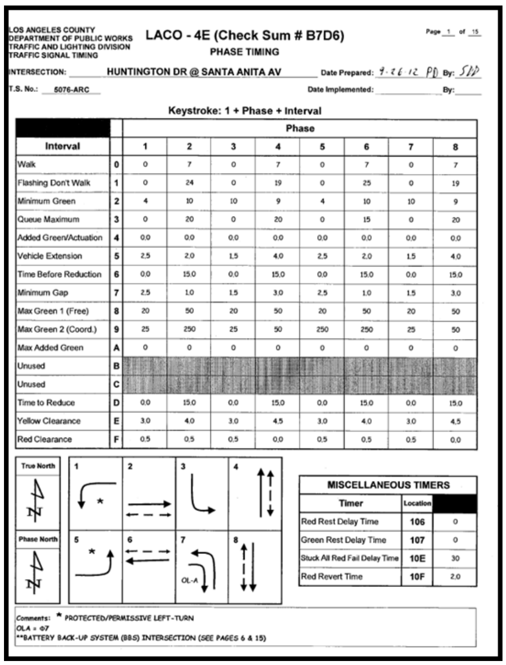
- measurements from sensors
- counts from traffic studies
- results from other models such as
  - SCAG TDM model (TransCAD)
  - Pasadena DTA (VISUM/VISSIM

CONTROL



Control elements:

- intersection signals and their plans/operational characteristics
- ramp meters and their plans/operational characteristics



LOS ANGELES COUNTY
DEPARTMENT OF PUBLIC WORKS
TRAFFIC AND LIGHTING DIVISION
TRAFFIC SIGNAL TIMING

LACO - 4E (Check Sum # B7D6)

PHASE TIMING

Page 1 of 15

INTERSECTION: HUNTINGTON DR @ SANTA ANITA AV Date Prepared: 9-26-12 PD By: [illegible]

T.S. No.: 5076-ARC Date Implemented: By:

Keystroke: 1 + Phase + Interval

		Phase							
Interval		1	2	3	4	5	6	7	8
Walk	0	0	7	0	7	0	7	0	7
Flashing Don't Walk	1	0	24	0	19	0	25	0	19
Minimum Green	2	4	10	10	9	4	10	10	9
Queue Maximum	3	0	20	0	20	0	15	0	20
Added Green/Actuation	4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Vehicle Extension	5	2.5	2.0	1.5	4.0	2.5	2.0	1.5	4.0
Time Before Reduction	6	0.0	15.0	0.0	15.0	0.0	15.0	0.0	15.0
Minimum Gap	7	2.5	1.0	1.5	3.0	2.5	1.0	1.5	3.0
Max Green 1 (Free)	8	20	50	20	50	20	50	20	50
Max Green 2 (Coord.)	9	25	250	25	50	250	250	25	50
Max Added Green	A	0	0	0	0	0	0	0	0
Unused	B								
Unused	C								
Time to Reduce	D	0.0	15.0	0.0	15.0	0.0	15.0	0.0	15.0
Yellow Clearance	E	3.0	4.0	3.0	4.5	3.0	4.0	3.0	4.5
Red Clearance	F	0.5	0.5	0.5	0.0	0.5	0.5	0.5	0.0

True North

Phase North

1 * 2 3 4 5 * 6 7 OL-A 8

MISCELLANEOUS TIMERS		
Timer	Location	
Red Rest Delay Time	106	0
Green Rest Delay Time	107	0
Stuck All Red Fail Delay Time	10E	30
Red Revert Time	10F	2.0

Comments: * PROTECTED/PERMISSIVE LEFT-TURN
OLA = Φ7
**BATTERY BACK-UP SYSTEM (BBS) INTERSECTION (SEE PAGES 6 & 15)

Figure 4-8: Intersection signal timing sheet

PARAMETERS

Fundamental diagrams for each link. The fundamental diagram illustrates the empirical relationship between flow and density (or occupancy). It conveniently summarizes the effects of:

- speed limit
- road characteristics
- driver behavior

The diagram can be obtained by measurements from sensors such as loops or procedures in the Highway Capacity Manual [2].

SCENARIO INFORMATION

Incidents that affect traffic flow. The current AMS effort focuses on lane blockage events, such as incidents that create bottlenecks. Lane blockages are obtained by cluster analysis, using PeMS loop data and CHP feed. Blockages are characterized by:

- location
- duration
- number of lanes
- capacity limit

4.5. MODEL CONSTRUCTION, CALIBRATION, AND VALIDATION

The main steps in the modeling process are illustrated in Figure 4-9:

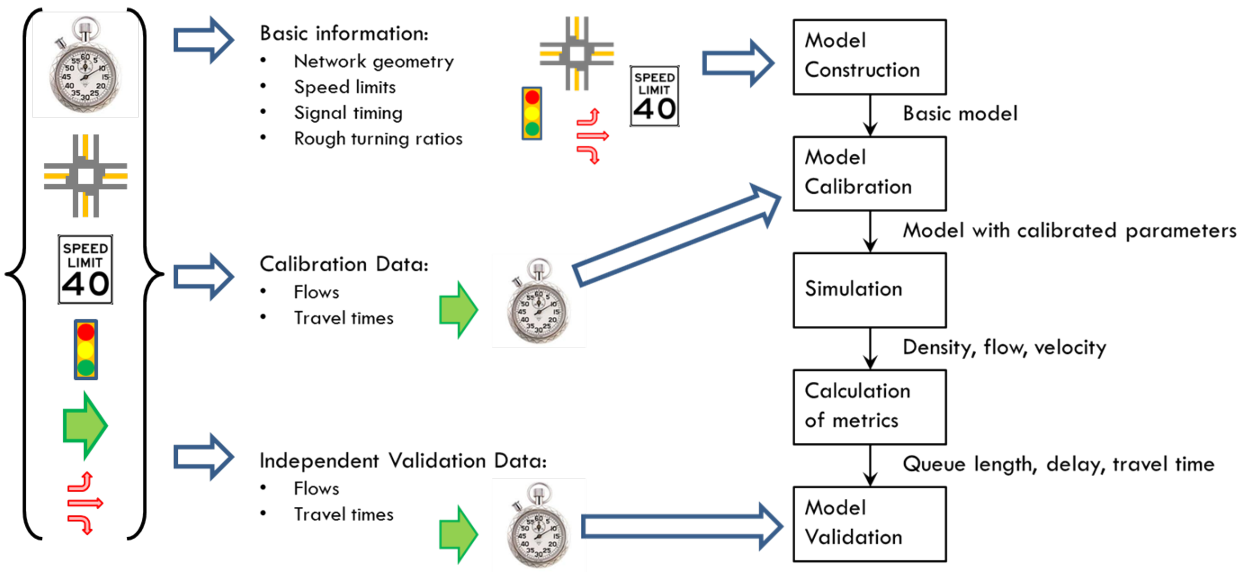


Figure 4-9: Model construction, calibration, and validation

From the body of data collected about the I-210 corridor (shown in brackets), the AMS team extracted:

- Basic information needed to create a model (network geometry, speed limits, signal timing, rough turning ratios)
- Calibration data (flows and travel times)
- Validation data independent of the calibration data (flows and travel times)

This made it possible to:

- Build a basic model
- Calibrate the model to reflect observed traffic conditions
- Run simulations to generate measures of density, flow, and velocity in the study area
- Calculate additional metrics such as travel time and delay
- Compare the flows and travel times from the simulation with observed flows and travel times from the validation data set to check the validity of the simulation results

The following sections describe the work of building and calibrating the arterial model, the freeway model, and the combined freeway+arterial model for the current phase of AMS, plus the calibration acceptance criteria used in the process. (Note that the arterial and freeway models were built and calibrated separately, then connected and simulated together. Results were visually inspected to ensure that the models behaved appropriately in concert.)

4.5.1. CALIBRATION CRITERIA

For a model to be useful, it must be calibrated. That is, it must be tested and adjusted so it reproduces real-world traffic conditions reasonably well. Without calibration, a model can generate unrealistic or misleading results, and if it cannot accurately depict the current traffic state, it is useless for predicting future conditions.

The following calibration criteria were established for the current AMS effort:

Table 4-2: Calibration criteria and acceptance targets

For arterial and freeway models:

Individual link flows	Target
Flow within 100 vph for link flows < 700 vph	> 85%
Flow within 15% for link flows between 700 and 2700 vph	> 85%
Flow within 400 vph for link flows > 2700 vph	> 85%
Individual link GEH < 5	> 85%

Sum of all link flows	**Target**
Total flow within 5% of measurements	< 5%
Total GEH < 4	< 4

For freeway model:

Spatio-temporal extent of congestion	Target
Recurrent bottleneck start time	Within 30 min
Recurrent bottleneck end time	Within 30 min
Recurrent bottleneck extent	Within 0.5 miles

4.5.2. ARTERIAL MODEL CONSTRUCTION AND CALIBRATION

The overall workflow for building and calibrating the arterial model follows the general practice for building engineering systems. The steps, as illustrated in Figure 4-10, are:

1. **Analyzing and cleaning the data**—The first step of the work flow is to clean and aggregate the various types of data collected (e.g., loop detector data, traffic study data, signal timing sheets).
2. **Calibrating the model components**—These data are then used to calibrate the CTM model, which means to decide the best values to use for parameters such as fundamental diagrams and inputs such as boundary flows and split ratios.
3. **Running the model**—The CTM simulation model is then run, which produces flow, density, and speed.
4. **Analyzing/aggregating the results into metrics**—Performance metrics like travel time, delay, level of service, vehicle hours traveled, and vehicle miles traveled are calculated from the simulation results.
5. **Validating the system against reality**—The simulated travel times and flows are compared against those measured in the field. If there are significant discrepancies between simulation and field measurements, the calibration process is repeated until results pass a reasonability check.

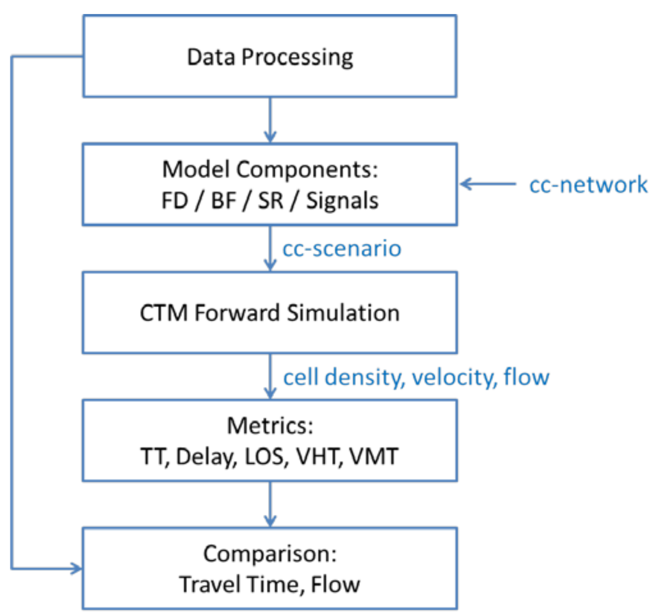


Figure 4-10: Workflow for building and calibrating arterial model

Each step in the workflow is described further in the following sections.

4.5.2.1. Data processing

Data processing is the act of filtering and extracting useful information from the vast amount of raw data gathered about the I-210 corridor.

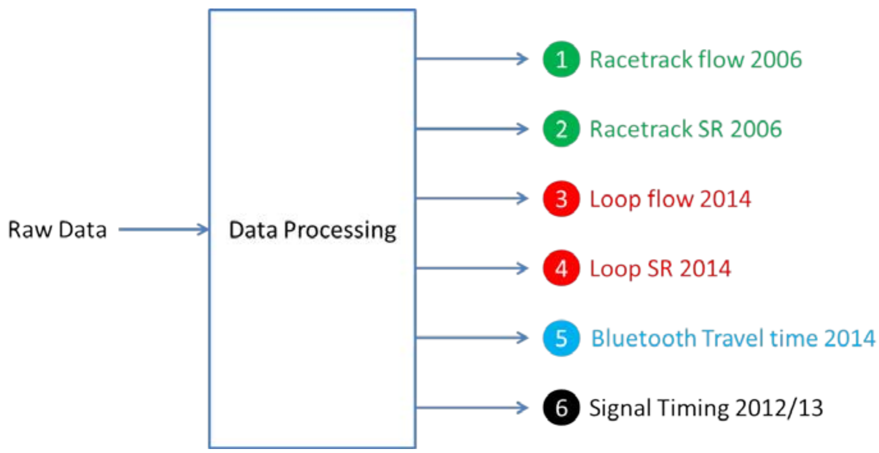


Figure 4-11: Processing the raw data to build and calibrate the arterial model

The data was extracted and categorized into the following types:

- Flows (a.k.a. counts) in vehicles/hour, either on a link across all lanes ("On Huntington westbound between 1st and Santa Anita, flow is 733 veh/hr") or for a specific movement at an intersection ("On Huntington westbound, 125 veh/hr turn left at Santa Anita")
- Split ratios in percentage ("On Huntington westbound, 17% of traffic turns left at Santa Anita")
- Travel time in seconds between two locations ("On Huntington westbound, the average travel time between Gateway and Santa Clara is 153 seconds")
- Signal timings, describing when the lights show red, yellow, and green

The data was drawn from the following sources:

- A traffic study carried out in 2006 around the racetrack in Arcadia (referred to as the "Racetrack" study); movement flows were counted manually on a few days when the racetrack was in session.
- Induction loops installed in the pavement on the freeway and on some arterial roads, which measure the flow continuously.
- Bluetooth sensors mounted at certain intersections record the time and ID of the nearby mobile Bluetooth devices. Travel time of Bluetooth devices is produced through the matching of ID at different mounting locations.
- Signal Timing Sheets provided by the operator of the signalized intersections (e.g., the city or Caltrans), covering a period from 2012 to 2013.

Note: All data was aggregated for the evening peak period of weekdays.

4.5.2.2. Model components

Figure 4-12 describes the calibration process to create the model components for simulation. The final output is the so-called **cc-scenario**, which consists of the cc-network plus all model components (boundary flows, split ratios, fundamental diagrams, signal timing).

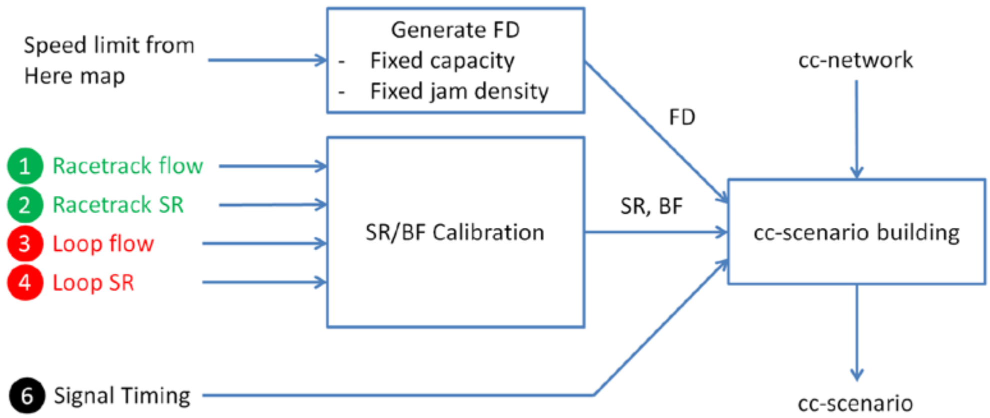


Figure 4-12: Creating model components needed for simulation

- **Cc-network**: With a map provided by Here.com, the AMS team generated a representation of the road network with links (each representing a road segment) and nodes (each connecting two or more road segments). Additional links were defined as:
  - *Source* links (where traffic enters the network)
  - *Sink* links (where traffic leaves the network)
- **FD**: The fundamental diagram (FD) components describe roadway parameters such as free flow speed (the speed during light traffic conditions), flow capacity (maximum possible flow often seen at a recurrent bottleneck), and jam density (number of cars per mile when traffic is standing still). They are created according to the Highway Capacity Manual [2]. The only inputs needed are the number of lanes and the free flow speed, which is approximated with the speed limit obtained from the Here.com map.
- **Signals**: For each signalized intersection, the signal plan active at 5pm was converted into a fixed-time plan in a format appropriate for the simulation. Where necessary, worst-case assumptions (for the main direction of traffic) were made to ensure minor side-street approaches obtained adequate green time.
- **BF and SR**: Boundary flows (BF) describe the amount of traffic that enters the network at each source link. Split ratios (SR) describe the fraction of traffic that turns at intersections and off-ramps (or any bifurcation in the network). The data available at the time of this study does not cover all the boundary flows and split ratios, due to limited instrumentation. The study therefore uses data measured elsewhere on the network to estimate the missing boundary flows and split ratios.

4.5.2.3. Calibration of split ratios and boundary flows

The split ratios and boundary flows are calibrated together in the process outlined in Figure 4-13. The underlying flow and split ratio data come from inductive loop sensors in Arcadia in 2014 as well as the Racetrack study of 2006.

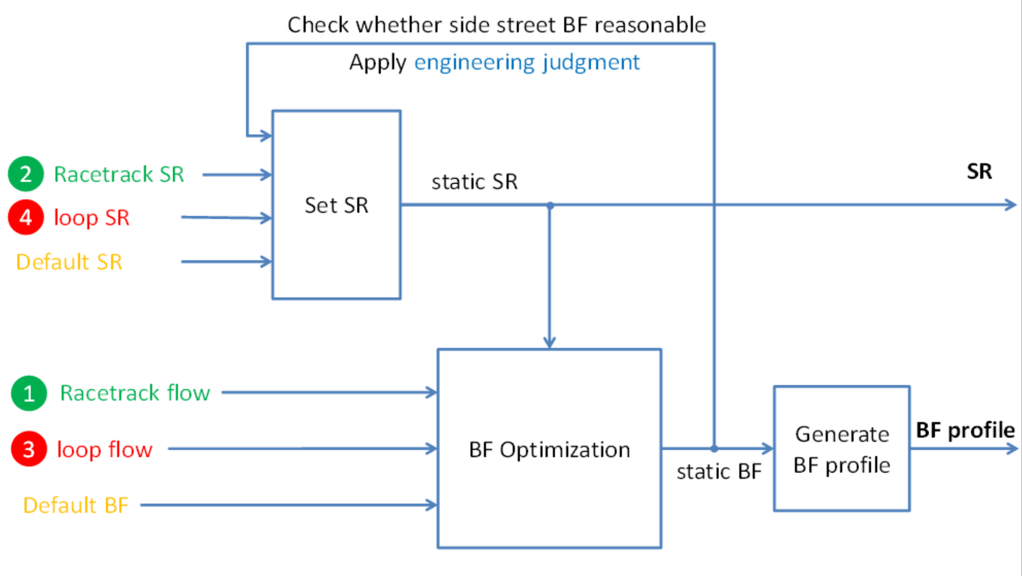


Figure 4-13: Calibration process of the split ratios and boundary flows for the arterial model

Split ratios: The split ratios are set directly. Where possible, they are computed based on the loop measurements in Arcadia. Otherwise, split ratios from the 2006 Racetrack study are used. At some intersections, no data is available; defaults values are used there.

Boundary flows: The boundary flows are computed by a quadratic optimization program. This optimization finds the best boundary flows that fit given target flows in the network and the split ratios from the previous step. The target flows are taken from loop measurements in Arcadia, where available. Furthermore, the loop data are used to scale the racetrack data of 2006, which are used as target flows at locations where no loop data was available. Where no data exist, default values are used.

Adjusting the values: After the optimization, the AMS team assessed the static boundary flows and split ratios. If unreasonable values existed, the team applied engineering judgment and adjusted the default values. For example, the split ratios at small side streets were adjusted to prevent an unrealistically high inflow. Some split ratios from the 2006 racetrack study were also adjusted to permit flow to agree more closely with the measured loop data on Huntington eastbound (between Santa Anita Ave and Second Ave, and again between Second Ave and the I-210 junction). This process is repeated until reasonable split ratios and boundary flow are obtained.

Boundary flow profiles: Finally, the static boundary flows are converted to boundary flow profiles to reflect the peak hour and its shoulders, as illustrated in Figure 4-14. Analysis of flow data during the peak period revealed that the flow profiles at different locations are the same shape, the only significant difference being the amplitude. Therefore, a generic flow profile was created that represents the typical shape. At each boundary, the static boundary flows were then used to scale the generic profile, resulting in an individualized boundary flow profile at each source link of the network:

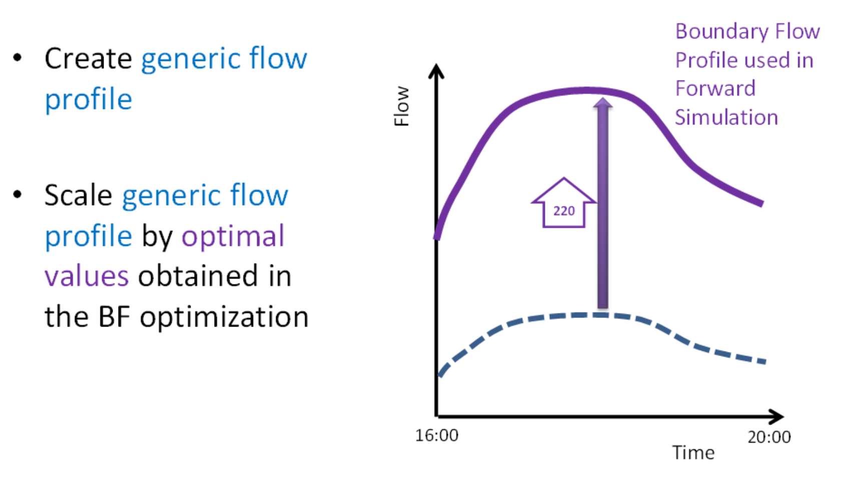


Figure 4-14 Process to generate boundary flow profiles given the results of the optimization

4.5.2.4. CTM forward simulation and calculation of metrics

With the network and model components created and calibrated, the CTM simulation model can be run to produce measures of traffic flow, speed, and density. From those simulation results, performance measures like travel time, delay, vehicle hours traveled, and vehicle miles traveled are calculated. Those performance measures are used to check the reasonableness of results and also to assess potential benefits of ICM strategies that may be deployed on the corridor.

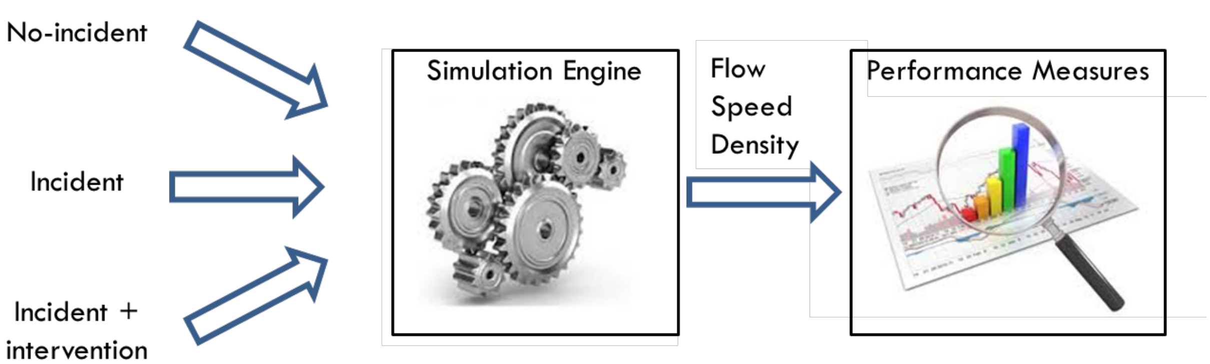


Figure 4-15: Using the simulation results for estimating the benefits of ICM implementation

Details of the metrics calculations can be found in section 9.6.

4.5.2.5. Comparison

After processing the data, calibrating the model, running a simulation, and calculating metrics, the last step in the workflow is to compare the simulated performance measures with actual observed measurements:

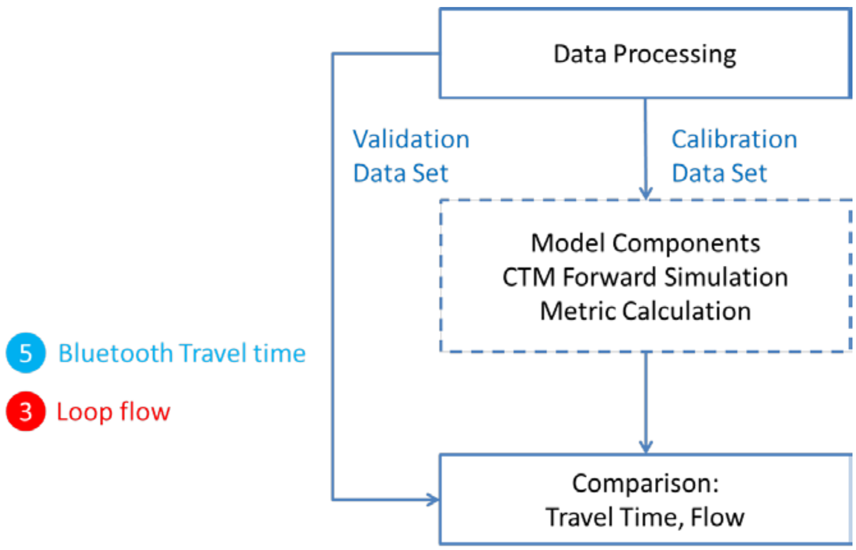


Figure 4-16: Comparing simulated and observed measurements

The comparison followed these steps:

1. The AMS team selected 21 days from March to May of 2014 that mimics the baseline situation being modeled.
2. Of these 21 days, the team used data from 15 days from March and April in the calibration and simulation process. This was the Calibration Data Set.
3. The simulated flow was then compared to measured flow (from loop data) from the 6 days in May (the Validation Data Set), according to the FHWA model calibration criteria.

Technically, making comparisons this way prevents over-fitting data to the model. Intuitively, if one imagines that the current time is the end of April, data from the past (March and April) can be used to calibrate the model. The goal is to predict future traffic status.

Flow comparison:

Figure 4-17 shows the comparison of the flows. Loop measurements are available at many locations on Huntington and its side streets. Their average flows are shown as the red bars. The average of the simulated flows are shown as the blue bars. A visual inspection shows that the simulated flows are close to the measured flows:

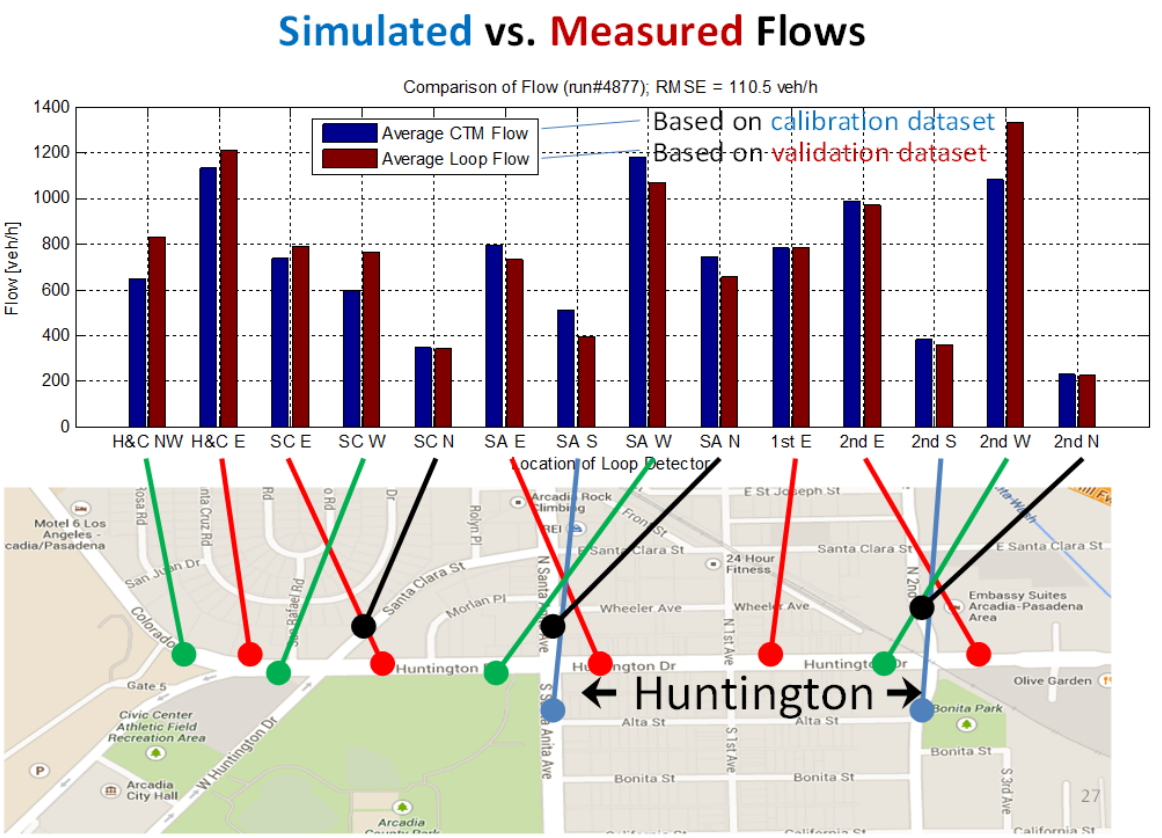


Figure 4-17: Comparison of simulated flows against real measurements

The team also compared the flows in greater detail on an hourly basis according to the FHWA criterion, as shown in Table 4-3. Since the simulation lasts 4 hours and there are 14 measurement locations, there are 56 comparisons. Hourly flow comparisons pass 43 times out of 56 possible. Individual link GEH statistics also pass 43 times out of 56 possible. A passing rate of 77% is not unreasonable for a preliminary, unfinished model.

Table 4-3: Validation of the simulation model across the PM peak period

			Hourly target hit			
Individual link flows	**Target**	**Passed cases**	**4-5pm**	**5-6pm**	**6-7pm**	**7-8pm**
Flow within 100 vph for link flows < 700 vph	> 85%	26/32 = 81%	4/5 = 80%	4/5 = 80%	10/10 = 100%	8/12 = 67%
Flow within 15% for link flow between 700 and 2700 vph	> 85%	17/24 = 71%	6/9 = 67%	6/9 = 67%	3/4 =75%	2/2 = 100%
Flow within 400 vph for link flows > 2700 vph	> 85%	0/0	N/A	N/A	N/A	N/A
Individual link GEH < 5	> 85%	43/56 = 77%	10/14 = 71%	10/14 = 71%	13/14 = 93%	10/14 = 71%
Sum of all link flows	**Target**	**Results**	**4-5pm**	**5-6pm**	**6-7pm**	**7-8pm**
Total flow within 5% of measurements	< 5%	3/4	Yes	Yes	Yes	No
Total GEH < 4	< 4	3/4	Yes	Yes	Yes	No

Some worst-case assumptions were made so that the model would be conservative. Some model limitations are:

- Sparse flow data on many side streets: Although a part of Arcadia is well equipped with sensors, no recent data along Colorado Blvd. was available during the time of the analysis. As a result, the team was dependent on data from 2006, which were measured during days when the racetrack was in session.
- Very sparse turn volume data: Almost entirely reliant on 2006 data.

Travel time comparison:

Travel times were not specified as a calibration target for Phase 1. Therefore, a detailed analysis of Bluetooth travel times was not performed. However, measured and simulated travel times were compared along a westbound portion of Huntington between Gateway and Santa Clara. A cursory examination of Bluetooth-measured data on weekdays between 4:00 pm and 6:00 pm suggests that travel times range from about 100 sec to 200 sec. Travel times from simulation ranged from about 80 sec to 195 sec. Further analysis is required before drawing conclusions from these preliminary findings.

4.5.3. FREEWAY MODEL CONSTRUCTION AND CALIBRATION

The building of the freeway model followed steps analogous to those of the arterial model. Details are slightly different in terms of the available data and process for imputing unmeasured inputs. The underlying model is a CTM, exactly the same as the arterial. The following steps were taken to construct and calibrate the I-210 westbound freeway model:

1. Build a network
2. Assess loop health
3. Calibrate fundamental diagrams
4. Select representative congestion patterns
5. Collect measured ramp flows and split ratios
6. Impute values for unknown on-ramp flows and off-ramp splits
7. Make manual corrections and a visual assessment
8. Compare flows and assess the calibration

Each of these steps is described below.

Step 1: Build a "coarse" network

The coarse network has the minimum number of nodes required to capture the important geometric features of the site. Nodes are placed at all locations with ramps or changes in the number of lanes. PeMS VDS stations are attached to the network. The coarse network has a total of 106 links and 107 nodes, shown in Figure 4-18. The links are broken down into 29 on-ramps, 23 off-ramps, and 54 mainline links, as illustrated in Figure 4-19.

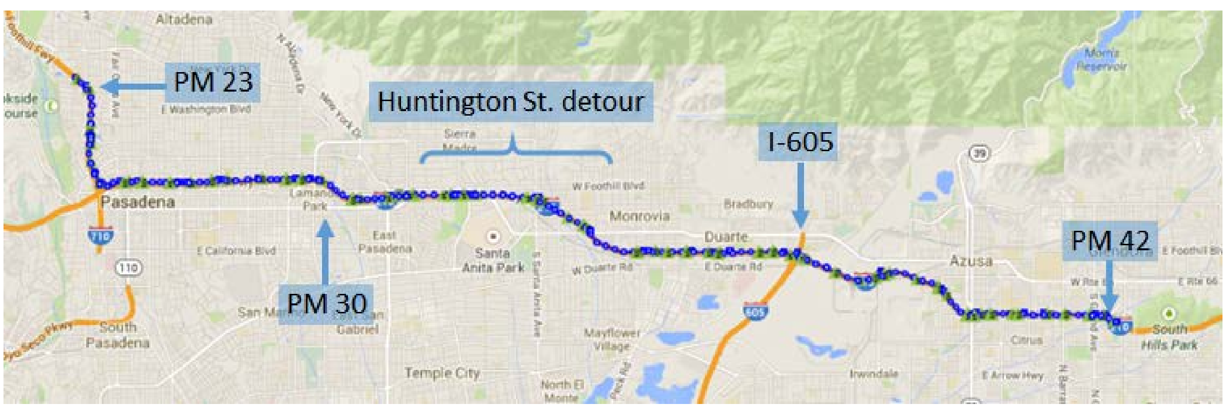


Figure 4-18: Freeway model network

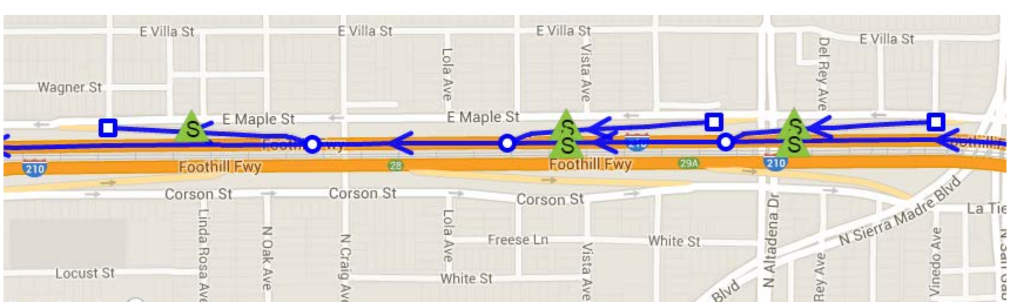


Figure 4-19: On-ramp, off-ramp, mainline links

Step 2: Assess loop health

For this network, the AMS team used the PeMS daily loop health diagnostic. For the period from May 13 to May 29 over the region of interest there were 91 stations with an average detector health of 81%.

Step 3: Calibrate fundamental diagrams

The team used the algorithm of [3] to fit a triangular FD (fundamental diagram) shape to the data. The mainline links were then divided into a smaller size to increase the precision of the simulation. In this case, the target time step was five seconds, and 1000' was set as the longest acceptable mainline link length.

The histogram of link lengths for this model is shown in Figure 4-20. This network (called the "fine" network, in contrast to the "coarse" network) has a total of 179 links and 180 nodes. Each link is then assigned the fundamental diagram corresponding to the sensor station that it is closest to. Figure 4-21 shows a sample FD calibration.

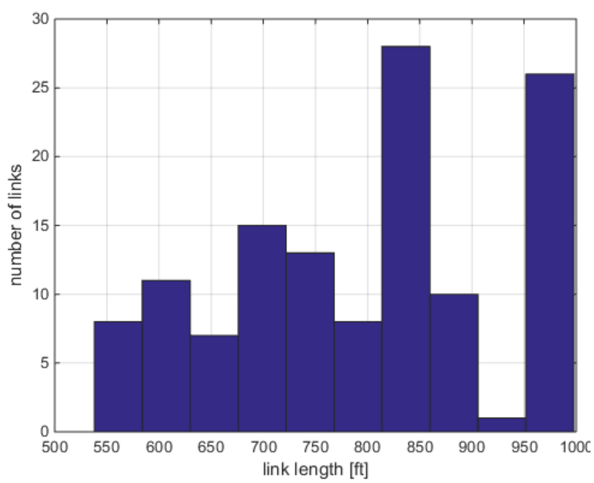


Figure 4-20: Link lengths for "fine" network

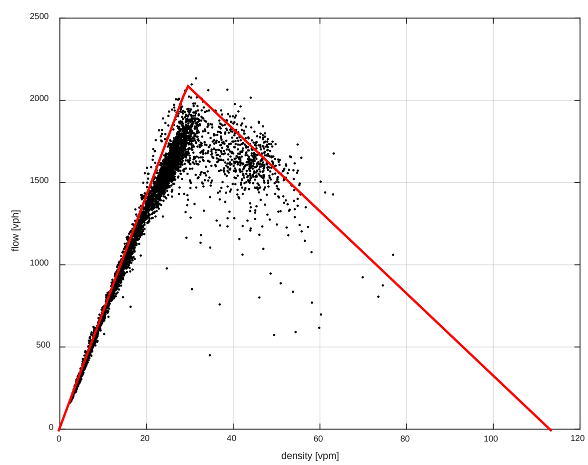


Figure 4-21: FD fit for VDS 717675

Step 4: Select representative congestion patterns

The representative day was chosen to be a weekday with good loop health and exhibiting typical recurrent congestion. The goal was to capture recurrent bottlenecks in the model and to be able to insert incidents with defined characteristics based on the cluster analysis described in chapter 5. Analysis of congestion patterns revealed the following:

- Some congestion formed on May 22 with no apparent incident. This situation is typical of freeways that operate at or near capacity.
- There is an apparent bottleneck in the afternoon of May 22 which activates at around 4pm at VDS 717642 (Altadena). However, mainline detection of the last few miles of the site was chronically poor. Therefore, the team did not include this as a calibration target because the poor detection surrounding it made it difficult to analyze.
- The main bottleneck and source of congestion on May 22 was considered to be between Baldwin and Michillinda.

Step 5: Collect measured ramp flows and split ratios

PeMS data was scrutinized through visual inspection and simple flow balance tests. This resulted in a stricter assessment of the overall count of good and bad detectors in the system during the study period (about 68%) than was evident from using the PeMS daily loop health diagnostic alone (81%), as described in step 2. The detector count is shown in Table 4-4.

In this step the AMS team collected from PeMS flows for good on- and off-ramps. The on-ramp flows were assembled into demand profiles. The off-ramp flows were used to compute split ratios. This was done by searching for a good mainline station between the given ramp and the next upstream or downstream ramp. If no such mainline detector existed, then the split ratio was left for the imputation algorithm to compute. Otherwise, the team took the appropriate ratio of measured off-ramp and mainline flows to obtain the split ratio profile.

Table 4-4: Count of good and bad detectors

	No detection	Bad detection	Good detection	Total
On-ramps	1	2	26	29
Off-ramps	1	10	12	23
Mainline	-	15	25	40

Step 6: Impute values for unknown on-ramp flows and off-ramp splits

Demands and split ratios for ramps with either no detection or bad detection were calculated with the technique described in [4]. This algorithm infers missing data by calculating the inflows required to realize the observed congestion on the mainline of the freeway. This algorithm is sometimes sensitive to inaccurate measurements, and the final model requires further fine tuning as described in step 7.

Step 7: Make manual corrections and a visual assessment

The automatic procedure produced a model that was calibrated for the full day of May 22. Manual adjustments were made to split ratios and on-ramp flows to reflect typical known characteristics on other days in 2013 when data are available. Additional adjustments were made to address flow balance mismatches where identified.

Figure 4-22 shows the detail of the speed contour during the main period of interest between 4pm and 8pm. Note again that the bad data at the downstream end near Sierra Madre and Altadena made it difficult to accurately study the congestion in that location of the freeway. (Dark red horizontal lines correspond to bad data, dark red squares to intermittently bad data, such as from weak or failing detectors.) For this reason, the target was to focus on reproducing accurately the recurrent bottleneck between Baldwin and Michillinda. On the target day, this bottleneck activates around 4:30pm, and congestion extends upstream reaching the I-605 interchange at 5:45 pm. The congestion then dissipates around 6:40pm.

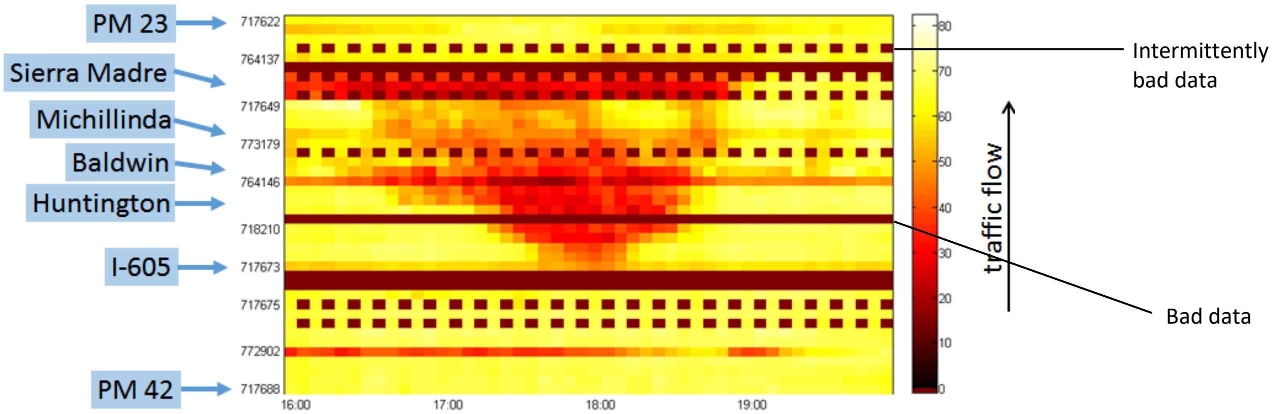


Figure 4-22: Speed contour for PM peak

Figure 4-23 shows the simulated speed contour plot for the period 4pm-8pm. The location, start time, end time, and extent of congestion have been faithfully reproduced.

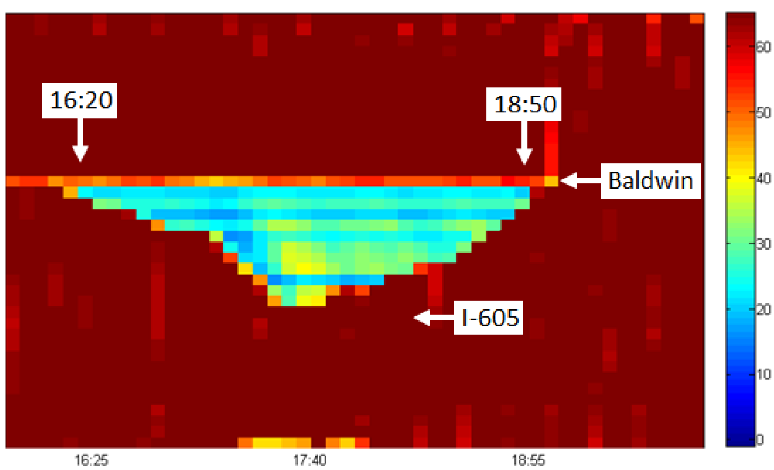
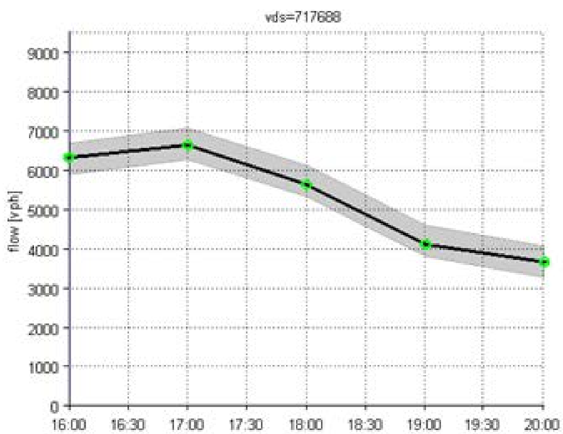


Figure 4-23: Simulated speed contour for PM peak

Step 8: Compare flows and assess the calibration

The team also checked simulated and measured hourly flows at each of the detector stations. Figure 4-24 provides representative samples of these comparisons. The solid black lines in these plots are simulated flow values. The gray bands represent measured flows with a 400 veh/hour tolerance. Green dots indicate hourly samples that fall within the band; red dots are samples that fall outside the band. Overall, 90% of simulated flows are within 500 veh/hour of measured flows.



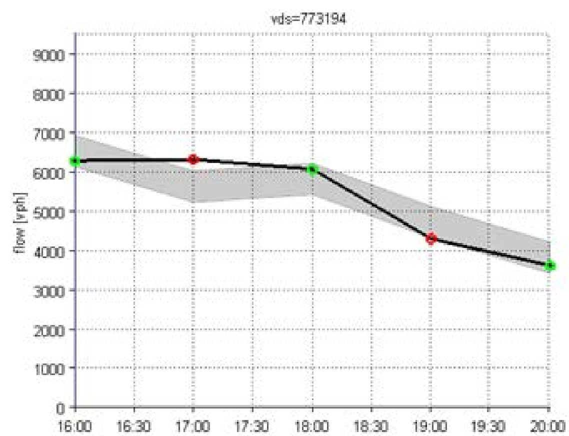


Figure 4-24: Two examples of simulated (black line) and measured (gray band) hourly flows

The FHWA calibration targets are shown in Table 4-5. These should be interpreted as calibration results for a preliminary version of an unfinished model. On the mainline where flows are typically around 6000 veh/hour, a 400 veh/hour tolerance corresponds to an error of about 6%. This is quite strict considering the noise floor for loop detector data.

Table 4-5: FHWA calibration targets

Individual link flows	Target	Passed cases	Hourly target achieved			
			4-5pm	5-6pm	6-7pm	7-8pm
Flow within 100 vph for link flows < 700 vph	> 85%	0/0	N/A	N/A	N/A	N/A
Flow within 15% for link flows between 700 and 2700 vph	> 85%	0/0	N/A	N/A	N/A	N/A
Flow within 400 vph for link flows > 2700 vph	> 85%	56/72 = 78%	14/18 = 78%	14/18 = 78%	15/18 = 83%	13/18 = 72%
Individual link GEH < 5	> 85%	55/72 = 76%	14/18 = 78%	14/18 = 78%	15/18 = 83%	12/18 = 67%
Sum of all link flows	**Target**	**Results**	**4-5pm**	**5-6pm**	**6-7pm**	**7-8pm**
Total flow within 5% of measurements	< 5%	4/4	Yes	Yes	Yes	Yes
Total GEH < 4	< 4	2/4	Yes	No	Yes	No

Spatio-temporal extent of congestion	Target	Measured	Simulated	Δ	Target achieved
Recurrent bottleneck start time	Within 30 min	4:30	4:20	10 min	yes
Recurrent bottleneck end time	Within 30 min	6:40	6:50	10 min	yes
Recurrent bottleneck extent	Within 0.5 miles	~6miles +/- 1/2 mile	~6miles	~1/2 mile	yes

4.5.4. COMBINED FREEWAY AND ARTERIAL MODEL

The separately calibrated freeway and arterial models were connected and simulated together. Results were visually inspected to ensure that the models behaved appropriately in concert. The only adjustment made was to tune off-ramp flow onto the Huntington off-ramp to reproduce the desired demand on the arterial network. Simulation results of the combined freeway and arterial model are detailed in section 5.3.

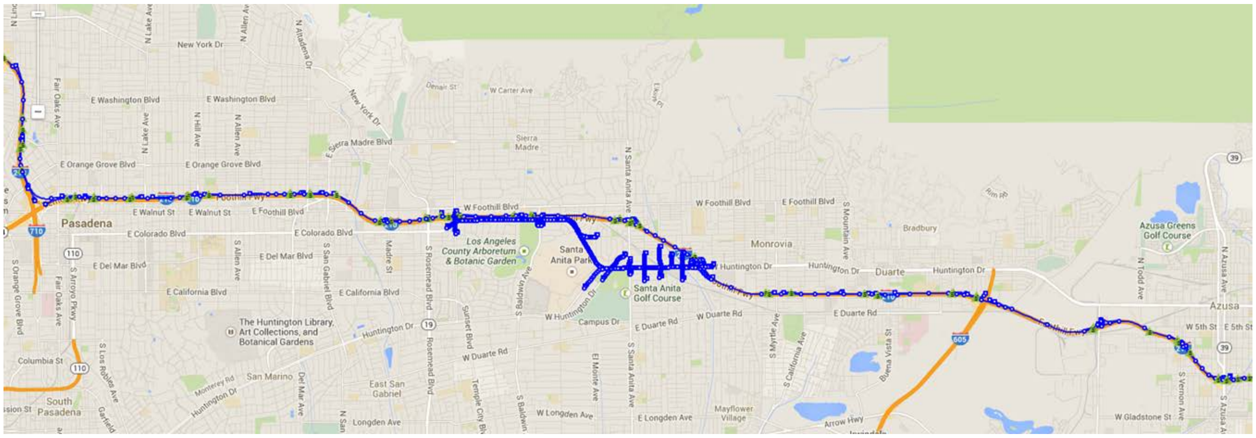


Figure 4-25: Combined freeway + arterial model network

5. ANALYSIS PROCESS AND SIMULATION RESULTS

After selecting a modeling approach and creating a model to capture existing corridor operations, the next steps in the AMS process are to:

- Identify incident scenarios along the corridor
- Choose control interventions to address the scenarios
- Run simulations to assess the interventions' effectiveness

For AMS Phase 1, the scenarios were chosen to show the most common type of incident and also to illustrate how changes to model inputs result in expected outputs. The scenarios were not chosen to evaluate the potential benefits of ICM, but rather as illustrative examples of the process. In Phase 2, stakeholders are expected to provide input regarding how interventions will be defined and what signal plan modifications are allowable. Therefore, signal plans presented in this Phase 1 report are not optimized.

The process unfolds like this:

1. **Cluster analysis.** The first step is to perform a clustering analysis to identify the occurrences of incidents and to characterize them. The analysis helped the AMS team answer key questions: How often do incidents occur? How many lanes are blocked and for how long? What is the spatial distribution of incidents? (While the operational assessment in chapter 3 looks at freeway bottlenecks and incidents along the corridor, the cluster analysis described in this chapter examines a smaller region in more detail using 2014 data.)

2. **Incident selection and simulation.** The next step is to choose the most common incident type and to run simulations to capture the extra delay caused by the incident and explore an intervention that can yield benefits to travelers. In carrying out this step, the AMS team used available data to estimate changes in flow patterns observed during incidents. These data were then used to adjust routing assumptions in the model.

3. **Results.** The results of the simulations reveal the effects of the intervention and the impact on performance in the study area.

5.1. CLUSTERING METHODOLOGY

The AMS team studied the location and severity of incidents along the I-210 corridor, both eastbound and westbound and for both AM (5 to 10 AM) and PM (3 to 8 PM) peaks, for the period from January 2014 to May 2014. The analysis applied to the section of I-210 between postmile 18 and 42 (between the Glendale Freeway and Grand Ave. in Glendora).

The data were obtained by comparing the CHP incident log on PeMS with traffic flow and speed contour plots from loop data. The analysis of traffic flow and speed contour plots makes it possible to detect incidents with impact on travel delays, while the CHP log provides a description of each incident and particularly the consequent number of lanes closed. Peak periods (not days) were categorized as incident periods if at least one of the following conditions held:

1. An incident was detected in the flow and speed contour plots from loop data.
2. An incident leading to a lane closure of more than 15 minutes was reported in the CHP log.

5.1.1. METHODOLOGY DETAIL

5.1.1.1. Classification process

The process of classifying peak periods into categories is illustrated in Figure 5-1 and follows these steps:

1. Holidays and weekends are removed from the data set so that only working days remain.
2. Speed and flow contour plots from PeMS are generated with consistent colormaps to enable efficient visual inspection.
3. By analyzing the contour plots, peak periods are classified into the following bins: “incident,” “special,” and “regular” (i.e., regular congestion). See sections 0 and 5.1.1.3 for details on identifying “special” and “incident” peak periods on contour plots.
4. Each “special” and “regular” peak period is then checked against the CHP log on PeMS to identify whether one or more lanes was blocked. If at least one lane was blocked for at least 15 minutes, the period is reclassified as “incident.”

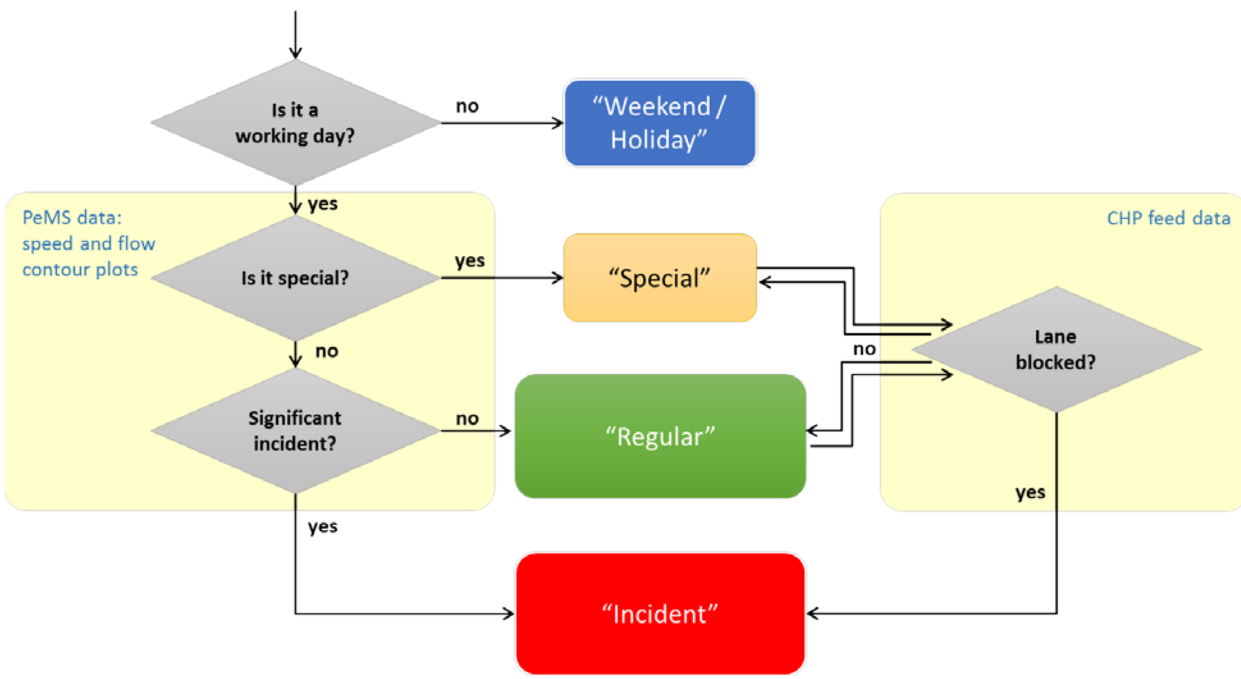


Figure 5-1: Classification process of the cluster analysis

5.1.1.2. Detecting "special" peak periods on contour plots

In general, two-dimensional contour plots are used to show traffic-related quantities as they vary across time and space. The spatial axis typically corresponds to a drivable series of links along a road network, such as I-210 W. The color of the plot indicates the value of the quantity of interest, such as flow, speed, or density. In this report, unless otherwise specified, contour plots are configured so that traffic flows from bottom to top (position is indicated on the vertical axis), and time evolves from left to right (time of day is indicated on the horizontal axis).

A peak is considered "special" if its contour plot shows traffic conditions that are clearly neither regular congestion nor a lane closure caused by an incident. An example of a special day is March 4, 2014 (shown in Figure 5-2), where a forward-moving jam emerges after 9am at milepost 50 and slowly moves forward. After five hours, it stops at milepost 25 where it remains stationary. During the evening peak, the jam grows due to the increased demand. At 7pm, the jam dissolves. Since the jam was moving forward, it is clearly not caused by an incident.

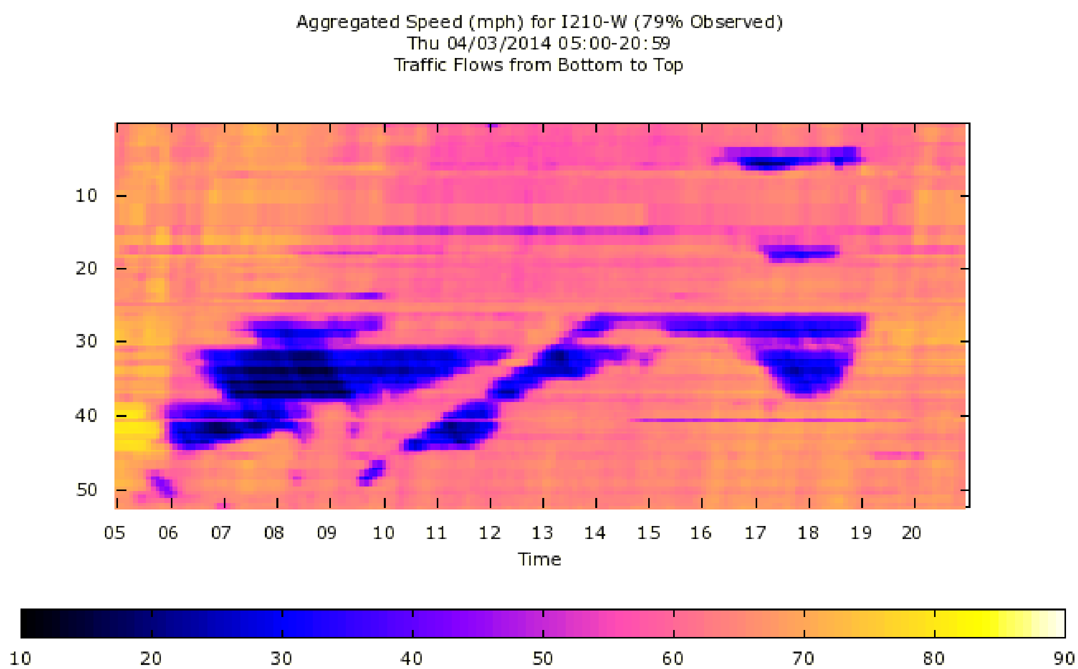


Figure 5-2: Example of a special day

5.1.1.3. Detecting "incident" peak periods on contour plots

An incident is identified on a contour plot if all of the following conditions hold:

- High speed downstream of the incident location (>50 mph)
- Low speed upstream of the incident location (<50 mph)
- Sharp drop in flow (>2400 vph) in less than 10 minutes
- Congestion lasts at least 30 minutes
- Congestion covers at least 3 miles

Figure 5-3 shows an example of an incident during the evening peak at 5pm near postmile 20. Traffic is very fast downstream of the incident (70 mph) and slow in the upstream congestion. The sharp drop in flow illustrated in the diagram is typical of an incident.

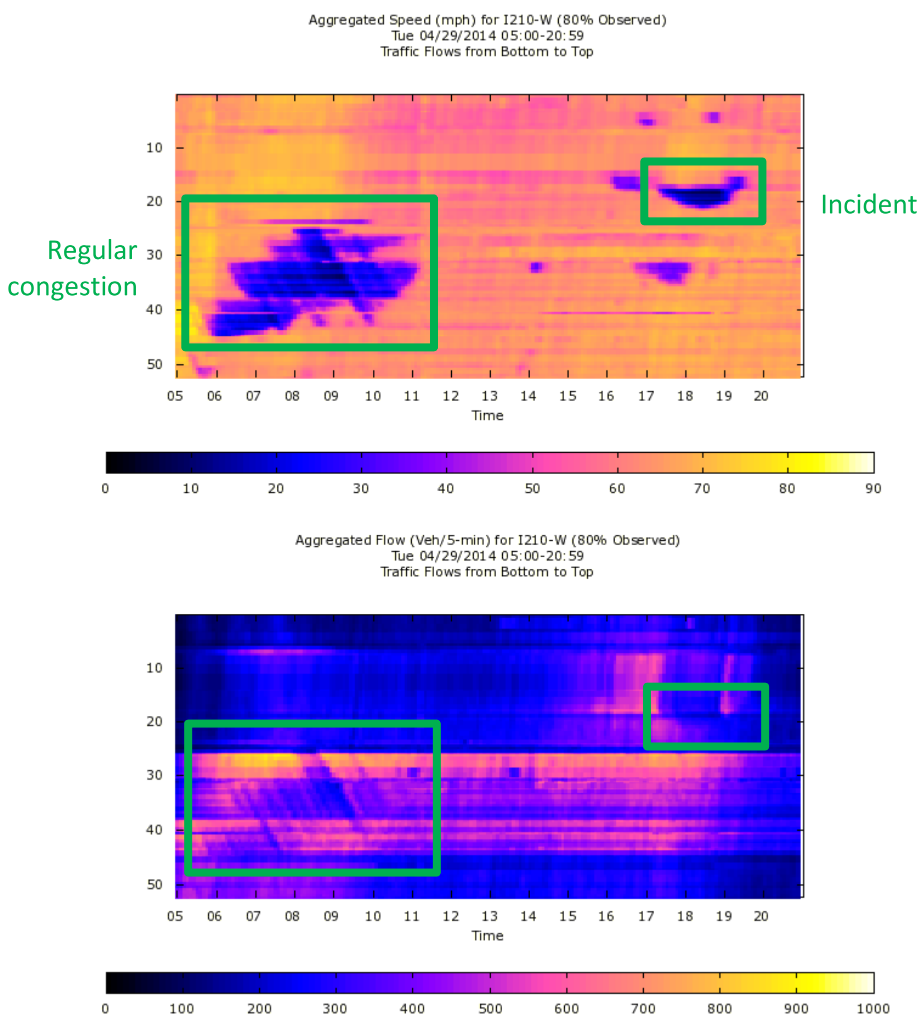


Figure 5-3: Regular congestion and incident in speed (top) and flow (bottom) contour plot

5.1.2. CLUSTERING RESULTS

The clustering results described in this section focus on the segment of I-210 between postmiles 22 and 36 only (between Arroyo Blvd. and the I-605 Freeway).

Figure 5-4 shows the results from analyzing both loop data and the CHP feed. Incidents (in red) were identified from both sources:

Eastbound – AM

		PeMS CHP			Total
		Non-incident	Incident	W'nd/H'day	
PeMS flow & speed	Regular	78	10	0	88
	Incident	3	5	0	8
	Others	4	1	0	5
	W'nd/H'day	0	0	50	50
Total		85	16	50	151

Westbound – AM

		PeMS CHP			Total
		Non-incident	Incident	W'nd/H'day	
PeMS flow & speed	Regular	66	27	0	93
	Incident	2	1	0	3
	Others	4	1	0	5
	W'nd/H'day	0	0	50	50
Total		72	29	50	151

Eastbound – PM

		PeMS CHP			Total
		Non-incident	Incident	W'nd/H'day	
PeMS flow & speed	Regular	46	37	0	83
	Incident	4	5	0	9
	Others	4	5	0	9
	W'nd/H'day	0	0	50	50
Total		54	47	50	151

Westbound – PM

		PeMS CHP			Total
		Non-incident	Incident	W'nd/H'day	
PeMS flow & speed	Regular	54	29	0	83
	Incident	3	7	0	10
	Others	5	3	0	8
	W'nd/H'day	0	0	50	50
Total		62	39	50	151

Figure 5-4: Cross analysis of incidents from loop data and CHP feed

Note that it would have been insufficient to inspect only PeMS contour plots or only the CHP data. There are many periods in which substantial incident-related congestion occurs that goes unreported in the CHP data. Likewise, there are many periods in which incidents occurred that did not meet all the conditions (described in section 5.1.1.3) applied in the contour plot analysis.

Figure 5-5 shows the totals in each bin for the AM and PM peaks both eastbound and westbound:

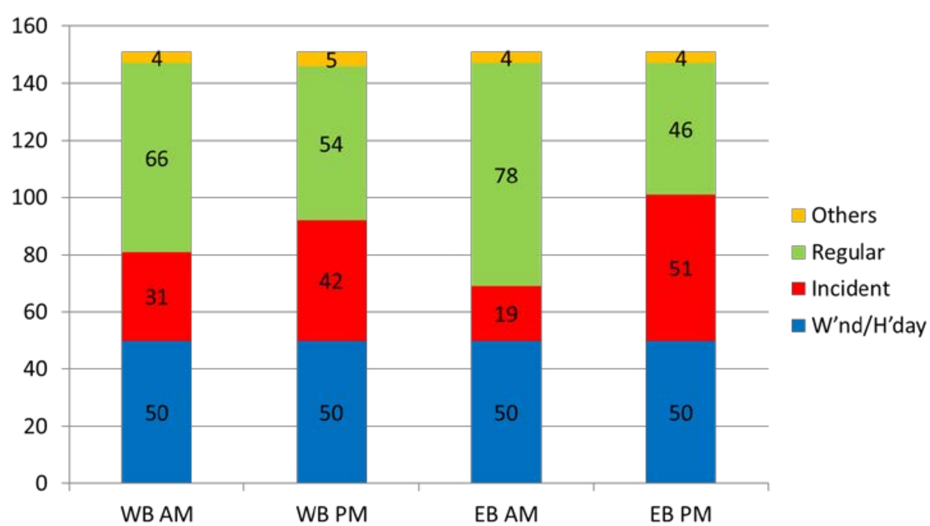


Figure 5-5: Clustering of days according to incident pattern from January 2014 to May 2014

Incident frequency. As shown in Figure 5-6, for most incident days only one incident occurs during the peak. Note that incidents refer to those reported by the CHP, so 0 incidents per peak period means there is evidence that incidents occur on those days but the CHP did not report anything.

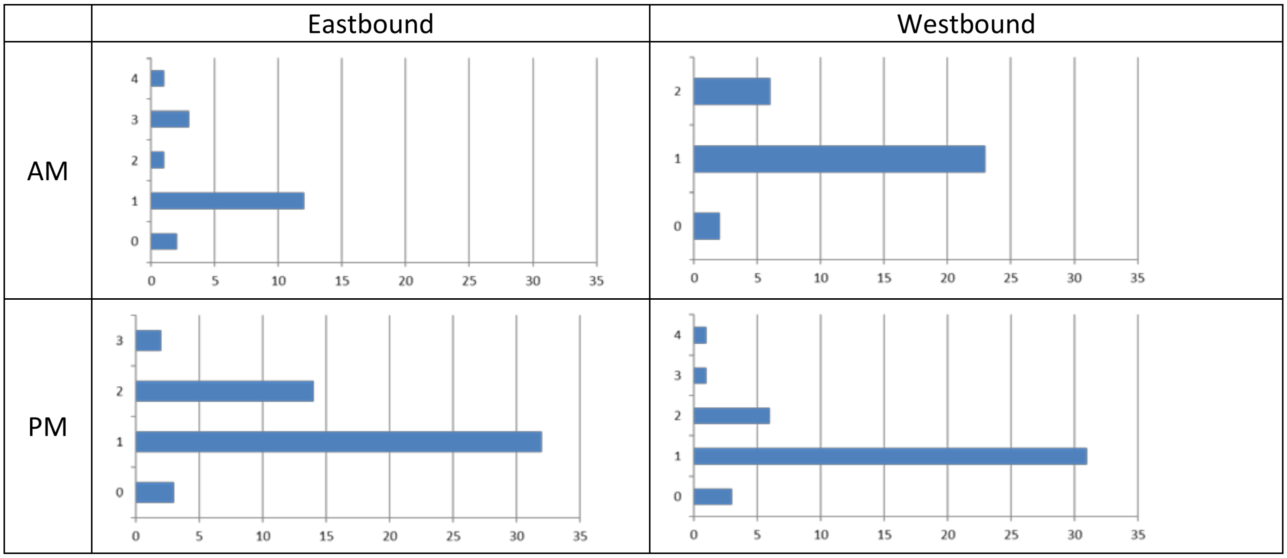


Figure 5-6: Number of CHP incidents recorded per incident peak period

Incident severity. The impact of an incident on the traffic is closely related to the number of mainline lanes closed and the duration of the closure. Figure 5-7 displays the distribution of incident severity according to those criteria. Note that the most common situation is when one lane is blocked for about 30 minutes.

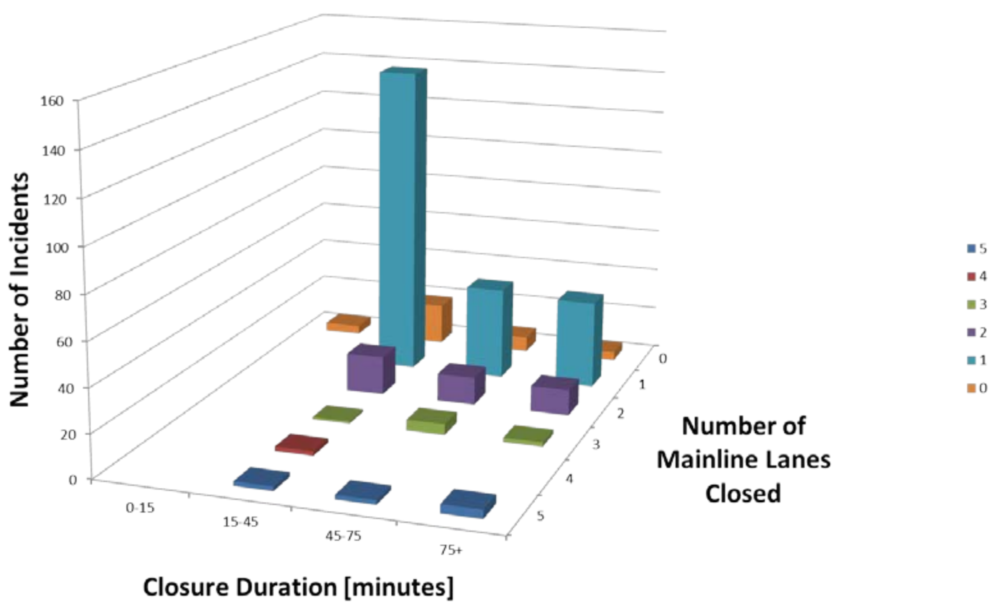


Figure 5-7: Incident severity, eastbound and westbound, all times of day. AM and PM peaks are similar and therefore not plotted separately. Number of mainline lanes closed = 0 means lane closure occurs on the ramp.

Incident distribution. Figure 5-8 and Figure 5-9 show the distribution of freeway incident locations for both directions and both peaks. This analysis agrees qualitatively with that in sections 3.2.1 and 3.2.3. Over the whole stretch between milepost 22 and 36, the average number of incidents across both directions and both peaks is 4.5 per mile. By comparison, in the area of the reroute (postmiles 30 to 33), the average is 3.9 incidents per mile. Incidents are distributed rather uniformly, although there tend to be more on the east side than the west side.

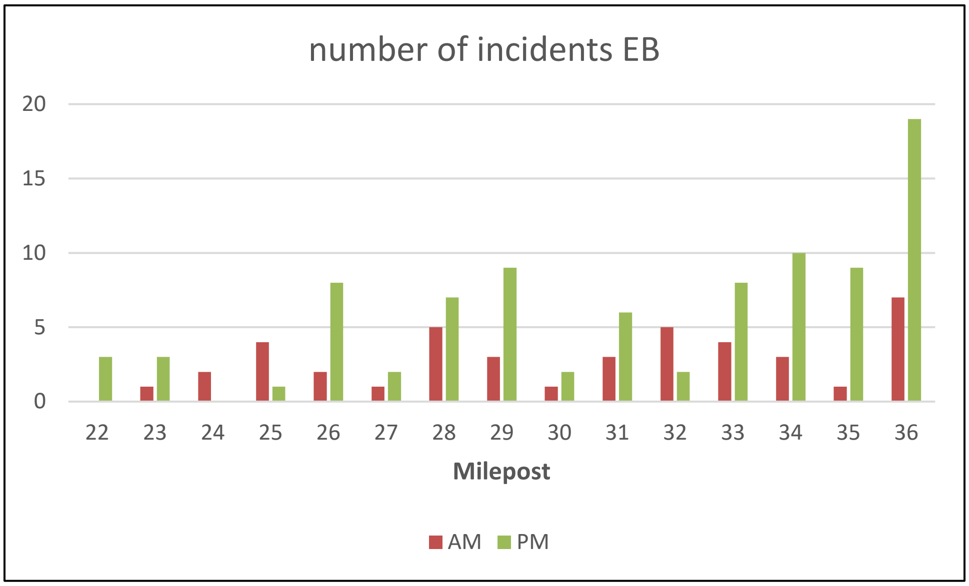


Figure 5-8: Number of incidents for eastbound traffic AM and PM peak (weekdays January to May 2014)

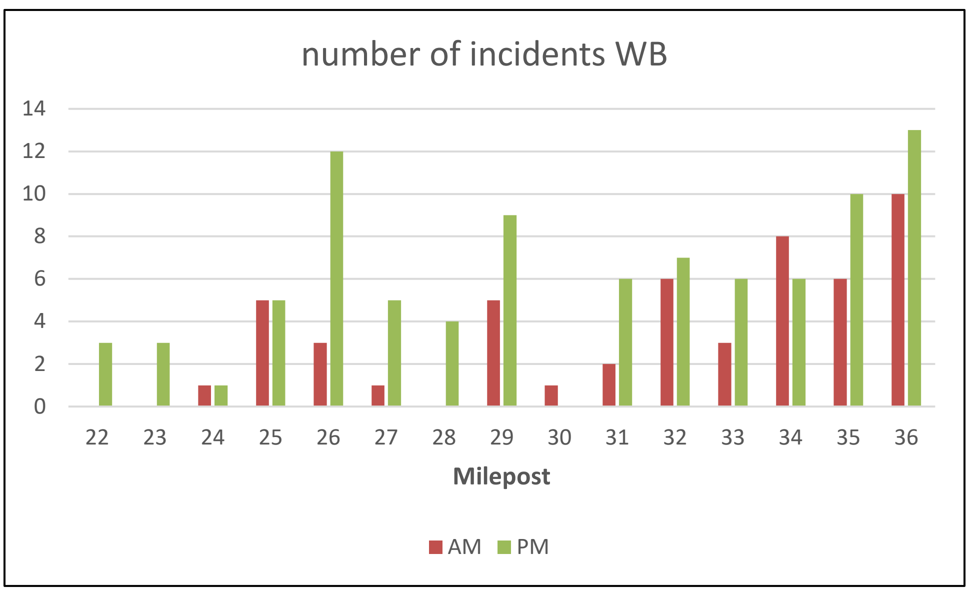


Figure 5-9: Number of incidents for westbound traffic AM and PM peak (weekdays January to May 2014)

5.2. INCIDENT SELECTION AND SIMULATION

5.2.1. NETWORK FOR SIMULATION

The network used for the simulation is illustrated in Figure 5-10. The simulated freeway extends from milepost 42 to 18, the area between S. Grand Ave. in Glendora and Lincoln Ave. in Pasadena. Beside the freeway, a part of the arterial network along Huntington Drive and Colorado Blvd. was modeled. This arterial segment is one possible reroute in case of an incident between the off-ramp at Huntington (milepost 33) and the on-ramp at Michillinda (milepost 30).

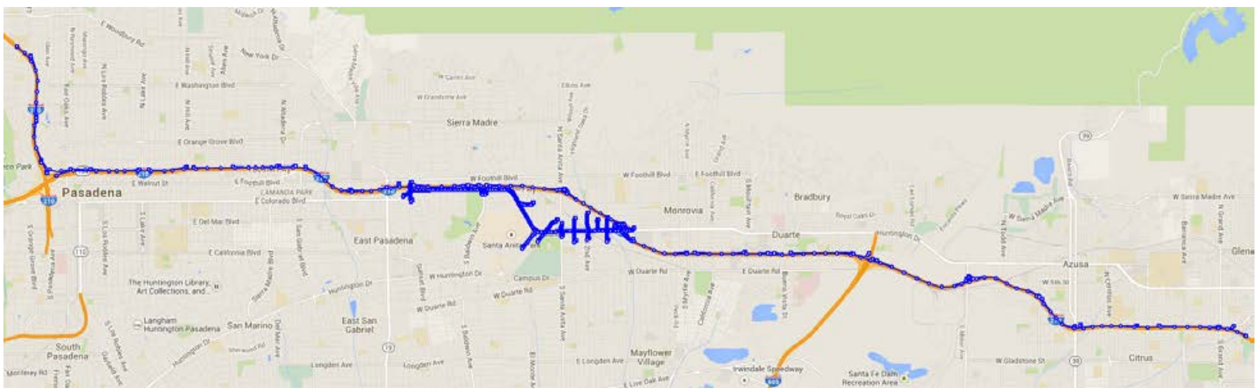


Figure 5-10: Simulation network

Because changes to signal plans on an arterial network influence all approaches of an intersection, in addition to the westbound direction the opposite direction was also modeled, as well as short sections on all side streets connected to those intersections. Within the 3.3 miles of the arterial network, 13 signalized intersections are part of the model. The only junction included without traffic signals is the on-ramp to the freeway at Michillinda.

5.2.2. CHOOSING INCIDENTS TO MODEL

Based on the cluster analysis, the AMS team chose to model the most common incident type, in which only one incident occurs during the peak period and one lane is blocked for 30 minutes (as suggested by the results of Figure 5-6 and Figure 5-7).

Driver behavior. To estimate changes in driver behavior when non-recurrent congestion is present, the team investigated an incident situation near Baldwin on I-210 westbound that lasted from 4:00 to 7:00pm on March 4, 2014, shown in Figure 5-11.

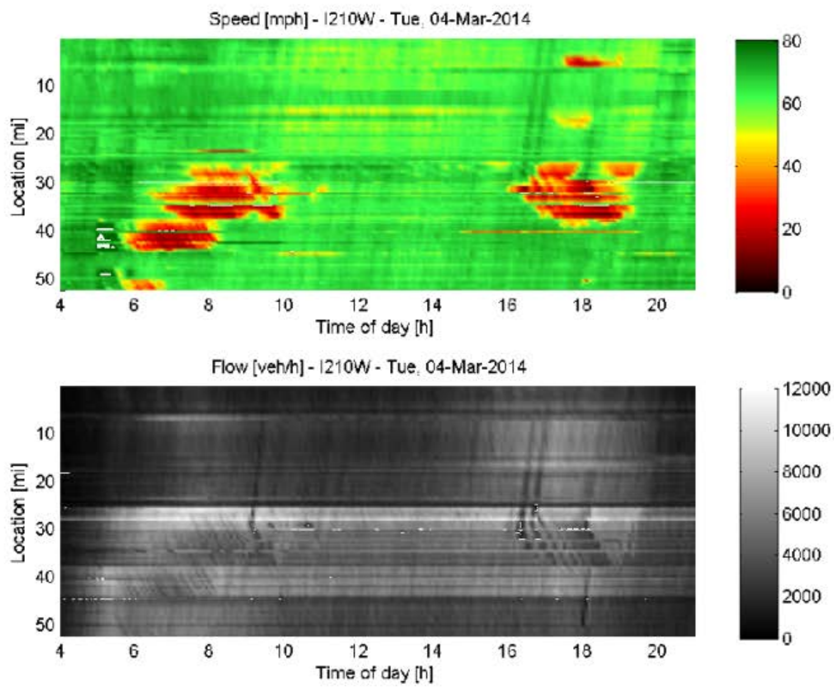


Figure 5-11: Speed and flow contour plots for I-210 westbound, March 4, 2014

Arterial measurements along Huntington Drive, also on March 4, 2014, show an unusual increase in westbound flow during the time period of the incident. As shown in Figure 5-12, the flow rate increases by about 300 to 600 veh/hour on average beyond the typical Tuesday median rate. For the purpose of the simulations that follow, the team assumed that the additional flow represents demand for trips that would ordinarily have occurred on the westbound freeway.

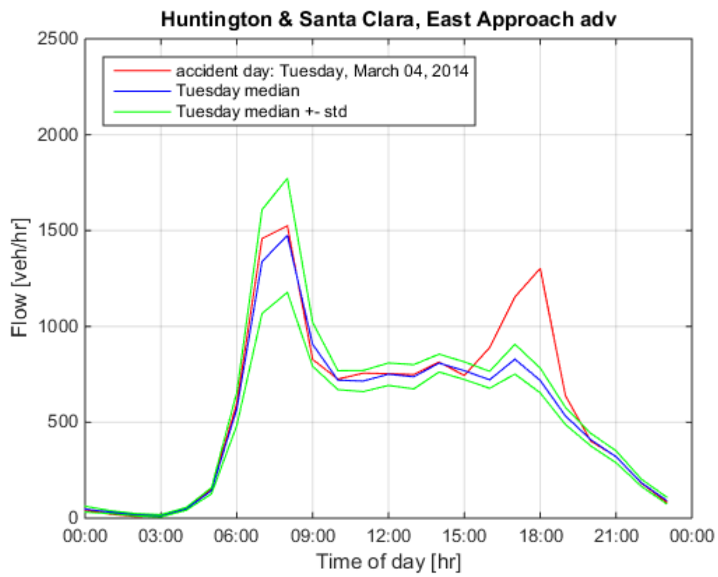


Figure 5-12: Arterial flow during an incident

Incident location. Based on data availability at the time of analysis, the AMS team used the section from Huntington to Michillinda as representative of the corridor. The distance between the Huntington and Michillinda ramps is about 3 miles, which is approximately one-fifth of the distance studied in the cluster analysis. Following this logic, an ICM strategy that aims to reroute part of the demand around an incident between Huntington and Michillinda applies to only one-fifth of the incidents that happen along the westbound part of the freeway.

Table 5-1 shows the number of representative incident periods for these categories:

- Over the space (15 miles) and time (January-May) in the cluster analysis
- Extrapolated over one year for the 15-mile section
- Over one year for the 3-mile section used to represent the corridor

Table 5-1: Representative peak periods with incidents

		15-mile section		3-mile section
Direction	**Time period**	**Number of representative periods in cluster analysis**	**Number of representative periods over one year**	**Number of representative periods over one year between Huntington and Michillinda**
EB	AM	19	46	9
	PM	51	123	25
WB	AM	31	75	15
	PM	42	102	20

Incidents are approximately evenly distributed in both eastbound and westbound directions. The benefits assessment in section 6.4 assumes that the modeled scenario applies 35 times per year. This number is calculated from scaling the cluster analysis to cover the westbound section between Huntington and Michillinda for both AM and PM peak periods (shaded amber in Table 5-1).

Incident parameters. Table 5-2 summarizes the parameters defined for modeling incidents for the current phase of AMS:

Table 5-2: Phase 1 incident modeling parameters

Parameter	Definition
Analysis year	2014, based on having available data on the I-210 freeway and some arterials
Time period of analysis	PM peak
Simulation period	4 PM - 8 PM
Freeway incident location	I-210 near Baldwin Ave. in Arcadia, chosen due to data availability at the time of analysis
Freeway incident severity and duration	Chosen to represent the most common incident type: one lane blocked for 30 minutes, starting at 4:30 PM and ending at 5:00 PM

5.2.3. SIMULATING INCIDENTS AND INTERVENTIONS

For AMS Phase 1, simulation studies focused on freeway incidents where drivers exit the freeway and seek an alternate route on the surrounding arterials. (Arterial incidents will be addressed in Phase 2.) Given the network in Figure 5-10, it was possible to simulate an incident with and without a management intervention. The modeled reroute applies directly to any incident that occurs on the westbound part of I-210 between Huntington and Michillinda, the section of the freeway chosen to represent the corridor.

The AMS team created the following simulations:

A. **No incident**. The no-incident simulation is the reproduction of a historical day without an incident (May 22, 2014). It is used as a baseline for calibrating the model.

B. **Incident—no intervention**. This simulation models traffic conditions during a representative incident, using existing infrastructure with no management intervention. It is meant to illustrate how the corridor performs in the absence of an ICM response strategy and thus serves as a benchmark for measuring the effectiveness of any intervention.

   The incident location is chosen to be about one mile downstream of the Huntington exit. The modeled capacity reduction corresponds to a blockage of one lane. This temporal bottleneck is active for 30 minutes between 4:30 PM and 5:00 PM.

From available data (shown in Figure 5-12), it was possible to estimate the number of additional vehicles/hour that exit the freeway if unusual congestion occurs. Figure 5-13 schematically illustrates the simulation setup, the location of the incident, and the flow rate of 400 veh/hour at which vehicles are assumed to reroute off the freeway and around the incident. The flow rate of 400 veh/hour corresponds to approximately 5% of mainline flow.

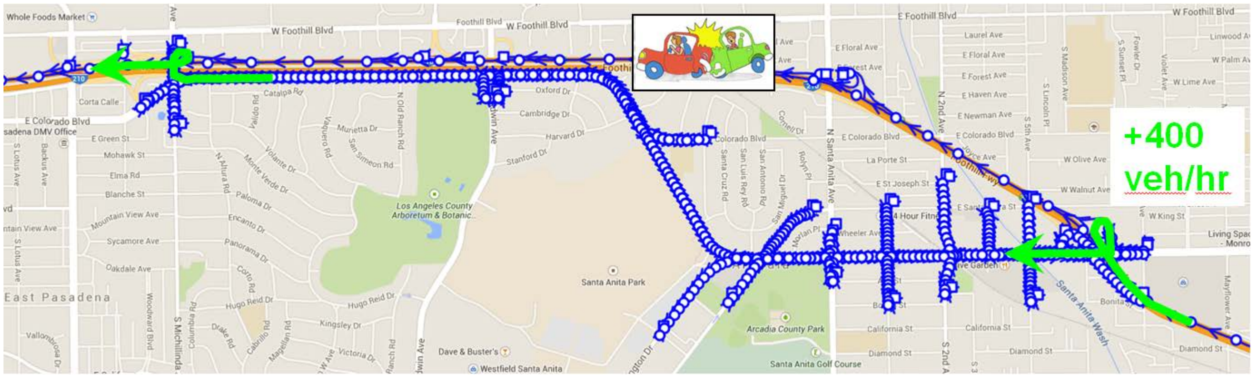


Figure 5-13: Freeway incident

C. **Incident—change signal timing plan**. In this simulation:

- Signal timing is changed to provide extra arterial capacity to support increased demand.
- Ramp metering is changed to facilitate re-entry onto the freeway downstream of the incident bottleneck.
- No changes are made to demand from upstream ramps.

The signal plans are modified to increase the capacity in the westbound and eastbound directions so that more traffic can be rerouted around the freeway incident. To ensure that no congestion occurs at the side streets, the new signal plans are chosen so that the capacity of the northbound and southbound directions is not changed. This was achieved by increasing the cycle length, thereby increasing the relative green time in the main direction while holding the relative green time on the side streets constant. Since the absolute loss time is independent of the cycle length, the relative loss time decreases when increasing the cycle time. The benefit of the reduced relative loss time is added to the relative green time in the main direction. In this simulation, a cycle length of 240 seconds was chosen, which is consistent with the existing flush plans in downtown Arcadia. In AMS Phase 2, stakeholders are expected to provide input regarding how interventions will be defined and what signal plan modifications are allowable.

D. **Incident—change signal timing plan; provide traveler information**. This simulation illustrates the effect of a hypothetical reroute in which additional vehicles exit the freeway. As shown in Figure 5-14, the off-ramp flow rate is increased to 600 veh/hour.

Agencies may use physical display devices such as Changeable Message Signs or Dynamic Trailblazer Signs (shown in black in Figure 5-14) or other means such as phone applications or radio broadcasting to communicate with travelers and try to actively influence their route choice.

Note that the only change between C and D is the assumed reroute. Once again, this intervention was not chosen to show potential benefits, but to demonstrate how the model behaves when inputs are changed.

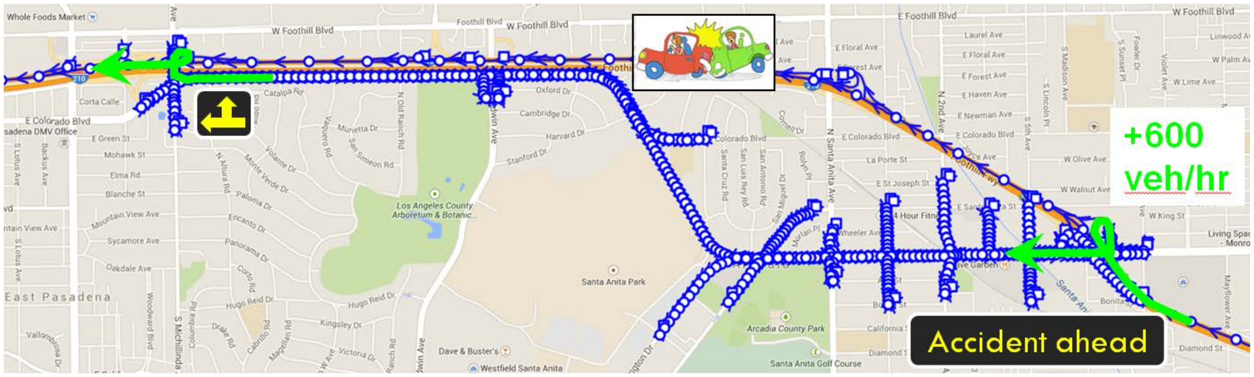


Figure 5-14: Freeway incident—change signal plan; provide traveler information

The main factors such as traffic demands remain the same for all simulations. Changes are made to specific inputs only. For example:

- To simulate an incident, the capacity of a certain link on the freeway was decreased for a limited amount of time. This creates a bottleneck which simulates a one-lane closure.
- Rerouting via the arterial network (with and without traveler information) was implemented by changing the split ratios at the Huntington off-ramp.
- To account for the additional percentage of traffic that routes from freeway to arterial and directly back onto the freeway, the split ratios at each intersection were adjusted according to the increased flow.

Table 5-3 summarizes the simulations in AMS Phase 1:

Table 5-3: Phase 1 simulations and interventions

Simulation	Intervention
A. No incident	None—baseline
B. Incident—no intervention	None—use existing infrastructure/operations
C. Incident—change signal plan	Signal synchronization
D. Incident—change signal plan; provide traveler information	Signal synchronization + traveler information

5.3. SIMULATION RESULTS

To visually display simulation results, the AMS team generated space-time plots showing the speed of traffic along a route as a function of position and time. Two plots are shown side by side for each of the four simulations—one for the westbound arterial on the left, and one for the westbound freeway on the right. In these contour plots:

- Traffic flows from bottom to top (position is indicated on the vertical axis), and time evolves from left to right (time of day is indicated on the horizontal axis).
- The color indicates the speed of traffic. High speed is represented in green for the freeway and in yellow for the arterial. Slow speeds (i.e., congestion) is indicated in red. Technically, each color represents a specific speed, as indicated by the colorbar next to each plot (units in miles per hour).

5.3.1. SIMULATION A: NO INCIDENT

The no-incident simulation is the reproduction of a historical day without an incident (May 22, 2014). It is used as a baseline for calibration.

One of the main inputs that is changed from simulation to simulation is the cycle time of the signal plans along the arterial route. From the data available during the study, most of the cycle times are 120 seconds, with the main exceptions being those at the freeway ramps, operated by Caltrans at the Huntington exit, with cycle times of 70 seconds. In the no-incident simulation, cycle times in reality are faithfully reproduced in the simulation.

The simulation results are shown in Figure 5-15. The contour plot on the left side indicates the velocity on the arterial network (Huntington Dr. and Colorado Blvd. westbound), while the right side represents the westbound section of the freeway.

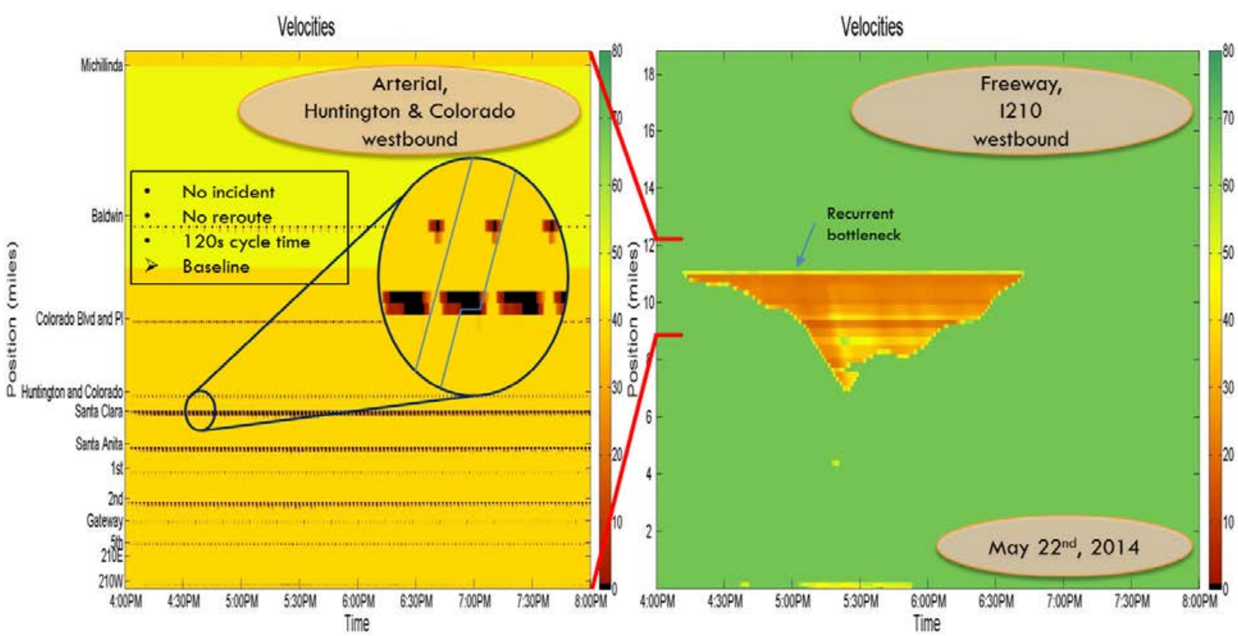


Figure 5-15: Simulation A—no incident (baseline)

The freeway shows some congestion caused at a recurring bottleneck between the exits of Santa Anita and Michillinda. At its largest extent, congestion spills back four miles. Otherwise, the freeway experiences free-flow conditions.

The arterial is mostly in free-flow. Congestion occurs only sporadically. As shown in the zoomed-in oval of the figure, queues emerge periodically at traffic lights, as expected. These queues dissipate completely within a few seconds after the signal turns green. In technical terms, no cycle failure occurs, because all traffic can be served within one cycle.

The trajectories of (virtual) vehicles provide another way of illustrating the relationship between time and space. Two vehicle trajectories are shown as blue lines in the zoomed-in oval. The slope of each trajectory indicates the speed of the vehicle. The first vehicle reaches the signal during the green phase and passes through without delay. The second vehicle reaches the signal during the red phase and waits in the queue, thus incurring a delay. After some time, the queue dissipates and vehicles continue to travel at free-flow speed without stopping a second time at the same signal.

5.3.2. SIMULATION B: INCIDENT, NO INTERVENTION

Simulation B illustrates the effect of an incident along the freeway, using the existing infrastructure and no additional intervention. The location was chosen to be about one mile downstream of the Huntington exit. The modeled capacity reduction corresponds to a blockage of one lane. This temporal bottleneck is active for 30 minutes between 4:30 PM and 5:00 PM.

As described in section 5.2.2, this simulation reproduces higher arterial flows similar to that observed in Figure 5-12. To model this effectively, split ratios along the reroute were adjusted. The split ratio at the Huntington off-ramp was modified to increase the flow rate by about 400 veh/h. Over the 30 minutes of the incident, this corresponds to 200 vehicles. Furthermore, all split ratios along the arterial network were adjusted to model the increased demand for through movements at each intersection. For this first simulation with an incident, the cycle times for the signals remained unchanged.

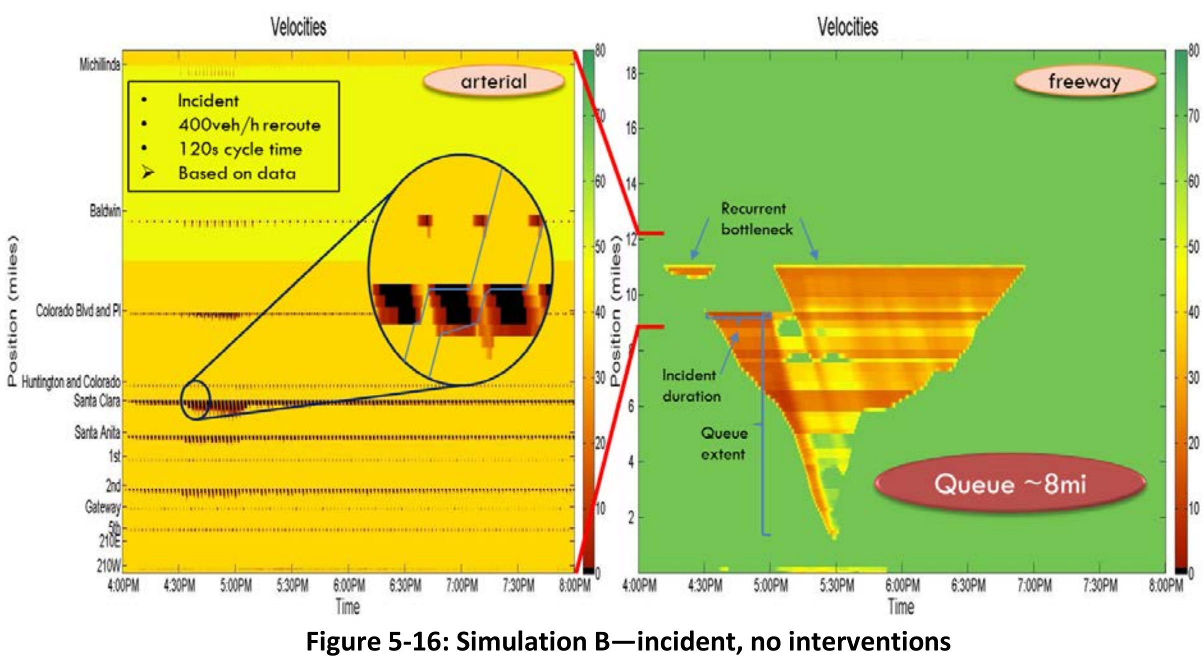


Figure 5-16: Simulation B—incident, no interventions

Simulation results are shown in Figure 5-16. The incident created at 4:30PM causes heavy congestion to emerge just downstream of the Huntington on-ramp. Congestions spills back for eight miles, significantly longer than in the baseline simulation.

The additional flow of the rerouted vehicles affects traffic patterns on the arterial. At all major intersections, significant increases of the queue lengths can be identified during the 30-minute period of the incident. In the zoomed-in oval at the cross street of Santa Clara in Figure 5-16, queues do not disappear completely in each cycle. This results in an increasing queue length over time. Moreover, cycle failures occur, i.e., some vehicles have to stop twice or more at the same traffic light, which leads to long delays. After the freeway incident is cleared, the arterial traffic conditions return to regular queues that are cleared in each cycle.

5.3.3. SIMULATION C: INCIDENT, CHANGE SIGNAL PLAN

The purpose of this simulation is to demonstrate how the model behaves when signal plans are changed, and to provide an intermediate step between simulation B and simulation D. The signal plans are simply modified to favor the westbound through movement. The ramp meter at the Michillinda on-ramp was adjusted to allow all demand onto the freeway downstream of the incident. All other simulation parameters are the same as in the previous simulation. Upstream ramp metering at the Huntington on-ramp was not modeled.

Figure 5-17 shows the simulation results. The traffic on the freeway is the same as in the previous simulation. This is expected, because the signal time change affects the traffic on the arterial only.

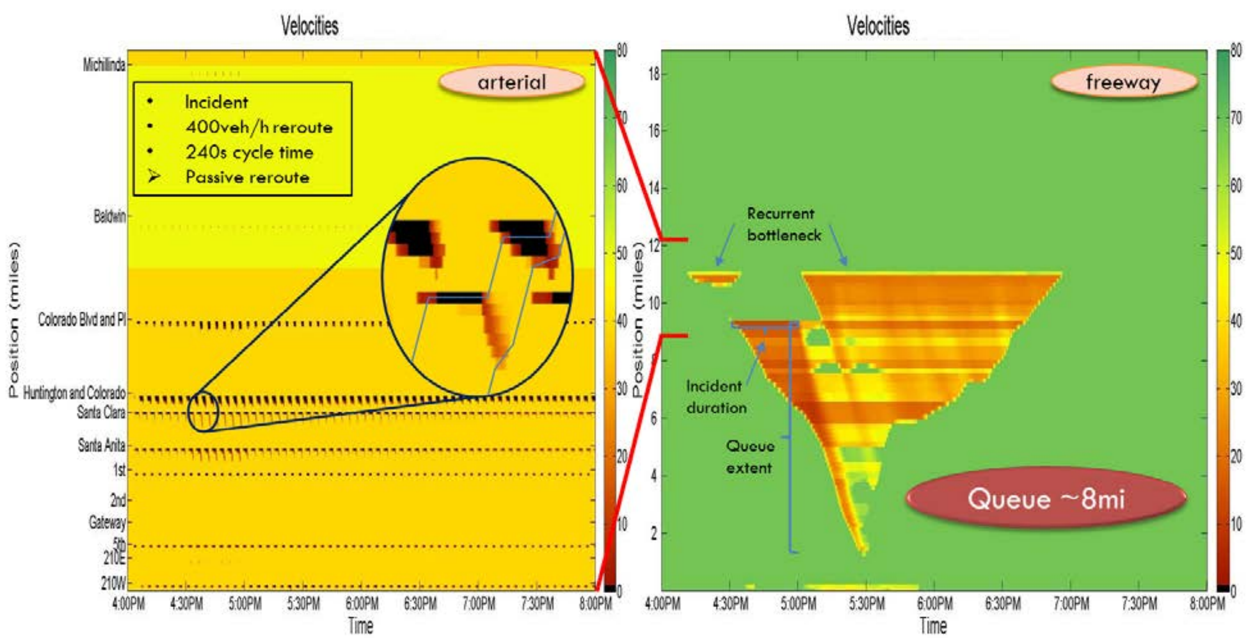


Figure 5-17: Simulation C—incident, change signal plan

The properties of the queues on the arterial network show a significant change. By looking at the contour plot, the greater intervals between the queues can be identified. A closer look at the zoomed-in oval confirms this fact. Moreover, as the vehicle trajectories show, all queues discharge within one cycle, which means that westbound arterial delays are much lower than in the previous simulation.

5.3.4. SIMULATION D: INCIDENT, CHANGE SIGNAL PLAN + TRAVELER INFORMATION

The purpose of simulation D is to demonstrate how the model behaves when a hypothetical reroute is performed. In practice, driver route choice may be influenced through the deployment of targeted messages on CMS, or by information dissemination via mobile apps or navigational systems. Signal plans are identical to those in simulation C.

In this simulation, an additional 200 veh/h were added to the reroute in addition to the original 400 veh/h in simulations B and C. Over the 30-minute duration of the incident, this corresponds to 300 rerouted vehicles instead of only 200 rerouted vehicles. Once again, this was realized by adjusting the split ratios at the off-ramp and along the arterial reroute. The settings for the traffic signals are the same as in simulation C.

Figure 5-18 shows the simulation results for the reroute. Since more traffic exits at the Huntington off-ramp, congestion on the freeway is reduced. The queue length is now only four miles, and the incident-related shockwave dissipates about 15 minutes sooner. Furthermore, the recurrent bottleneck, which activates after the incident is cleared, has a smaller impact in this simulation.

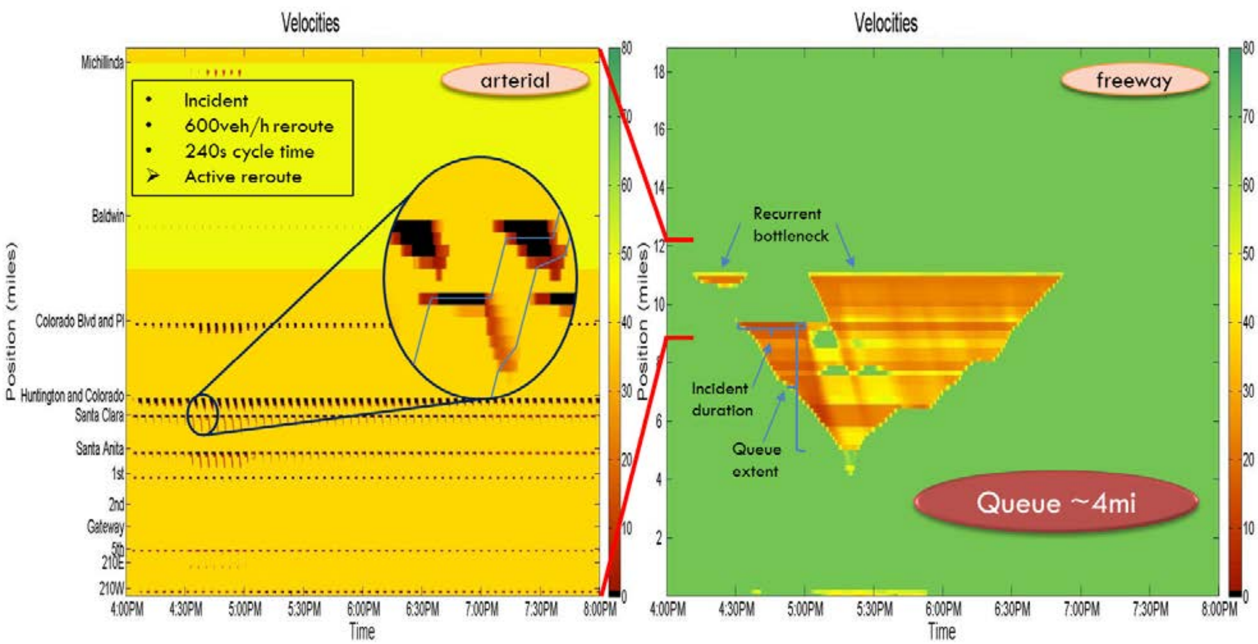


Figure 5-18: Simulation D—incident, change signal plan + traveler information

Once again, arterial traffic is displayed on the left side of the figure. Differences in queue lengths along the arterial between simulations C and D are too slight to be distinguished in Figure 5-18. The additional demand is accommodated by the signals and all queues discharge in each cycle (see trajectories). No queues extend far enough to interfere with an upstream signal.

5.4. PERFORMANCE RESULTS

VMT and VHT results are summarized in Table 5-4 and Table 5-5. Although the simulation itself is four hours long (from 4pm to 8pm), very little congestion occurs downstream of Michillinda or after 7pm. Therefore, results presented here focus temporally on the three hours from 4pm to 7pm, and spatially on the part of the freeway affected by congestion as well as all of the arterial streets in the model. Separate columns show results for the following categories:

- The freeway westbound direction is where the incident occurs.
- The arterial westbound direction is affected because of the rerouted traffic.
- Arterial eastbound is affected because of the intervention applied on the arterial to mitigate congestion.
- The “others” column captures the rest of the network not covered by the first three columns. It includes the on-ramps and off-ramps on the freeway, as well as side streets, and left and right turn pockets on the arterial streets.

Table 5-4: Vehicle miles traveled, calculated from 3-hours of simulation

Simulation	Freeway WB	Arterial WB	Arterial EB	Others*	Whole network
A. No incident (baseline)	200,184	8,474	12,319	27,818	248,795
B. Incident, no intervention	199,613	8,982	12,319	27,849	248,763
C. Incident, change signal plan	199,609	8,985	12,395	27,877	248,866
D. Incident, change signal plan + traveler information	199,322	9,355	12,395	27,910	248,982

* Others = on-ramps, off-ramps, side streets and turn pockets on arterial

Table 5-5: Vehicle hours traveled, calculated from 3-hours of simulation

Simulation	Freeway WB	Arterial WB	Arterial EB	Others*	Whole network
A. No incident (baseline)	3,628	336	565	830	5,359
B. Incident, no intervention	4,279	370	565	853	6,067
C. Incident, change signal plan	4,278	347	648	1,028	6,301
D. Incident, change signal plan + traveler information	4,023	360	648	1,014	6,045

* Others = on-ramps, off-ramps, side streets and turn pockets on arterial

The tables shows the results for all four simulations:

A. The values for simulation A (the baseline simulation) are used as reference metrics.

B. Simulation B, the first incident simulation, shows a significant increase in VHT for the freeway network, as well as for Huntington/Colorado westbound and the total sum. This result is exactly as expected.

   The decrease of the VMT on the freeway can be explained by the reduced number of vehicles due to drivers exiting the freeway in search of an alternate route. The opposite effect occurs on the arterial network, which shows an increase of VMT on westbound Huntington/Colorado, as expected.

C. Simulation C is presented to demonstrate how the model behaves when signal plans are changed, and to provide an intermediate step to understand differences between simulation B and simulation D. In simulation C, the freeway metrics are quite similar to simulation B. As no changes have been made specifically to the freeway, this result is as expected. The deployment of the new signal plan with longer cycle length and offset coordination improves westbound traffic on the arterial. However, eastbound traffic is negatively impacted as indicated by the VHT values.

   The “others” column, which includes freeway on-ramps and off-ramps as well as arterial side streets and turn pockets, is also negatively affected. About 75% of the increase of VHT in the others column is caused by side streets and left- and right-turn pockets, as might be expected of a signal plan that favors the westbound through movements.

D. Simulation D is presented to demonstrate how the model behaves when a hypothetical reroute is performed. Simulation D shows an improvement in total VHT as compared to simulation B. The reduction in freeway VHT and VMT results from additional vehicles exiting from the freeway and using the reroute facilitated by the signal plan in simulation C. Increased demand on the westbound arterial appears as additional VHT in the table. Between simulations C and D, the eastbound arterial traffic is not affected.

   The bottom line is that the improvement in traffic conditions on the freeway and westbound arterial are at the expense of traffic in the eastbound direction and on side streets. Although total VHT is improved, other considerations may influence the choice of intervention for deployment. In Phase 2, stakeholders are expected to provide input regarding how interventions will be defined and what signal plan modifications are allowable.

6. ASSESSING COSTS AND BENEFITS

Having run simulations and measured the effects of intervention strategies, it is now possible to determine costs and benefits. This chapter describes the initial estimation of costs and benefits in AMS Phase 1.

The status of existing infrastructure was assessed, including freeway, arterial, and support infrastructure. The team identified two risk areas for the I-210 pilot: (1) real-time situational awareness on the arterials and (2) ability to disseminate travel information to influence driver route choices. As a result, arterial sensors and CMS received the focus of attention in the study.

Numerous questions arose about including or excluding certain costs involving highly shared communication and software assets. One can argue that the only costs that should be 100% borne by the ICM project are those related to TMC-to-DSS communication, the DSS system, the system engineering efforts, and the management time needed to manage, review, and approve the overall creation and deployment of the pilot. Chapter 10 (Appendix C) presents several ways to identify costs and benefits for the I-210 Pilot, including an approach preferred by the AMS team, which will be discussed and evaluated in Phase 2.

This chapter presents infrastructure costs at two levels: (1) across the corridor and (2) over the simulated network only. These costs focus on improvements to arterial sensors and CMS only. Finally, benefits realized in simulation are assigned dollar values and discussed.

INFRASTRUCTURE NEEDS

Sensing capabilities. The ability to measure roadway flows, intersection turning counts, and ramp volumes is critical to estimation of real-time traffic conditions. These flows, counts, and volumes are normally obtained using either loop or video devices. These devices are typically connected to local cabinets where the data they measure is used for localized control of ramps and intersections. However, to be useful for an ICM system, their data must also be available to a centralized communication network (often accessed through a TMC), so that a central decision support system can utilize the data to recommend traffic management strategies

Control infrastructure. The success of the strategy also depends on the availability of the control infrastructure required to implement the intervention strategy. Control infrastructure includes freeway ramp meters, arterial signal controllers, and information dissemination tools such as CMS.

The current AMS analysis considers the need for existing, new, and upgraded infrastructure elements.

COST ASSESSMENT

This report evaluates costs along several dimensions and presents a number of costing approaches. Device costs are drawn mainly from:

1. **MOU I80**—Memorandum of Understanding for the I-80 ICM project [7]

2. **PSR/PR**—Project Study Report / Project Report to Request Programming in the 2014 SHOPP and Provide Project Approval (07-LA-210 PM R24.7/R44.92)
3. **LACFP**—Los Angeles County Metropolitan Transportation Authority (Metro) 2015 Call for Projects

BENEFITS CALCULATION

The following benefits are calculated in this report:

1) Costs savings from reduction in delay
2) Cost savings from reductions in vehicle operating costs
3) Cost savings from reductions in emissions
4) Cost savings from improved travel time reliability

The benefits of reductions in delay, vehicle operating costs, emissions, and travel time reliability were computed with the help of Cal-B/C v5.0 Corridor [8], developed by Caltrans and System Metrics Group.

Safety is often considered a benefit. Incidents have been correlated with secondary accidents. However, the degree of increase or decrease in accidents related to a change in incident duration is not agreed upon. Safety improvements will therefore be measured after project deployment and are not considered in the current benefits calculations.

STRATEGY FOR COMPARING COSTS AND BENEFITS

At the present stage of the Connected Corridors pilot, useful estimates are not available for many of the costs related to either the decision support system or operations and maintenance. In addition, only a subset of the corridor has been simulated. Thus, the calculation of costs and benefits in this version of the AMS report is not intended to be used to assess the value of ICM. Nevertheless, a number of approaches for comparing costs and benefits were considered:

- **Direct comparison**. In this approach, the benefits apply strictly to what was simulated (a 3-mile, westbound portion of the corridor), and costs include only those infrastructure upgrades needed to implement the ICM strategy in that simulated spatio-temporal area.
- **Extrapolation**. In this approach, costs from PSR/PR and LACFP are also considered, and benefits are extrapolated across the entire corridor. Costs are included or not based on several considerations:
    - Are the upgrades in use 100% of the time or only during the deployment of an ICM strategy to address incidents (for example, 20% of the time)?
    - Are the improvements motivated specifically by the need for ICM, or would they have occurred anyway as part of a jurisdiction’s expected upgrades?
    - Are the improvements limited to traffic management elements, or do they include additional items such as landscaping, irrigation, drainage, etc.?

In this report, costs and benefits are calculated according to the direct comparison approach. Chapter 10 (Appendix C) presents several additional ways to identify costs and benefits for the I-210 Pilot, including an approach preferred by the AMS team, which will be discussed and evaluated in Phase 2.

CHAPTER ORGANIZATION

The following sections present:

- Corridor-wide freeway, arterial, and support infrastructure and costs
- Infrastructure and costs over the simulated network only
- Calculation of benefits
- Benefit/cost discussion

6.1. CORRIDOR-WIDE FREEWAY INFRASTRUCTURE

Table 6-1 summarizes the desired level of freeway infrastructure for an ICM system:

Table 6-1: Desired freeway infrastructure

Infrastructure category	Proposed level of infrastructure
Freeway mainline sensing	Loop detectors between all ramps providing counts and occupancies
Freeway ramp sensing	Loop detectors at all ramps providing in-flow and out-flow counts
Ramp metering control	All on-ramps equipped with ramp meters connected to adjacent freeway sensors and to the TMC

However, the detailed analysis of freeway data quality in chapter 8 identifies known issues with the infrastructure, such as incomplete sensing resulting from geometrical peculiarities, misplaced loops, etc. The causes of many of the issues are uncertain and require more investigation; it is therefore not possible to assign a meaningful cost estimate to them at this time.

Maintenance and upgrades of infrastructure in Table 6-1 is consistent with existing trends. Any issues discovered in chapter 8 are therefore considered to be maintenance issues that are independent of a decision to implement ICM. For these reasons, additional freeway infrastructure in these categories is not considered in this cost assessment.

6.2. CORRIDOR-WIDE ARTERIAL AND SUPPORT INFRASTRUCTURE

6.2.1. PRIORITIZING ARTERIAL INTERSECTIONS

For the purpose of implementing an ICM system, all signalized intersections along the corridor were studied in order to determine their role, functionality, and importance within the corridor.

The primary criteria used to determine the importance of intersections include:

- Road size—size of intersecting streets (major arterial vs. minor arterial vs. small street)
- Distance—distance to freeways and incident scenarios of interest
- Coverage—spatial data coverage
- ADT—average daily traffic volumes

The level of importance was then used to determine:

1) Data requirements for modeling
2) Prioritization in data-gathering efforts
3) Where to spend limited funds on additional traffic counts
4) Data requirements for real-time control
5) Where sensing infrastructure needed to be upgraded
6) Where signals needed to be upgraded

A detailed prioritization based on data available at the time of the study has a total of five levels (1 = highest priority). A summary is provided in Table 6-2; details are provided in a reference spreadsheet [9].

1. Level 1 intersections are considered crucial to corridor operations. These are intersections of two major arterials, or intersections at off-ramps (or on-ramps to the I-210 freeway), or areas near and around incident scenarios of interest.

2. Level 2 intersections consist of additional intersections along the frontage roads in Pasadena, large intersections near I-710 and SR-110, as well as those situated on a long stretch between two level 1 intersections (such as along Huntington and Duarte).

3. Level 3 intersections fill in gaps in data coverage along major arterials at intersections with minor arterials.

4. Level 4 intersections consist of those at two minor arterials.

5. Level 5 intersections are those that involve small residential or small commercial streets.

Table 6-2: Summary of intersection priority groups

Intersection priority group for I-210 corridor	Quantity
1: Crucial intersections	108
2: Large intersections	35
3: Along major arterials	34
4: Minor arterials	81
5: Small residential or small commercial streets	284
Total	542

6.2.2. INFRASTRUCTURE REQUIREMENTS

This infrastructure needs and costs assessment considers only the 177 intersections in the top three priority levels. Requirements fall roughly into three main categories: sensing, control, and communication connectivity. The importance of high-quality sensing capabilities cannot be overstated. Inadequate sensing hinders the ability to build and calibrate a model, undermines real-time situational awareness, and jeopardizes the ability of a DSS to accurately recommend incident management strategies.

- **Sensing capabilities**: This assessment recommends measuring incoming flows on all legs for all 177 intersections. In addition, turning counts are needed on all legs for the 143 intersections in the top two levels of priority.
- **Signal controller capabilities**: Each signal on a potential reroute street should be able to select among a range of signal timings corresponding to typical AM and PM peaks, as well as flush plans to facilitate the deployment of an ICM strategy.
- **Communication connectivity**: All controllers for all 177 intersections in the top three priority levels must be connected to the TMC so that they can transmit sensed data and receive signal plan execution requests.

Table 6-3: Summary of arterial infrastructure requirements

Infrastructure category	Proposed level of infrastructure	Current status of I-210 corridor
Arterial sensing of through movement counts	Measured for 177 intersections	Not achieved consistently
Arterial sensing of turning counts	Measured for 143 intersections	Not achieved consistently
Arterial signal control	Storage for adequate signal plans to implement ICM strategies	Acceptable
Connection of controllers to TMC	All controllers connected to a TMC	Not achieved consistently

This analysis shows that significant upgrades to the corridor are required in order meet the proposed level of infrastructure needed for a successful ICM effort. However, these upgrades are also required for general performance improvements not related to incidents along the corridor.

In general, detailed sensor data on arterials are not archived, except in very few locations, and the data tend not to be available at a central TMC. In contrast, signal controllers are typically connected to a central TMC and are able to receive commands. Given the information available at the time of this study, all Pasadena and Arcadia intersections are connected. Signals along Huntington Dr. in both Monrovia and Duarte were connected as part of an LA County signal synchronization effort. In Monrovia and Duarte there may be a few controllers along Foothill and Duarte Rd. that are not connected. Recent upgrades are ongoing.

The signals owned and operated by Caltrans at intersections connecting to I-210 ramps are not currently connected to a centralized TMC. However, these upgrades are consistent with existing state-wide efforts to upgrade to 2070 controllers, and were already planned for the corridor at a future date. The AMS team is therefore not considering these upgrades as ICM costs. We understand that some readers may hold a different opinion and hope that this document will form a focal point for discussions of this type.

6.2.3. INFRASTRUCTURE COST ASSUMPTIONS

This cost assessment emphasizes the importance of capabilities for arterial sensing and dissemination of traveler information. For these types of items, capital and O&M cost estimates are shown in Table 6-4. According to the April 17, 2012 Memorandum of Understanding for the I-80 ICM project [7], the unit capital cost of adding one loop detector and configuring it as a system detector, thus providing real-time data to a TMC, is about $15,000. According to the same source, the unit capital cost of adding one video detector is about $20,000. A video detector can be configured to provide both turning counts and incoming flows. This comparison suggests that in cases where any particular intersection leg would require more than one additional loop to meet the sensing requirement, it would be more cost-effective to install a video detector.

Table 6-4: Infrastructure cost assumptions (individual elements)

Item	Capital Cost	Source	O&M	Source
Add video count capability	20000	MOU I80	350	MOU I80
Retrieve video counts to TMC	1000	Estimate	350	MOU I80
Add turning count to existing video	1000	Estimate	0	Estimate
Add 2 system detectors	30000	MOU I80	800	MOU I80
Enhance 2 advance sensors to system detectors	1000	Estimate	800	MOU I80
Add 1 turning system detector	15000	MOU I80	400	MOU I80
Get turning count from multi-loop detector	1000	Estimate	400	MOU I80
Connect controller to TMC	12000	Estimate	500	Estimate
Freeway CMS	300000	PSR/PR	10000	Estimate
Arterial CMS	26000	MOU I80	1000	MOU I80

6.2.4. ASSESSING ARTERIAL INFRASTRUCTURE UPGRADES

The existing infrastructure on each of the 177 high-priority intersections was assessed to determine where the required sensing capabilities already existed, and also to strategize a least-cost approach to achieving the requirements for all legs of each of the intersections. The methodology for assessing infrastructure improvement is as follows:

1. Consider all intersection legs for which video detection currently exists. Although each of these intersections is already configured to measure through flows, they may not be configured to provide this information to the TMC. For each of these intersections, there are two potential improvements:
    a. Provide communications connectivity so that any measured flow data can be forwarded along to the TMC.
    b. Reconfigure the video equipment to obtain left-turn or right-turn counts where appropriate.
2. Assess the remaining sensing requirements for each intersection leg and classify each leg into one of two groups:
    a. Intersection legs for which it may be possible to meet the requirement by either reconfiguring existing loop detectors or by installing, at most, one additional loop.
    b. Intersection legs for which it is more cost-effective to simply install and configure a video camera to obtain the required flows and turning movements.

    Within the first group, there are several possible improvements:

    a. Upgrade communications connectivity so that counts from existing advance detectors are made available to the TMC, thus converting them into so-called "system detectors."
    b. Consider cases where three- or four-loop turn bay sensors exist and it may be possible to reconfigure one of the loops to obtain turning counts. This second improvement is considered for both right-turn counts and left-turn counts separately.
    c. Install one additional loop to obtain either left-turn or right-turn counts.

This methodology was applied to the list of signalized intersections. Detailed results are presented in a spreadsheet of infrastructure sensing enhancements [9]. A summary of the enhancements and costs broken down over each jurisdiction is provided in Table 6-5:

Table 6-5: Arterial sensing enhancements and costs

			Retrieve video count data to TMC	Add video-based left turning count	Add video-based right turning count	Add video device	Enhance sensors to system detectors	Get left turning count from a three-or-four-loop turn bay sensor	Add loop left turning count sensor	Get right turning count from a three-or-four-loop turn bay sensor	Add loop right turning count sensor	All investments
Unit cost to add - >		Capital	1,000	1,000	1,000	20,000	1,000	1,000	15,000	1,000	15,000	
		O&M	350	0	0	350	800	400	400	400	400	
Arcadia	Total number of legs that require the enhancement - >		33	29	31	24	4	15	0	0	14	Arcadia
	Total cost for this enhancement - >	Capital	33,000	29,000	31,000	480,000	4,000	15,000	0	0	210,000	802,000
		O&M	11,550	0	0	8,400	3,200	6,000	0	0	5,600	34,750
Duarte	Total number of legs that require the enhancement - >		0	0	0	17	11	7	0	0	7	Duarte
	Total cost for this enhancement - >	Capital	0	0	0	340,000	11,000	7,000	0	0	105,000	463,000
		O&M	0	0	0	5,950	8,800	2,800	0	0	2,800	20,350
Irwindale	Total number of legs that require the enhancement - >		0	0	0	25	4	4	0	0	4	Irwindale
	Total cost for this enhancement - >	Capital	0	0	0	500,000	4,000	4,000	0	0	60,000	568,000
		O&M	0	0	0	8,750	3,200	1,600	0	0	1,600	15,150
LA County	Total number of legs that require the enhancement - >		13	13	13	19	10	4	0	0	4	LA County
	Total cost for this enhancement - >	Capital	13,000	13,000	13,000	380,000	10,000	4,000	0	0	60,000	493,000
		O&M	4,550	0	0	6,650	8,000	1,600	0	0	1,600	22,400
Monrovia	Total number of legs that require the enhancement - >		0	0	0	32	28	18	0	0	18	Monrovia
	Total cost for this enhancement - >	Capital	0	0	0	640,000	28,000	18,000	0	0	270,000	956,000
		O&M	0	0	0	11,200	22,400	7,200	0	0	7,200	48,000
Pasadena	Total number of legs that require the enhancement - >		115	102	92	117	77	93	4	4	101	Pasadena
	Total cost for this enhancement - >	Capital	115,000	102,000	92,000	2,340,000	77,000	93,000	60,000	4,000	1,515,000	4,398,000
		O&M	40,250	0	0	40,950	61,600	37,200	1,600	1,600	40,400	223,600
Whole corridor	**Total number of legs that require the enhancement - >**		**161**	**144**	**136**	**234**	**134**	**141**	**4**	**4**	**148**	**Whole corridor**
	Total cost for this enhancement - >	**Capital**	**161,000**	**144,000**	**136,000**	**4,680,000**	**134,000**	**141,000**	**60,000**	**4,000**	**2,220,000**	**7,680,000**
		O&M	**56,350**	**0**	**0**	**81,900**	**107,200**	**56,400**	**1,600**	**1,600**	**59,200**	**364,250**

6.2.5. INFORMATION DISSEMINATION

- **Proposed level of infrastructure:** Changeable message signs (CMS) inform drivers about travel times through various paths. They are needed at major intersections (arterial CMS) and at freeway off-ramps (freeway CMS).
- **Current status:** There are currently two freeway CMS. One is visible from the westbound direction before Allen Avenue; the other is visible from the eastbound direction before S. Magnolia Street. There are currently 10 existing arterial CMS, shown in Figure 6-1.
- **Proposed upgrade and consequent cost:** Ten additional freeway CMS would enable effective information about travel time on freeway and arterial reroutes. The cost estimate for freeway CMS is $500,000 capital and $10,000 for operations and maintenance.

  The locations of proposed arterial CMS are shown in Figure 6-1. The cost estimate for arterial CMS is $25,000 capital and $1,000 for operations and maintenance.

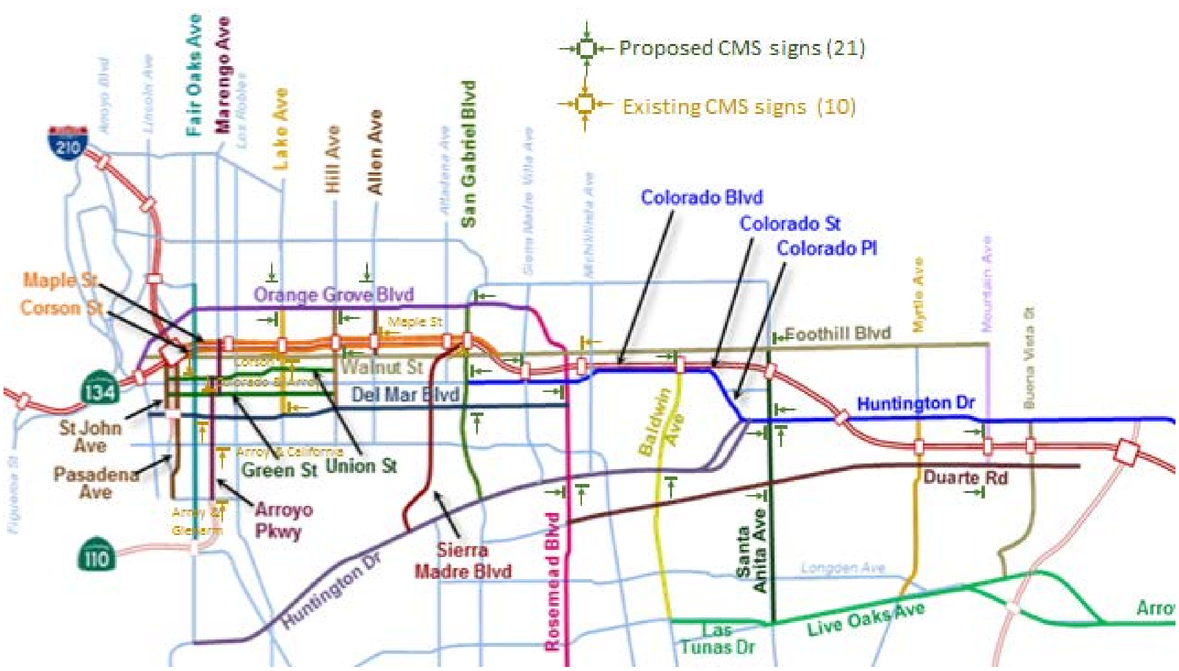


Figure 6-1: Existing and proposed arterial changeable message signs

Table 6-6 summarizes the cost of upgrading the corridor's CMS:

Table 6-6: Cost summary for changeable message signs

			Arterial CMS	Freeway CMS	Total cost
	Unit cost	Capital	25,000	500,000	
		O&M	1,000	10,000	
Arcadia	Number		8	4	**Arcadia**
	Cost	Capital	200,000	2,000,000	**2,200,000**
		O&M	8,000	40,000	**48,000**
Duarte	Number		0	1	**Duarte**
	Cost	Capital	0	500,000	**500,000**
		O&M	0	10,000	**10,000**
Irvindale	Number		0	0	**Irvindale**
	Cost	Capital	0	0	**0**
		O&M	0	0	**0**
LA County	Number		0	0	**LA County**
	Cost	Capital	0	0	**0**
		O&M	0	0	**0**
Monrovia	Number		2	1	**Monrovia**
	Cost	Capital	50,000	500,000	**550,000**
		O&M	2,000	10,000	**12,000**
Pasadena	Number		11	4	**Pasadena**
	Cost	Capital	275,000	2,000,000	**2,275,000**
		O&M	11,000	40,000	**51,000**
Whole corridor	**Number**		**21**	**10**	**Whole corridor**
	Cost	**Capital**	**525,000**	**5,000,000**	**5,525,000**
		O&M	**21,000**	**100,000**	**121,000**

6.2.6. SUMMARY

Table 6-7 summarizes the cost of the proposed upgrades per infrastructure category and per city along the I-210 corridor:

Table 6-7: Summary of all infrastructure costs allocated to the I-210 Pilot

$		Arterial sensing	Information dissemination	Total
				Annual
Arcadia	Capital	802,000	2,200,000	**3,002,000**
	O&M	34,750	48,000	**82,750**
Duarte	Capital	463,000	500,000	**963,000**
	O&M	20,350	10,000	**30,350**
Irwindale	Capital	568,000	0	**568,000**
	O&M	15,150	0	**15,150**
LA County	Capital	493,000	0	**493,000**
	O&M	22,400	0	**22,400**
Monrovia	Capital	956,000	550,000	**1,506,000**
	O&M	48,000	12,000	**60,000**
Pasadena	Capital	4,398,000	2,275,000	**6,673,000**
	O&M	223,600	51,000	**274,600**
Central	Capital	0	0	**0**
	O&M	0	0	**0**
Whole corridor	**Capital**	**7,680,000**	**5,525,000**	**13,205,000**
	O&M	**364,250**	**121,000**	**485,250**

6.3. INFRASTRUCTURE COSTS FOR SIMULATION AREA

This section of the AMS report focuses on costs pertaining to the infrastructure used as part of the simulation. This approach allows a fair comparison between the benefits achieved in the simulation and the infrastructure costs required to realize them.

The scope includes the sensing improvements along Huntington and Colorado, as well as the CMS signs on the freeway and arterial. Specific improvements are as follows:

- Improved arterial sensing on nine intersections
  - Baldwin Ave at I-210 EB
  - Colorado Blvd. at Baldwin
  - Colorado Blvd. at Colorado Pl.
  - Huntington Dr. at Colorado Pl.
  - Huntington Dr. at Santa Clara St.

- Huntington Dr. at Santa Anita Ave.
- Huntington Dr. at 5th Ave.
- Huntington Dr. at I-210 EB
- Huntington Dr. at I-210 WB

- Three CMS signs providing information along the arterial
- Two CMS signs providing information along the freeway

As noted in chapter 4, benefits are calculated only over the incidents along the westbound portion of I-210. However, the infrastructure improvements along Huntington and Colorado are also applicable to eastbound reroutes. In other words, other ICM strategies may reuse Huntington and Colorado for reroutes in the opposite direction. These benefits were excluded from the calculations. To have a fair "apples-to-apples" comparison of benefits and costs, the infrastructure costs in Table 6-8, below, were divided by a factor of two, as shown in Table 6-9.

Table 6-8: Total costs for infrastructure in simulations

$		Arterial sensing	Information dissemination	Active rerouting
				Annual
Arcadia	Capital	182,000	1,075,000	**1,257,000**
	O&M	6,750	23,000	**29,750**
Duarte	Capital	0	0	**0**
	O&M	0	0	**0**
Irwindale	Capital	0	0	**0**
	O&M	0	0	**0**
LA County	Capital	0	0	**0**
	O&M	0	0	**0**
Monrovia	Capital	164,000	0	**164,000**
	O&M	5,600	0	**5,600**
Pasadena	Capital	0	0	**0**
	O&M	0	0	**0**
Central	Capital	0	0	**0**
	O&M	0	0	**0**
Whole corridor	**Capital**	**346,000**	**1,075,000**	**1,421,000**
	O&M	**12,350**	**23,000**	**35,350**

This AMS report considers two levels of infrastructure:

- The existing infrastructure level
- The level reached by upgrading arterial sensing and information dissemination capabilities

Table 6-9 summarizes the levels of infrastructure, the capabilities enabled by each, and the capital and O&M costs of implementing each level.

Table 6-9: Levels of infrastructure for analysis

<table>
<tr><th colspan="2"></th><th>Existing infrastructure</th><th>Incident, change signal plan + traveler information</th></tr>
<tr><td colspan="2">Description</td><td>• Some important counting information is either nonexistent or unavailable at TMC.
• Some controllers do not have sufficient capability or are not connected to TMC.
• Insufficient information dissemination.</td><td>• All necessary counting information is available at TMC.
• All important signals can be controlled from TMC.
• Sufficient information dissemination.</td></tr>
<tr><td colspan="2">Proposed ICM strategy for the analysis</td><td>No intervention</td><td>Cycle time 240s on reroute
Upstream information</td></tr>
<tr><td colspan="2">Rerouting behavior</td><td>400 veh/hr reroute</td><td>600 veh/hr reroute</td></tr>
<tr><td rowspan="5">Capabilities</td><td>Freeway sensing</td><td>VDS at on-ramps and ML at all freeway entrances/exits</td><td>VDS at on-ramps and ML at all freeway entrances/exits</td></tr>
<tr><td>Ramp metering</td><td>Connected to TMC</td><td>Connected to TMC</td></tr>
<tr><td>Arterial sensing</td><td>Partial</td><td>Total</td></tr>
<tr><td>Connection of controllers to TMC</td><td>Partial</td><td>Total</td></tr>
<tr><td>Information dissemination</td><td>No</td><td>Arterial and freeway CMS</td></tr>
<tr><td colspan="2">Capital/O&M</td><td>0</td><td>Capital cost: $710,500
O&M cost: $17,675/year</td></tr>
<tr><td colspan="2">20-year life-cycle cost
4% discount rate</td><td>0</td><td>$950,709</td></tr>
</table>

6.4. BENEFIT ASSESSMENT

The benefit assessment was carried out with the help of the corridor version of Cal-B/C, a PC-based spreadsheet model developed by Caltrans' Economic Analysis Branch and System Metrics Group [8]. Cal-B/C has been widely used to evaluate the life cycle benefit/cost of proposed state highway and public transit projects.

The AMS team used Cal-B/C to estimate benefits in delay reduction, vehicle operating cost reduction, and emissions reduction. Benefits from improvement in travel time reliability were calculated separately, as described in section 6.4.2.

6.4.1. REDUCTION IN DELAY, VEHICLE OPERATING COST, AND EMISSIONS

The performance metrics calculated from the simulation results are used as input to Cal-B/C to calculate the benefits in delay reduction, vehicle operating cost reduction, and emissions reduction. These inputs, such as vehicle miles traveled (VMT) and vehicle hours traveled (VHT), are listed in Table 5-4 and Table 5-5, respectively.

Cal-B/C typically takes data with no-build and build scenarios for year 1 and year 20, respectively. Since a forecast for year 20 is not currently available, the team assumed the data for year 20 is exactly the same as year 1 for the sake of this analysis.

Benefit in delay reduction is simply the reduction in VHT, multiplied by a nominal value of time. Cal-B/C carries out a standard net present value analysis by discounting future benefits with an interest rate. Emissions and vehicle operating costs require estimates on the highway emission factor and fuel consumption rate. Cal-B/C has lookup tables for these numbers, and uses average speed estimated from VHT and VMT to search in the lookup tables.

Other inputs to Cal-B/C include the default value of time for automobiles ($12.5/hour), average vehicle occupancy for automobiles (1.15 person/vehicle), and the number of projected incident periods per year (35) as calculated using clustering analysis, and displayed in Table 5-1.

6.4.2. TRAVEL TIME RELIABILITY

Travel time reliability affects the time drivers must include in their schedules in order to arrive at their destinations on time. It is largely affected by the occurrence and severity of incidents.

For the current analysis, the team considered only two types of days: those with no major incident, and those with a single incident (as in the simulations). This assumption is quite preliminary and will be refined in the next phase of AMS. For each of the three routes (freeway westbound, arterial westbound, and arterial eastbound), the steps are to take travel time data with and without intervention and build a Bernoulli distribution for travel time. The 95th percentile travel time is then used as the planning time, which is the time drivers must include in their schedules to arrive at their destinations on time.

Benefit in reliability improvement is calculated by multiplying the reduction in planning time (or 95th percentile travel time) by the volume of traffic and the value of time.

6.4.3. SIMULATION D: INCIDENT, CHANGE SIGNAL PLAN + TRAVELER INFORMATION

The benefits shown in Table 6-10 are intended only to illustrate the methodology with a worked example. These values do not represent an assessment of the potential of an ICM deployment. They only reflect the benefits realizable with a limited and non-optimized intervention strategy.

Table 6-10: Benefits for simulation D (incident, change signal plan + traveler information)

20-year benefit for simulation D		Whole network	Freeway WB	Arterial WB	Arterial EB	Others*
Delay	Delay reduction (person*hr)	16,905	205,275	8,050	-66,815	-129,605
	Benefit	$143,590	$1,743,596	$68,376	-$567,524	-$1,100,859
Reliability	Planning time reduction (person*hr)	201,397	204,547	12,880	-16,030	N/A
	Benefit	$1,710,657	$1,737,413	$109,402	-$136,158	N/A
Vehicle Operating Cost	Benefit	-$194,203	$77,531	-$36,214	-$108,366	-$127,154
Emissions	Emission reduction (tons CO2-eq)	-796	169	89	-474	-580
	Benefit	-$28,980	$8,976	-$2,541	-$16,046	-$19,370
Total	Benefit	$1,631,064	$3,567,516	$139,024	-$828,094	-$1,247,382

* Others = on-ramps, off-ramps, side streets on arterial

Overall, the westbound freeway and the westbound arterial benefit from the intervention deployed in simulation D, and the eastbound arterial and side streets are impacted negatively.

Delay reductions are calculated from changes in VHT. Therefore, the westbound freeway benefits from having less traffic during the incident; the westbound arterial benefits from the change in signal timing; and the eastbound arterial and side streets are worse off, which cancels out much of the benefits achieved on the westbound directions.

For this example of the methodology, travel time reliability was calculated only along the main east and west directions of the network. Links in the “Others” category were omitted. Future analysis should reconsider the inventory of routes included in this category. Most of the benefit for travel time reliability comes from the reduced variation in freeway travel time.

Vehicle operating costs and emissions costs were calculated with Cal B/C. The calculation is dependent on variation in speed and VMT. The westbound freeway has a reduction in VMT, and positive benefits are achieved. The westbound arterial has an increase in VMT due to the reroute, and this contributes to an increase in emissions and vehicle operating costs. The eastbound arterial and “Others” category of links both have slight increases in VMT, but the main effect is the increase in VHT and resulting lower speeds that cause the increase in emissions and vehicle operating costs.

The example shown in this report illustrates how the impacts will vary among groups of drivers, some gaining and some losing. One group of drivers benefits by not being subjected a severe slowdown that would have affected an extra 4 miles along the freeway. Another group of freeway drivers benefit over the next 1.5 hours, because the queue through the recurrent bottleneck is shorter than it would have been. The disbenefits are distributed among drivers on the arterial in the form of extra wait time at a traffic light approaching from a side street or at turn pockets. The resulting net benefits in this example come out positive.

6.5. COST/BENEFIT DISCUSSION

Cost/benefit analyses are used in many contexts, and their results and interpretation can have far-reaching consequences both for a program and for stakeholder expectations. This document does not present a direct cost/benefit analysis for the following reasons:

1. Stakeholders have not yet come to agreement on the items to be included as costs and the percentages of those costs to be allocated to the I-210 Pilot.
2. The corridor model, needed to run the simulations determining the benefits, will not be complete until Phase 2 of the AMS effort.
3. Intervention strategies have not yet been designed or approved.
4. A number of costs (systems, salaries, etc.) are not yet known.
5. Benefits such as safety improvements are not yet known.

Given these limitations, it was not possible to present a meaningful cost/benefit analysis for the corridor at this time. However, Chapter 10 (Appendix C) presents several ways to identify costs and benefits for the I-210 Pilot, including an approach preferred by the AMS team, which will be discussed and evaluated in Phase 2.

7. CONCLUSION FOR AMS PHASE 1

Outcomes of AMS Phase 1 include the following:

- The AMS effort has achieved a comprehensive inventory of the I-210 corridor, a detailed assessment of I-210 freeway data quality, and a categorization of corridor incidents.
- Essential sections of funding applications were supported by the successful corridor analysis.
- A new model was developed over the Phase 1 test area.
- The model, including both freeway and arterial roads, was successfully calibrated.
- A common incident type with and without intervention was simulated and evaluated.
- A costs and benefits methodology was demonstrated.

All of these accomplishments are now ready to be applied in AMS Phase 2.

ANALYSIS

When AMS work began, there was no single place where all corridor information was assembled; data was fragmented into multiple databases, across jurisdictions and facilities, stored in different formats, and organized separately. One success of Phase 1 is the extensive amount of data collected about the I-210 corridor, the identification of data gaps, and additional studies performed to fill those gaps. Synthesis of these data reveal a broad, detailed, and holistic picture of the I-210 corridor characteristics, operational challenges, capabilities, and user needs.

The analysis effort of Phase 1 achieved a comprehensive characterization of the I-210 corridor, including a detailed assessment of I-210 freeway data quality and a categorization of corridor incidents. This assessment provided the context for subsequent steps in the AMS process and was instrumental in shaping such decisions as the extent of the freeway to be modeled and in identifying key data gaps for additional traffic studies.

The in-depth assessment of data quality from loop detectors on the I-210 freeway identifies and prioritizes key areas of sensing improvements. These improvements are crucial for real-time situational awareness and model calibration. Inadequate, incomplete, or contradictory data increases risk to the pilot deployment, and may lead operators to make inaccurate assessments about corridor operational needs. Data is the lifeblood of traffic analysis and management, and the importance of high-quality data—including its timeliness, accuracy, and coverage—cannot be overstated.

Although freeway data along the I-210 is generally good, the I-210 Pilot will rely on the continued efforts of Caltrans to maintain existing sensor infrastructure and to improve known issues identified in Chapter 8, such as:

1. Ramps for which no VDS is listed in PeMS
2. Stations which appear in PeMS to be in a constant failure mode
3. Stations that are working but do not capture an entire cross section of flow
4. PeMS configuration errors
5. Configuration uncertainty, where the exact location of sensors is not clear from PeMS
6. Stations that are suspected of having counting errors

A large-scale Synchro model of the I-210 corridor was assembled that includes all intersection signal plans active at 5:00 pm, as well as approach flows and turning volumes from all area traffic studies between 2006 and 2014. There are over 500 intersections coded into the Synchro model, including about 450 signalized intersections, 63 stop-controlled intersections, and 110 intersections with observed traffic counts. Stakeholders have requested the Synchro model and the data used to populate it in order to enhance their operational capabilities. This Synchro model is the repository for "static" arterial data in a single, electronic format. In addition, the team now has software tools to extract this data and provide it to the macroscopic model.

The AMS team performed a cluster analysis on the I-210 freeway to determine the distribution of incidents: their frequency, location, severity, and duration. In Phase 1, this information was then used to select a common incident type to simulate on the Phase 1 test area and to carry through each step of the AMS methodology.

FUNDING SUPPORT

Two funding applications were supported by the Phase 1 assessment of the I-210 corridor:

- PSR/PR—Project Study Report / Project Report to Request Programming in the 2014 SHOPP and Provide Project Approval (07-LA-210 PM R24.7/R44.92). $20 million approved and in process.
- LACFP—Los Angeles County Metropolitan Transportation Authority (Metro) 2015 Call for Projects. $6 million awaiting approval.

MODELING

The Connected Corridors team is working to build new simulation tools using a macroscopic approach. The advantages of this model include its conceptual simplicity, appropriateness for the control and management strategies outlined in the Concept of Operations, and the fact that all parameters of the model are directly observable from field data.

The macroscopic modeling approach is based on a Cell Transmission Model (CTM) framework in which the road is divided into cells, or links. The evolution of traffic state corresponds to vehicles entering and leaving each cell. A fundamental diagram relationship between vehicular flow and density influences the number of vehicles that may enter or leave during any time step in the simulation. This simple framework is sufficient to recreate traffic congestion dynamics. When combined with actuators to control flow at intersections and ramp merges, traffic control strategies on freeways and arterials may be simulated.

To model a corridor using a CTM framework, only the following information is needed:

- **Supply**—a network of roads
- **Demand**—turning ratios at each diverge and boundary flows at each network entry
- **Control**—signal plans
- **Parameters**—fundamental diagrams
- **Scenario information**—in the current AMS effort, incidents affecting traffic flow

IMPUTATION AND CALIBRATION

Although it is physically possible to measure every required input for a CTM-type model, budget and time constraints impose data limitations. To address these issues, the team devised imputation methods to estimate the most likely values for missing data. Tools were also developed to permit human fine-tuning of the resultant data values through engineering judgment. This results in a calibrated model.

On the freeway, demands at on-ramps and split ratios at off-ramps with no or poor detection are calculated together using an algorithm based on [4]. This algorithm generates flow and split ratio profiles at a time granularity of five minutes.

Due to the more limited data available on arterials, a different algorithm is used in which constant boundary flows over a peak period are calculated based on constant split ratios. Using an average flow profile, the static boundary flows are then scaled appropriately.

The model was calibrated on the Phase 1 test area that included a westbound portion of the I-210 and a parallel arterial. On the freeway, hourly flows achieved their calibration targets at a rate of 78%. In addition, the spatio-temporal extent of the modeled congestion occurred within 10 minutes and 0.5 miles of the measured targets. On the arterial, hourly flows were within their targets for about 77% of cases.

In sum, these results are considered good for a preliminary model. The conclusion is that the imputation methods are appropriate and produce reasonable simulation models. During Phase 1, the imputation methods have been further developed to:

- Scale up to the entire corridor
- Adjust both flows and split ratios together
- Enable improved time granularity

SIMULATION

Based on the cluster analysis, a representative incident was simulated on the freeway during the PM period in which one lane is blocked for 30 minutes. An intervention was simulated consisting of signal synchronization, downstream ramp meter adjustment to allow traffic to re-enter the freeway downstream of the incident, and a hypothetical change in traveler routing.

The results inspire confidence that the model works as expected. Both arterial and freeway traffic are modeled together in a CTM framework. The model generates incident congestion and recurrent congestion appropriate to the changes in inputs.

Based on simulations, this report describes how benefits may be assessed within the test area. The assessment is not intended to be an evaluation of the benefits of ICM, but rather an illustrative example of the proposed methodology. This work lays the foundation for the next phase of AMS, which will complete the modeling of the corridor, define intervention strategies, and select the best strategies for deployment.

COSTS AND BENEFITS METHODOLOGY

In Phase 1, the team focused on identifying infrastructure upgrades such as sensing capabilities and improved information dissemination to travelers. As part of the ongoing systems engineering process, infrastructure requirements will continue to be identified, including control functions, communications connectivity, and decision support.

The benefits of reductions in delay, vehicle operating costs, emissions, and travel time reliability were computed with the help of Cal-B/C v5.0 Corridor[8], developed by Caltrans and System Metrics Group. Relative benefits with and without the intervention were calculated for the simulated incident.

Due to the tentative nature of the results and ongoing discussions with stakeholders on cost assumptions, this Phase 1 report does not present a direct benefit/cost comparison. This report should not be seen as an evaluation of the benefits of ICM, but rather an illustrative example of the methodology to be carried forward into Phase 2.

There are multiple purposes for cost estimates and therefore multiple approaches for assessing costs of a project. In Phase 1, the team focused on sensing improvements to reduce risk to modeling accuracy and real-time situational awareness during the pilot deployment. A fair comparison between benefits and costs is difficult at this point given the limited size of the Phase 1 test area. These issues will be revisited and methods will be further refined.

8. PLANNING FOR AMS PHASE 2

Analysis, modeling, and simulation (AMS) is an evaluation process that supports the Connected Corridors effort for the I-210 Pilot Project, and proceeds in phases along with the planning, implementation, deployment, and evaluation of the I-210 Pilot Project itself.

Building on results and lessons learned from Phase 1, the main goal of AMS Phase 2 is to generate and evaluate incident response plans[1].

While Phase 1 of AMS focused on methodologies, Phase 2 will assemble a process for generating incident response plans across a range of locations and severity. A selection of these incidents and response plans will be selected for detailed simulation. Key processes in Phase 2 are illustrated in Figure 8-1.

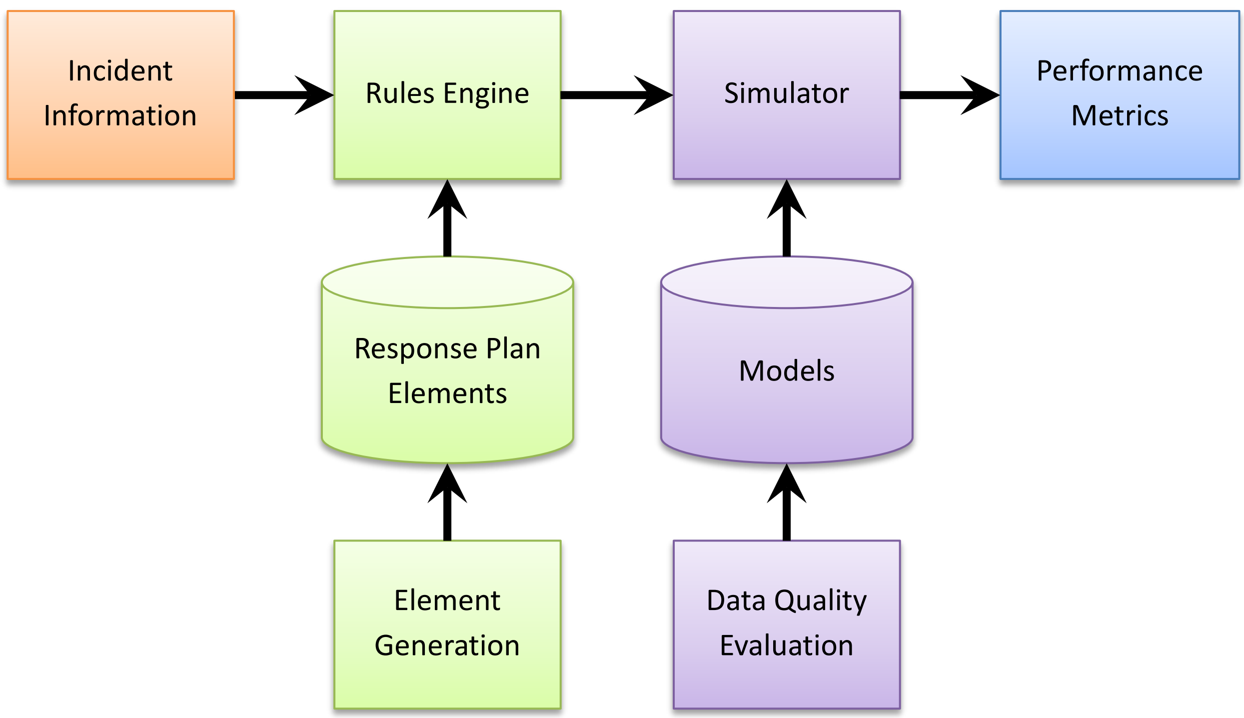


Figure 8-1: Key processes in AMS Phase 2

The bulk of the work can be categorized into two parts: (1) work to support the response plan generation, highlighted in green; and (2) work to support the response plan evaluation, highlighted in purple.

[1] Response plans are simply referred to as "management strategies" elsewhere in this report, but moving forward in Phase 2 these response plans will have a specific, defined structure as described below.

The generation of response plans includes both the creation of a menu of response plan elements as well as determining and capturing the rules to assemble such elements into a deployable plan or set of plans. The evaluation of response plans includes understanding data quality, and removing incorrect or inconsistent data as well as sufficiently calibrating a model to evaluate the possible effectiveness of a response plan.

The key process across the top of Figure 8-1 takes information about the incident as input. Based on this incident information, a rules engine generates a candidate response plan. Response plans are then simulated and performance metrics, such as person-delay-hours are calculated. The performance metrics determine the effectiveness of each candidate response. As development proceeds, this is envisioned to be an iterative process through which good structures for rules and well performing response plan elements are continually improved.

In practice, deployment of a response plan may be complex, subject to available assets, multi-agency approval, etc. A more detailed view of this process is illustrated in Figure 8-2. The role of AMS is to explore and refine the process in cooperation with stakeholders to insure the final process is successful.

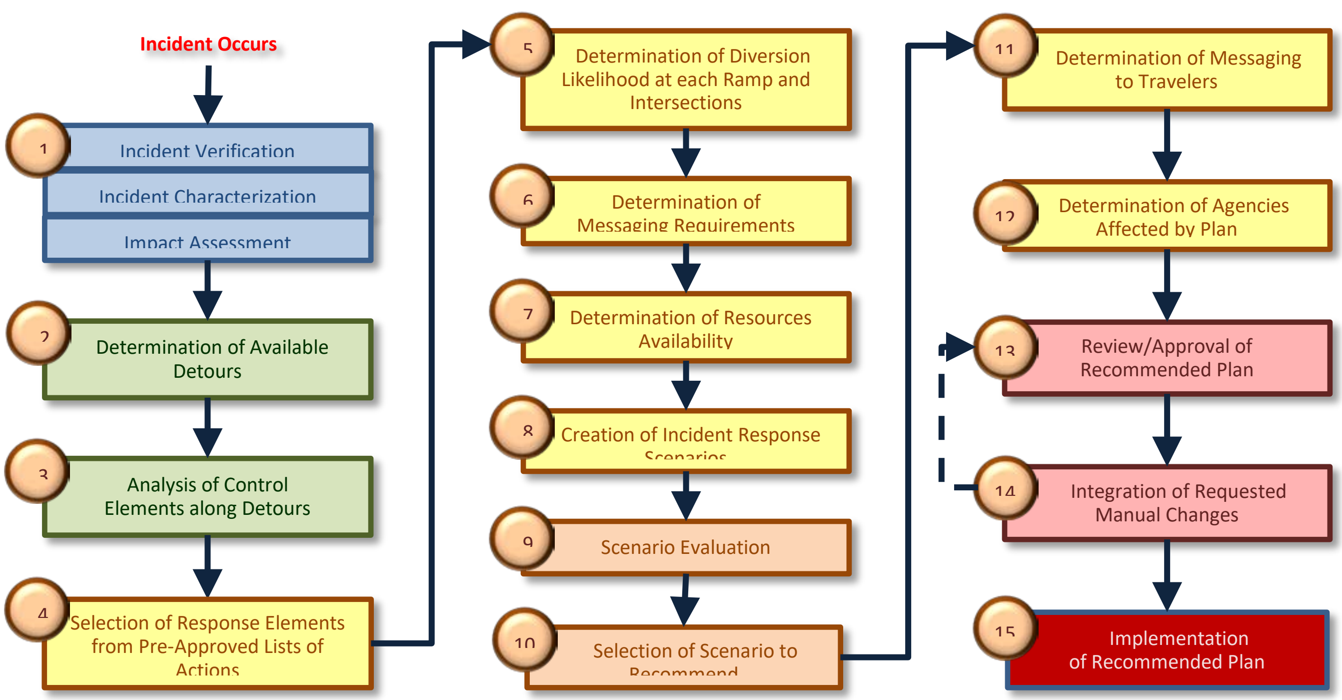


Figure 8-2: Example process for incident response plan deployment

8.1. RESPONSE PLAN GENERATION

There are two main efforts to generating response plans. One effort is to create a menu of response plan elements that can be combined in multiple ways to make up a range of response plans. The second effort is to determine and capture the rules that will be used to assemble the elements into a deployable plan or set of plans.

8.1.1. RESPONSE PLAN ELEMENTS

A response plan consists of each of the elements illustrated in Figure 8-3. While all of these elements are necessary for a pilot deployment, initial efforts in phase 2 of AMS will focus on the first three elements: (1) detour routes, (2) intersection signal control requests, and (3) ramp meter control requests.

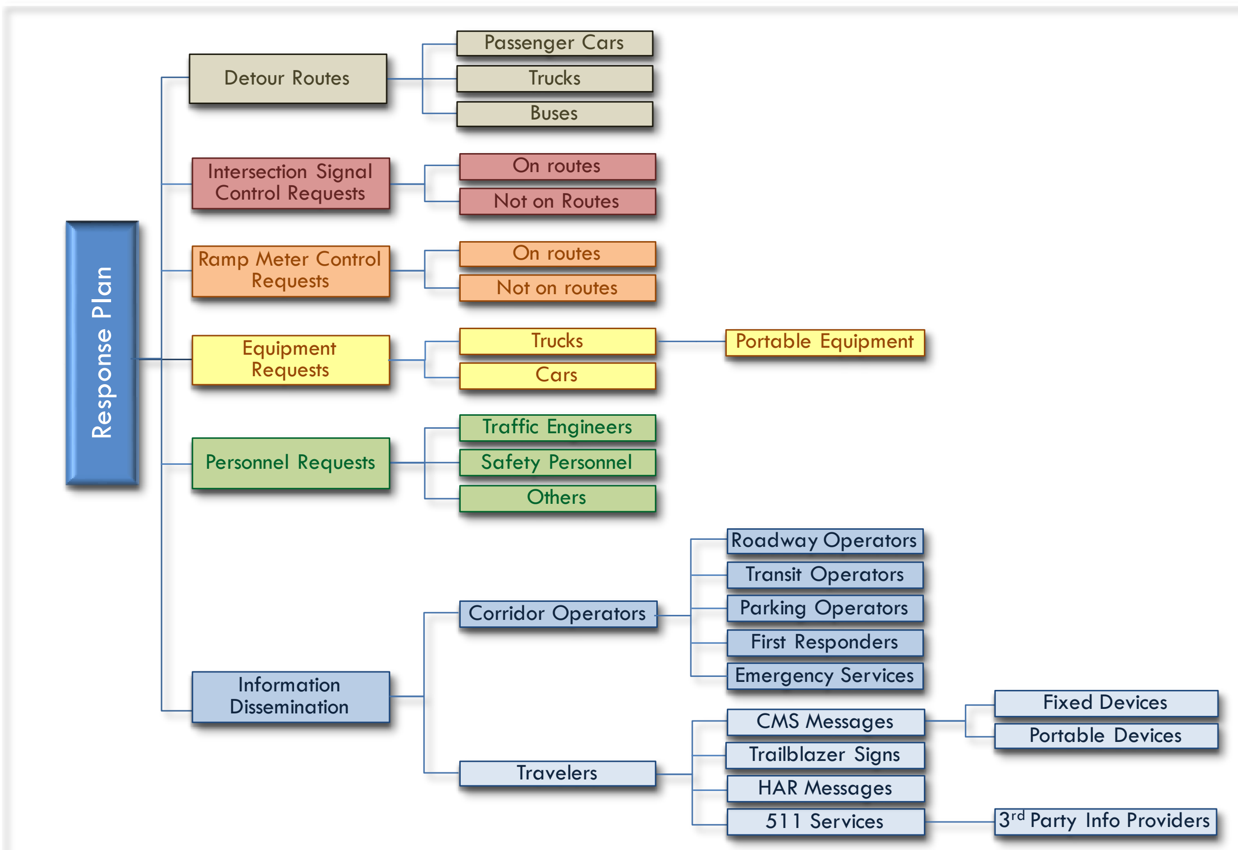


Figure 8-3: Elements of a response plan

The detour routes will be determined, for example, using incident severity and location information. Intersections and ramp meters along these routes will have associated with them a menu of plans that can be invoked to provide additional capacity favoring traffic movements along each route.

Candidate signal timing plans along possible detour routes will be generated using the Synchro model described in Section 3.6. These plans may be imported to the simulation model for evaluation.

8.1.2. RULES ENGINE

The rules engine will capture the process of real-world incident response by encoding key traffic management decision points that are similar, in spirit, to existing practices on the I-210 corridor. Corridor stakeholders will inform, define, and evaluate the engine's specific processes, rules and data that, together, select appropriate response plan elements and assemble these elements into one or more candidate response plans tailored to a given incident.

The rules engine under development in this phase will generate detour routes, intersection control requests, and ramp meter control requests sufficient to inform plan-evaluation simulations that generate response plan performance metrics. The rules engine will also generate a representative breadth and depth of the other portions of the response plan – that is, the portions that are not strictly required by the metrics simulation – but may not generate of all elements represented in the figure.

A business process rules engine is designed to bridge the gap between expert domain knowledge and computer programming. Rules are expressed in a way that is accessible to non-programmers, but in a framework that generates executable code for the rules engine to run. The rules engine is intended to support management of complex rulesets with many cases, while running efficiently and quickly.

The KIE Workbench Business Logic Integration Platform has been chosen for capturing and running the rules-based response plan generation process. KIE Workbench is a suite of Web services that include jBPM for modeling business processes, Drools for business rules management, and UberFire for users to access and run the response plan generation tool.

The response plan generation tool will allow an incident manager to enter incident definition information, and generate one or more candidate response plans. A sample illustration of the incident definition information entry and resulting response plan screens is shown below.

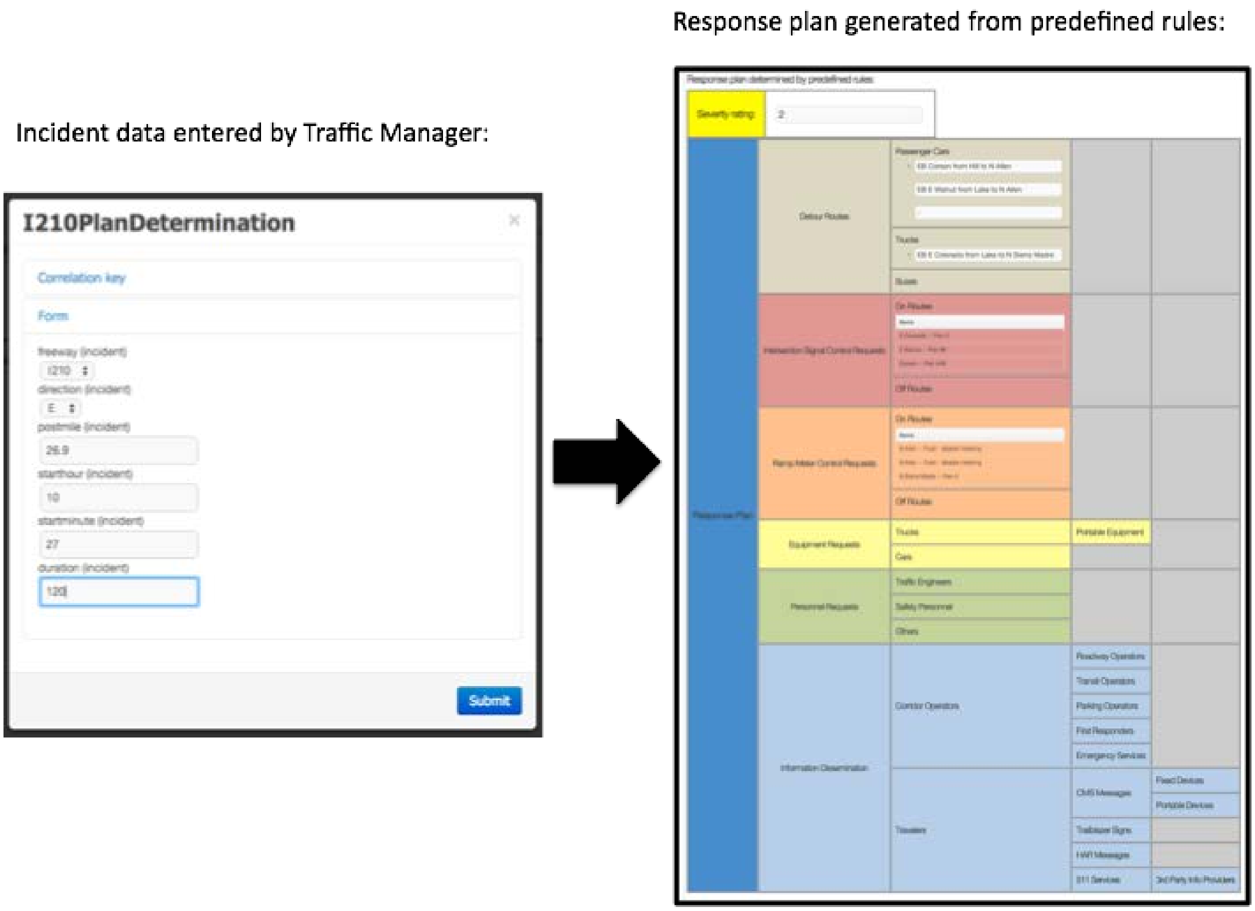


Figure 8-4: Example incident definition information entry and response plan screens

Underneath these user screens is the incident plan selection business process, an example of which is shown graphically in the jBPM Modeler screenshot below.

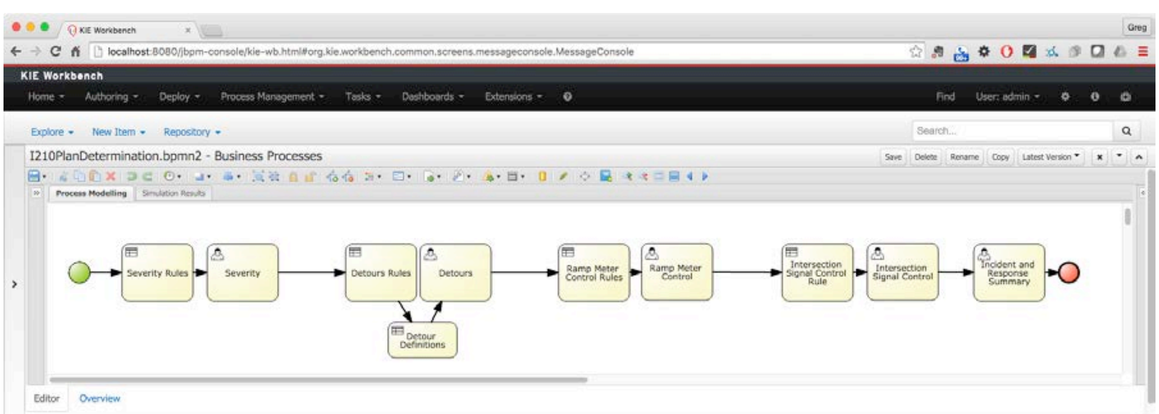


Figure 8-5: Example incident plan selection business process

The supporting rules separate rule logic from rule condition data, so that each can be managed and maintained separately. This also facilitates future changes to the business logic.

Examples of a rule definition and its supporting data are shown in the figures below.

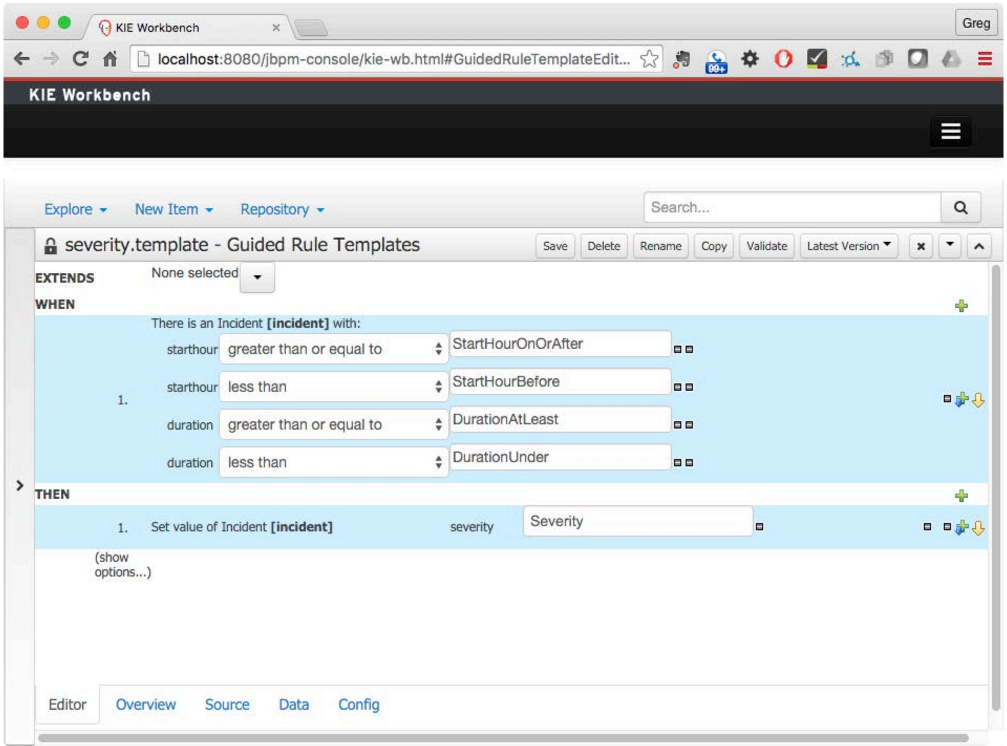


Figure 8-6: Example rule definition template

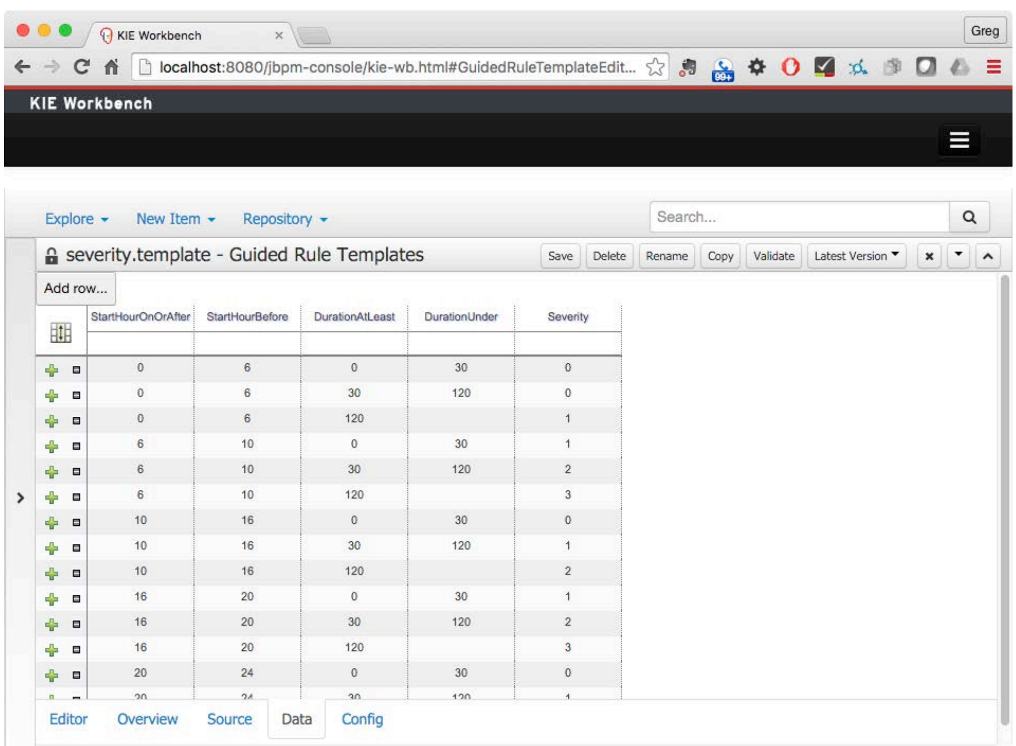


Figure 8-7: Example supporting data for rule definition

8.2. RESPONSE PLAN EVALUATION

During AMS Phase 2, efforts will be renewed to understand and track data quality on the I-210 corridor. The best data available will be used to calibrate a model of the corridor. Simulations of the model will be used to evaluate effectiveness and workability of the generated response plans.

8.2.1. DATA QUALITY

There are several goals related to data quality. The first is to work proactively with stakeholders to improve the quality and coverage of real-time data that will be made available to the pilot deployment. A second goal is to identify and remove bad data from any calibration or validation data set. A third goal is to cluster available data into patterns and to understand the extent to which resulting models are representative of the corridor.

Methods for data quality study will reuse methods employed in AMS phase 1, such as mass balance across fully accounted traffic volumes. In addition, outliers and suspicious patterns will be identified and removed. For example, data within a specific category such as HOV flows, should be consistent. Figure 8-8 illustrates a situation in which the HOV flow pattern of two detectors along a westbound portion of I-210 appears not to match those of the others (indicated by pink arrows). Suspicious data such as these will be removed from calibration and validation data sets.

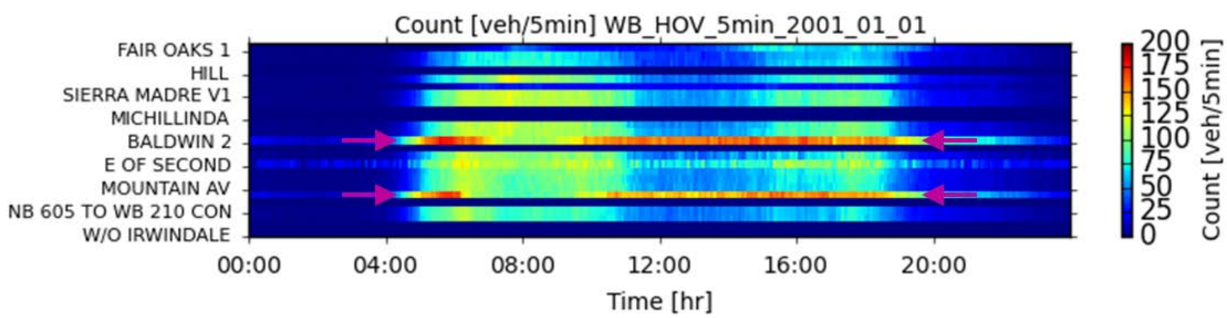


Figure 8-8: Median vehicle counts on HOV lane along westbound portion of I-210

Multiple sources of demand data will be used to generate seed origin-destination matrices for model calibration. These sources include the SCAG regional model (implemented in TRANSCAD), and cell tower data. These seed matrices will then be adjusted based on measured link flows, such as those in Figure 8-8.

8.2.2. SIMULATION

Candidate response plans will be evaluated through simulation. Toward this end, models will be built to emulate the behavior of the corridor. The key calibration priorities will be to match conditions near and around freeways and identified reroutes. Arterial streets toward the edges of the corridor, although included in the model, will be not be subject to equal scrutiny.

Aimsun has been chosen as the platform for the model to be developed in 2016. This choice was made to model diversion behavior resulting from (1) non-recurrent, incident related congestion and (2) secondary diversion effects due to the response plan itself. An example of an Aimsun model is displayed in Figure 8-9.

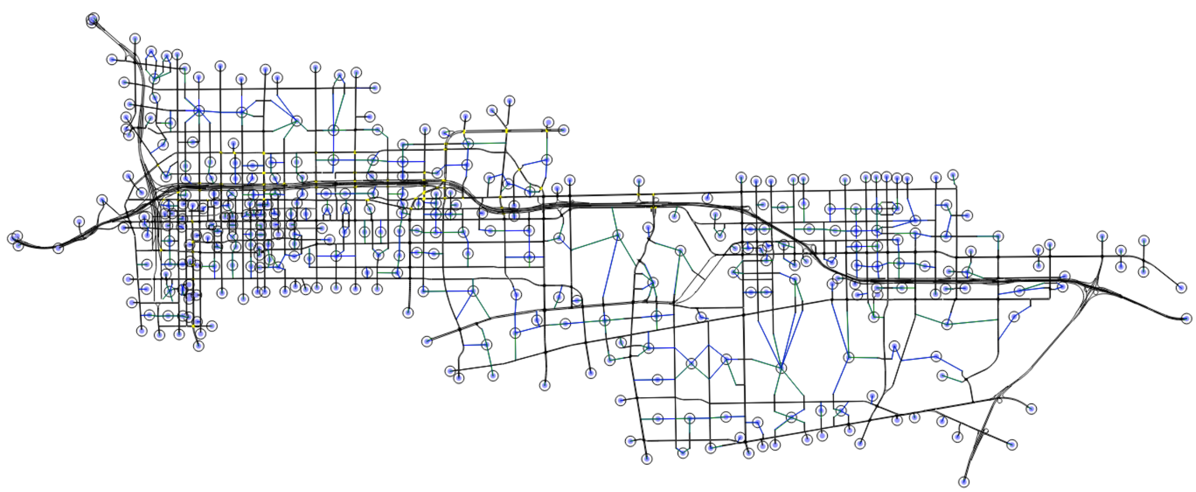


Figure 8-9: Example of Aimsun corridor model

9. APPENDIX A: ASSESSING FREEWAY LOOP DATA

Reliable, high-quality sensing capabilities are critical to both AMS and the development of an ICM system. Indeed, the importance of these capabilities cannot be overstated: Inadequate sensing hinders the ability to build and calibrate a model, undermines real-time situational awareness, and jeopardizes the ability of a Decision Support System to achieve projected benefits.

This chapter reports the health of the traffic measurement infrastructure—specifically, loop detectors embedded in the roadway—along the I-210 Pilot site. The purpose is to identify a set of reliable sensors with which to build and calibrate a model of the freeway. Future model development will also include a set of optimally healthy days as well as sensors.

Any procedure for calibrating a traffic model, and the AMS team's automated calibration procedure in particular, will be sensitive to errors in the input traffic data. For example, a mainline detector station that undercounts traffic volume by 10% (i.e., misses 1 out of every 10 vehicles) will result in a modeled capacity that is 10% lower than the true value, and will therefore lead to an exaggerated prediction of congestion and delay. The quality of data required for traffic modeling is therefore higher than what is needed for monitoring and performance measurement alone. The team found, in conducting this study, that the PeMS detector health diagnostic, which was designed to measure and track performance, is not sufficient for the modeling task. The methodology presented here introduces an additional "flow balance" test intended to identify car counting errors that are invisible to the PeMS tests.

In addition to the enhanced data checks, the team has identified a need for better tools for gathering, summarizing, and browsing all of the information needed for model building. This information includes lane counts, HOV gates, exact detector locations, detector health, and more. This chapter suggests the use of aerial photographs and a system of annotations, as well as an abstracted freeway diagram for the purpose of gathering and documenting the relevant characteristics of the site.

This chapter is organized into the following sections:

- Methodology for assessing freeway loop data
- Loop health analysis for I-210E
- Loop health analysis for I-210W
- Recommendations for improving loop health for I-210

9.1. METHODOLOGY

This section describes a procedure for assessing the suitability of loop detector data for building simulation models of freeways. The procedure relies on the Caltrans Performance Measurement System (PeMS), which gathers, evaluates, and stores loop measurements from freeways in California. The procedure also utilizes a network representation of the freeway, consisting of a graph (nodes and links) with added information about the number of lanes, location of sensors, etc.

The procedure consists of this sequence of steps:

1. Conduct an inventory of vehicle detection stations (VDS).
2. Examine photographs of the site to gather more information.
3. Divide the freeway into segments to organize the detector information.
4. Review the PeMS loop health summary.
5. Create a freeway diagram to highlight the information collected so far.
6. Perform a flow balance analysis to find additional detector errors.
7. Analyze the results of the data checks.
8. Prioritize action items for improving detector health.

The following subsections describe each step in detail.

9.1.1. CONDUCT A VDS INVENTORY

Given the freeway and limiting postmiles of the site, the list of all vehicle detection stations (VDS) can be retrieved from PeMS. This can be done using either the PeMS website or the PeMS Data Clearinghouse, like this:

- **Website**: From the PeMS home page [10], select “Freeways” from the “Facilities & Devices” menu. Then click the link corresponding to your freeway in the “fwy” column. The table that appears can be downloaded and filtered for the desired postmile range.

- **Data Clearinghouse**: From the PeMS home page, click the “Data Clearinghouse” link. In the drop-down menu, choose “Station Metadata” type and the desired Caltrans district, then click “Submit.” Download text files corresponding to the dates you wish to model. Again, these files can be filtered for the desired range of postmiles.

9.1.2. EXAMINE SITE PHOTOGRAPHS

In addition to the station inventory, a significant amount of information must be collected from the site itself: number of lanes, locations of lane drops and lane adds, HOV gates, and so forth. Aerial and street-level photographs available from Google Maps are valuable sources of this information. The photographic images are also a useful context for preserving and browsing the data. The AMS team does not currently have a good tool for doing this, and this exercise simply screen-captured a number of aerial photos and pasted them into a PowerPoint slide deck. Tags were then added to the photos, as shown in Figure 8-1.

Figure 9-1: Sample aerial photo with tags

The tags were added like this:

- Each station in the inventory list was located in the photos. In most cases this required a street-level inspection. To do this, the team searched Google's street-level images for loop detector cut-outs in the pavement. The exact location of these markings was indicated in the photo with green rectangles. For stations that could not be found, yellow rectangles were placed at their assumed location. A text box with information about the identity of the station (its VDS number, type, number of loops, name, postmile) was placed beside it.
- Tags were placed every 500' to 1000' indicating the number of general purpose, HOV, and auxiliary lanes in the segment. The figure shows one such tag with the text "4+1," meaning that the segment has 4 general purpose lanes, 1 HOV lane, and no auxiliary lane.
- Tags were added marking the beginning and end of HOV gates, as shown in the figure.
- Tags were added on each on-ramp and off-ramp, indicating the number of lanes at the gore. This information is used in modeling to determine the capacity of the ramp.
- Segment markers, explained in section 8.1.3, were added.

The process of inspecting the detectors one by one in the street-level photographs should reveal the following common problems:

- Detectors whose stated location is incorrect.
- Ramps that are unknown to PeMS because they lack detection.
- Ramp and mainline stations with detection that does not cover all lanes. This is common for segments with auxiliary lanes.

9.1.3. DIVIDE THE FREEWAY INTO SEGMENTS

Next, the freeway is divided into a sequence of "segments" delimited by mainline and HOV detector stations. These segments are numbered in order from 1 to n, and the segment index tag is added to the aerial image deck.

The process of segmenting the freeway can be carried out either by hand or automatically with the aid of a network. The manual procedure requires an interface that allows the user to define a segment by its upstream mainline and HOV stations, its on-ramps, off-ramps, and downstream mainline and HOV stations. The alternative is to provide a means of constructing a simple network with sensors attached to the links, from which the segment representation can be automatically inferred.

9.1.4. REVIEW LOOP HEALTH SUMMARY

PeMS runs a daily diagnostic on the data it receives from the loop detector stations and computes a score between 0 and 100 for each station. The score corresponds to the percentage of loops in the station that are deemed to be "good" on that day, according to a series of checks performed on the flow and occupancy measurements of each loop. Details of this procedure can be found in the "System Calculations" section of the PeMS website, under the "Detector Diagnostics" heading, and in [5] on the Connected Corridors website.

Historical recordings of this test are readily available from both the PeMS website and the Data Clearinghouse. In this case the clearinghouse is preferred because it allows large amounts of information to be downloaded easily. A sample of the data is shown in Table 8-1. The colors in the matrix indicate health for a particular station on a particular day: green is 100%, yellow is 50%-99%, red is less than 50% health. This table suggests that VDS 774033 and 716563 are in a state of permanent failure, while VDS 774031 and 774035 experience intermittent failures. The PeMS diagnostic also classifies failures into several failure modes: Line Down, Controller Down, No Data, Insufficient Data, Card Off, High Values, Intermittent, Constant, and Feed Unstable. Once a VDS has been found to be failing, investigation into its particular mode of failure can provide useful information for deciding a course of action.

Table 8-1: Sample PeMS detector diagnostic table

	774013	774011	717594	774031	774033	717595	763606	716563	774035	717601	717600	716565	763608	716567	717607	717605
1-Oct-14	100	100	100	100	0	100	100	0	100	100	100	100	100	100	100	100
2-Oct-14	100	100	94	100	0	100	100	0	100	100	100	100	100	100	100	100
3-Oct-14	100	100	96	100	0	100	100	0	100	100	100	100	100	100	100	100
4-Oct-14	100	100	96	100	0	100	100	0	100	100	100	100	100	100	100	100
5-Oct-14	100	100	99	100	0	100	100	0	100	100	100	100	100	100	100	100
6-Oct-14	100	100	98	100	0	100	100	0	100	100	100	100	100	100	100	100
7-Oct-14	99	99	94	99	0	95	95	0	99	95	95	95	95	95	95	95
8-Oct-14	100	100	100	51	0	100	100	0	51	100	100	100	100	100	100	100
9-Oct-14	100	100	100	0	0	100	100	0	0	100	100	100	100	100	100	100
10-Oct-14	100	100	100	0	0	100	100	0	0	100	100	100	100	100	100	100
11-Oct-14	100	100	100	100	0	100	100	0	100	100	100	100	100	100	100	100
12-Oct-14	100	100	100	100	0	100	100	0	100	100	100	100	100	100	100	100

The matrix of historical PeMS detector diagnostic values is used to identify the following:

- Stations that are in permanent failure.
- Unreliable stations in intermittent failure.
- A subset of days with above average detector health. These days will constitute a data set for calibrating the freeway model.
- The general trend of overall detector health for the site.

9.1.5. CREATE FREEWAY DIAGRAM

It is useful to put the information collected so far into a summarized and condensed format that allows the user get a high-level understanding of the facility. An example of such a view is provided in Figure 8-2. This can be understood as an enrichment of the PeMS freeway diagram of Figure 8-3, with additional markings pertinent to the modeling task. The enhanced diagram includes the following information:

- HOV, mainline, on-ramp, and off-ramp station numbers
- color-coded detector health
- locations with incomplete coverage (i.e., missing lanes, indicated in blue)
- segment tags
- mainline lane counts
- ramp gore lane counts
- HOV gate locations (indicated with bold arrows)
- ramps without detection (currently unknown to PeMS)

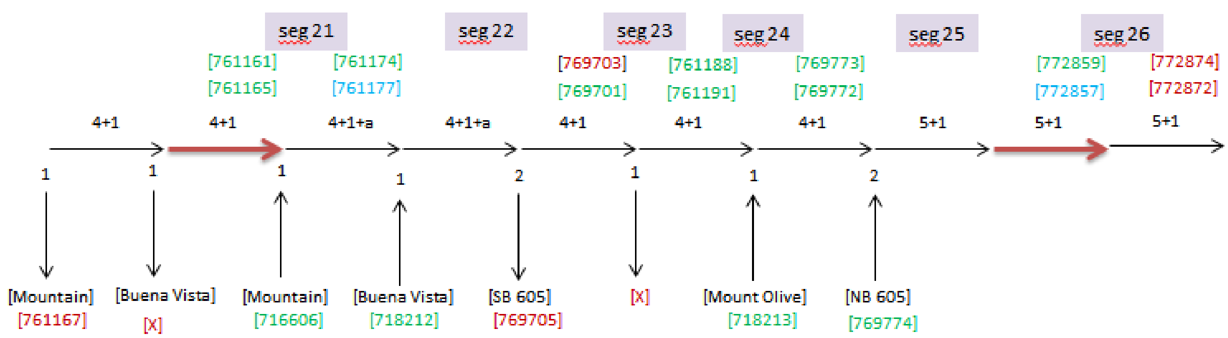


Figure 9-2: Abstracted representation of the freeway

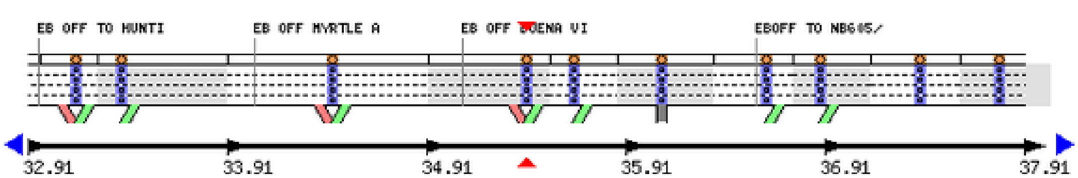


Figure 9-3: PeMS freeway diagram

Figure 8-2 was composed using the following symbols:

Table 8-2: Symbols for the enhanced freeway diagram

4+1+a →	Mainline stretch with 4 general purpose lanes, 1 HOV lane, and 1 auxiliary lane.
4+1 →	Mainline stretch with an HOV gate.
1 ↑	On-ramp with one lane at the gore point
[761161] [761165]	VDS pair with HOV station 761161 and ML station 761165. The font color represents station health: green is good, red is bad, blue means that the station does not cover all lanes.
2 ↓	Off-ramp with two lanes at the diverge point.
[Buena Vista] [718212]	Street name and VDS for an off-ramp or on-ramp. A red [X] indicates a ramp with no detection.
seg 22	Segment number.

9.1.6. COMPUTE FLOW BALANCE ERRORS

While the PeMS health diagnostic does a good job of identifying stations with gross errors (e.g., no communication, occupancy/flow mismatch), it does not identify stations with more subtle counting errors, which are nevertheless sufficient to throw off the model calibration algorithms. A simple method for capturing these errors is to perform a flow balance analysis on each of the segments of the freeway. This check was originally introduced in FREQ, a segment-based simulator which would only perform simulations on input data that was within 5% of perfect balance.

The flow balance check calculates, for each segment i and day d, two error quantities $e_{am}(i,d)$ and $e_{pm}(i,d)$. These represent the imbalance of flow entering and exiting the segment over the morning and evening periods.

$$e_{am}(i,d) = 100 \times \left(1 - \frac{veh\_in_{am}(i,d)}{veh\_out_{am}(i,d)}\right)$$

$$e_{pm}(i,d) = 100 \times \left(1 - \frac{veh\_in_{pm}(i,d)}{veh\_out_{pm}(i,d)}\right)$$

Here $veh\_in_{am}(i,d)$ and $veh\_out_{am}(i,d)$ represent the total number of vehicles that enter and exit the segment between midnight and noon, while $veh\_in_{pm}(i,d)$ and $veh\_out_{pm}(i,d)$ are analogous quantities for the second half of the day.

$$veh\_in_{am}(i,d) = \sum_{t=midnight}^{noon} f_{ml\_up}(i,d,t) + f_{or}(i,d,t)$$

$$veh\_out_{am}(i,d) = \sum_{t=midnight}^{noon} f_{ml\_dn}(i,d,t) + f_{fr}(i,d,t)$$

$$veh\_in_{pm}(i,d) = \sum_{t=noon}^{midnight} f_{ml\_up}(i,d,t) + f_{or}(i,d,t)$$

$$veh\_out_{pm}(i,d) = \sum_{t=noon}^{midnight} f_{ml\_dn}(i,d,t) + f_{fr}(i,d,t)$$

$f_*(i,d,t)$ are five-minute flows for time t on a given set of stations represented by the subscript quantity $\{ml\_up, ml\_dn, or, fr\}$. ml_up and ml_dn are, respectively, the upstream and downstream stations. These may or may not include the HOV stations (depending on user preference). or and fr represent all of the on-ramps and off-ramps in the segment.

Both the sign and the magnitude of $e_*(i,d)$ are important. A negative sign suggests either an excess of incoming traffic or a deficit of outgoing traffic, while a positive sign indicates the contrary.

To assess the quality of the data over a range of days, we define the average errors for segment i ($e_{am}(i)$ and $e_{pm}(i)$), the total average error ($e(i)$), and the corresponding values for the magnitudes of the error ($\bar{e}_{am}(i)$, $\bar{e}_{pm}(i)$, and $\bar{e}(i)$).

$$e_{am}(i) = mean\_over\_days\left(e_{am}(i,d)\right)$$

$$e_{pm}(i) = mean\_over\_days\left(e_{pm}(i,d)\right)$$

$$e(i) = 0.5 * \left(|e_{am}(i)| + |e_{pm}(i)|\right)$$

$$\bar{e}_{am}(i) = mean\_over\_days(|e_{am}(i,d)\ |)$$

$$\bar{e}_{pm}(i) = mean\_over\_days\left(|e_{pm}(i,d)\ |\right)$$

$$\bar{e}(i) = 0.5 * (\bar{e}_{am}(i) + \bar{e}_{am}(i)\ )$$

9.1.7. ANALYZE RESULTS OF THE DATA CHECKS

The results of the two data checks—PeMS' health diagnostic and the flow balance test—must be considered in combination in order to determine the suitability of each detector station for building a simulation model. The procedure is as follows:

1. Segments with errors below 5% are considered good for modeling. Errors between 5% and 10% are acceptable for modeling, but are also low priority candidates for repair. Segments with errors above 10% cannot be included in the model calibration process; they must either be fixed or ignored.

2. Determine the causes of flow imbalances above 10%. Common problems include:
    a. Counting bias, indicated by sequential pairs of segments with complementary error signs, such as a segment with 12% error followed by another with -15% error.
    b. Incomplete lane coverage. There were several instances of stations where the PeMS lane count (and thus the flow measurement) did not include an auxiliary lane.
    c. Faulty stations. Large flow imbalances are often coupled with a "bad" PeMS health report for one or more stations in the segment. Faulty stations that cause large flow imbalances are high-priority candidates for repair.

9.1.8. PRIORITIZE ACTION ITEMS

The final step in the procedure is to collect the action items from the analysis step and to prioritize them. The sizes of the flow imbalances caused by faulty detectors should be considered: larger flow imbalances suggest that a larger amount of traffic is being miscounted by the faulty detector, and thus it should be placed at a higher priority for repair.

9.2. LOOP HEALTH ANALYSIS FOR I-210 EAST

9.2.1. VDS INVENTORY

The I-210 East freeway site begins on SR-134E at Figueroa and Colorado Ave. and stretches 31 miles, past the freeway interchanges with I-210 and I-605, to Grand Ave. in Glendora. The full inventory of detector stations can be found in Table 8-3. There are a total of 134 VDSs: 74 mainline stations (41 general purpose, 39 HOV), 28 on-ramp stations, 22 off-ramp stations, and 4 freeway connector stations.

Table 8-3: I-210E VDS inventory

Fwy	City	Abs PM	ID	Name	Lanes	Type
SR134-E	Los Angeles	10.66	774013	TOWNSEND	1	HOV
SR134-E	Los Angeles	10.66	774011	TOWNSEND	4	Mainline
SR134-E	Los Angeles	11.52	717594	FIGUEROA	1	Off-ramp
SR134-E	Los Angeles	11.52	716563	FIGUEROA	1	On-ramp
SR134-E	Los Angeles	11.52	717595	FIGUEROA	4	Mainline
SR134-E	Los Angeles	11.52	763606	FIGUEROA	1	HOV
SR134-E	Los Angeles	11.64	774035	COLORADO	1	On-ramp

SR134-E	Los Angeles	11.64	774031	COLORADO	4	Mainline
SR134-E	Los Angeles	11.64	774033	COLORADO	1	HOV
SR134-E	Pasadena	12.45	717601	SAN RAFAEL	4	Mainline
SR134-E	Pasadena	12.45	717600	SAN RAFAEL	1	Off-ramp
SR134-E	Pasadena	12.45	716565	SAN RAFAEL	1	On-ramp
SR134-E	Pasadena	12.45	763608	SAN RAFAEL	1	HOV
SR134-E	Pasadena	13.18	716567	ORANGE GROVE	1	On-ramp
SR134-E	Pasadena	13.18	717607	ORANGE GROVE	1	HOV
SR134-E	Pasadena	13.18	717605	ORANGE GROVE	1	Off-ramp
SR134-E	Pasadena	13.18	717606	ORANGE GROVE	4	Mainline
SR134-E	Pasadena	13.34	770172	EB 134 TO DEL MAR	1	Off-ramp
I210-E	Pasadena	24.49	770169	EB 134 TO WB 210 CON	3	Mainline
I210-E	Pasadena	24.49	770170	EB 210 TO WB 134 #1	1	Fwy-Fwy
I210-E	Pasadena	24.49	770419	EB 210 TO COLORADO	1	Off-ramp
I210-E	Pasadena	24.81	717628	WALNUT	1	Mainline
I210-E	Pasadena	24.81	763878	WALNUT	1	Off-ramp
I210-E	Pasadena	25.12	717631	FAIR OAKS 1	4	Mainline
I210-E	Pasadena	25.12	763614	FAIR OAKS 1	1	HOV
I210-E	Pasadena	25.12	768916	NB 710 EXT TO EB 210	2	Fwy-Fwy
I210-E	Pasadena	25.48	773131	FAIR OAKS OFF	2	Fwy-Fwy
I210-E	Pasadena	25.72	761093	MARENGO	1	HOV
I210-E	Pasadena	25.72	716585	MARENGO	1	On-ramp
I210-E	Pasadena	25.72	717633	MARENGO	6	Mainline
I210-E	Pasadena	25.98	769269	LAKE AVE OFF(LAKE 1)	2	Off-ramp
I210-E	Pasadena	26.47	761098	LAKE 2	1	HOV
I210-E	Pasadena	26.47	716587	LAKE NB	1	On-ramp
I210-E	Pasadena	26.47	717635	LAKE 2	5	Mainline
I210-E	Pasadena	26.68	769272	HILL AVE OFF	1	Off-ramp
I210-E	Pasadena	27.14	717638	HILL 1	5	Mainline
I210-E	Pasadena	27.14	761102	HILL 1	1	HOV
I210-E	Pasadena	27.14	716589	HILL NB	1	On-ramp
I210-E	Pasadena	27.63	717640	ALLEN	5	Mainline
I210-E	Pasadena	27.63	761105	ALLEN	1	HOV
I210-E	Pasadena	27.63	716590	ALLEN	1	On-ramp
I210-E	Pasadena	27.98	737480	ALTADENA	2	Off-ramp
I210-E	Pasadena	28.28	763908	SIERRA MADRE V1	2	Off-ramp
I210-E	Pasadena	28.58	768923	SIERRA MADRE OFF	2	Off-ramp
I210-E	Pasadena	28.68	717646	SAN GABRIEL	5	Mainline
I210-E	Pasadena	28.68	716593	SAN GABRIEL	1	On-ramp
I210-E	Pasadena	28.68	761109	SAN GABRIEL	1	HOV
I210-E	Pasadena	29.44	717650	SIERRA MADRE V2	5	Mainline
I210-E	Pasadena	29.44	717651	SIERRA MADRE V2	1	Off-ramp
I210-E	Pasadena	29.44	716595	SIERRA MADRE V2	1	On-ramp
I210-E	Pasadena	29.44	761112	SIERRA MADRE V2	1	HOV
I210-E		30.029	737490	ROSEMEAD 1	1	HOV
I210-E		30.029	716598	ROSEMEAD NB	1	On-ramp
I210-E		30.029	717654	ROSEMEAD 1	4	Mainline
I210-E	Arcadia	30.299	717658	MICHILLINDA	2	Off-ramp
I210-E	Arcadia	30.299	717659	MICHILLINDA	4	Mainline

I210-E	Arcadia	30.299	716600	MICHILLINDA	1	On-ramp
I210-E	Arcadia	30.299	717641	MICHILLINDA	1	HOV
I210-E	Arcadia	30.689	773155	VAQUERO	1	HOV
I210-E	Arcadia	30.689	773154	VAQUERO	5	Mainline
I210-E	Arcadia	31.239	717666	BALDWIN	3	Off-ramp
I210-E	Arcadia	31.239	761115	BALDWIN	1	HOV
I210-E	Arcadia	31.239	716603	BALDWIN	1	On-ramp
I210-E	Arcadia	31.239	717667	BALDWIN	4	Mainline
I210-E	Arcadia	32.349	717671	SANTA ANITA 2	3	Off-ramp
I210-E	Arcadia	32.349	717672	SANTA ANITA 2	4	Mainline
I210-E	Arcadia	32.349	716605	SANTA ANITA 2	1	On-ramp
I210-E	Arcadia	32.349	761117	SANTA ANITA 2	1	HOV
I210-E	Arcadia	32.789	773193	E OF SECOND	4	Mainline
I210-E	Arcadia	32.789	773195	E OF SECOND	1	HOV
I210-E	Monrovia	33.149	761128	HUNTINGTON 1	4	Mainline
I210-E	Monrovia	33.149	761126	HUNTINGTON 1	1	HOV
I210-E	Monrovia	33.149	761130	HUNTINGTON WB	3	Off-ramp
I210-E	Monrovia	33.149	718205	HUNTINGTON WB	1	On-ramp
I210-E	Monrovia	33.379	718207	HUNTINGTON EB	1	On-ramp
I210-E	Monrovia	33.379	761141	HUNTINGTON 2	4	Mainline
I210-E	Monrovia	33.379	761138	HUNTINGTON 2	1	HOV
I210-E	Monrovia	34.439	761149	MYRTLE AV	1	HOV
I210-E	Monrovia	34.439	761152	MYRTLE AV	4	Mainline
I210-E	Monrovia	34.439	761154	MYRTLE AV	2	Off-ramp
I210-E	Monrovia	34.439	718209	MYRTLE AV	1	On-ramp
I210-E	Duarte	35.409	761167	MOUNTAIN	1	Off-ramp
I210-E	Duarte	35.409	761165	MOUNTAIN	4	Mainline
I210-E	Duarte	35.409	761161	MOUNTAIN	1	HOV
I210-E	Duarte	35.409	716606	MOUNTAIN	1	On-ramp
I210-E	Duarte	35.649	761174	BUENA VISTA	1	HOV
I210-E	Duarte	35.649	761177	BUENA VISTA	4	Mainline
I210-E	Duarte	35.649	718212	BUENA VISTA	1	On-ramp
I210-E	Duarte	36.089	769705	EB 210 TO SB 605	2	Fwy-Fwy
I210-E	Duarte	36.089	769703	HIGHLAND	1	HOV
I210-E	Duarte	36.089	769701	HIGHLAND	4	Mainline
I210-E	Duarte	36.619	761191	MOUNT OLIVE DR / 605	4	Mainline
I210-E	Duarte	36.619	761188	MOUNT OLIVE DR / 605	1	HOV
I210-E	Duarte	36.619	718213	MOUNT OLIVE DR / 605	1	On-ramp
I210-E	Irwindale	36.889	769773	NB 605 TO EB 210 CON	1	HOV
I210-E	Irwindale	36.889	769774	NB 605 TO EB 210 CON	1	On-ramp
I210-E	Irwindale	36.889	769772	NB 605 TO EB 210 CON	4	Mainline
I210-E	Irwindale	37.389	772857	SAN GABRIEL RIVER	4	Mainline
I210-E	Irwindale	37.389	772859	SAN GABRIEL RIVER	1	HOV
I210-E	Irwindale	37.789	772872	W/O IRWINDALE	4	Mainline
I210-E	Irwindale	37.789	772874	W/O IRWINDALE	1	HOV
I210-E	Irwindale	38.069	774990	IRWINDALE 1	1	Off-ramp
I210-E	Irwindale	38.298	718214	IRWINDALE	1	On-ramp
I210-E	Irwindale	38.298	761199	IRWINDALE	1	HOV
I210-E	Irwindale	38.298	761206	IRWINDALE	4	Mainline

I210-E	Irwindale	38.789	772889	ZACHARY PADILLA	1	HOV
I210-E	Irwindale	38.789	772887	ZACHARY PADILLA	4	Mainline
I210-E	Irwindale	39.339	718215	VERNON	1	On-ramp
I210-E	Irwindale	39.339	761220	VERNON	4	Mainline
I210-E	Irwindale	39.339	761214	VERNON	1	HOV
I210-E	Azusa	39.929	717680	AZUSA SB	2	Off-ramp
I210-E	Azusa	39.929	765477	AZUSA 1	4	Mainline
I210-E	Azusa	39.929	770407	AZUSA 1	1	HOV
I210-E	Azusa	39.929	717679	AZUSA SB	1	On-ramp
I210-E	Azusa	39.999	717684	AZUSA 2	4	Mainline
I210-E	Azusa	39.999	761222	AZUSA 2	1	HOV
I210-E	Azusa	39.999	717683	AZUSA NB	1	On-ramp
I210-E	Azusa	40.189	772905	PASADENA AVE	1	HOV
I210-E	Azusa	40.189	772903	PASADENA AVE	4	Mainline
I210-E	Azusa	40.849	761228	CITRUS SB	2	Off-ramp
I210-E	Azusa	40.849	768945	CITRUS 1	1	HOV
I210-E	Azusa	40.849	718216	CITRUS SB	1	On-ramp
I210-E	Azusa	40.853	765486	CITRUS 1	4	Mainline
I210-E	Azusa	40.989	718469	CITRUS 2	4	Mainline
I210-E	Azusa	40.989	715972	CITRUS NB	1	On-ramp
I210-E	Azusa	40.989	761240	CITRUS 2	1	HOV
I210-E	Azusa	41.389	772917	E/B 210-W/O BARRANCA	4	Mainline
I210-E	Azusa	41.389	772919	E/B 210-W/O BARRANCA	1	HOV
I210-E	Glendora	41.979	717690	GRAND AV	1	On-ramp
I210-E	Glendora	41.979	761242	GRAND AV	1	HOV
I210-E	Glendora	41.979	717692	GRAND AV	4	Mainline
I210-E	Glendora	41.979	717691	GRAND AV NB	1	Off-ramp
I210-E	Glendora	42.589	772932	E/O GLENDORA	4	Mainline
I210-E	Glendora	42.589	772934	E/O GLENDORA	1	HOV
I210-E	Glendora	42.889	772953	BONNIE COVE	4	Mainline
I210-E	Glendora	42.889	772955	BONNIE COVE	1	HOV

9.2.2. AERIAL PHOTOGRAPHY

A set of 128 annotated aerial photographs covering the length of the site, collected from Google Maps, can be found on the Connected Corridors website [11].

9.2.3. FREEWAY SEGMENTATION

The 37 valid mainline/HOV station pairs define 36 freeway segments. Table 8-4 provides information for each of the segments: limiting mainline and HOV detectors, the on-ramps and off-ramps, and the presence or absence of an HOV gate.

Table 8-4: I-210E segments

id	ML in	HOV in	ML out	HOV out	OR	FR	has HOV gate
1	774011	774013	717595	763606	-	717594	FALSE
2	717595	763606	717601	763608	716563	717600	TRUE
3	717601	763608	717606	717607	716565	[717605, 770172]	FALSE
4	717606	717607	717631	763614	716567	763878	TRUE
5	717631	763614	717633	761093	[768916, 773131]	-	FALSE
6	717633	761093	717635	761098	716585	769269	TRUE
7	717635	761098	717638	761102	716587	769272	TRUE
8	717638	761102	717640	761105	716589	-	FALSE
9	717640	761105	717646	761109	716590	[737480, 768923]	TRUE
10	717646	761109	717650	761112	716593	[763908, 717651]	FALSE
11	717650	-	717654	-	716595	717658	FALSE
12	717654	-	717659	-	716598	-	FALSE
13	717659	717641	773154	773155	716600	-	FALSE
14	773154	773155	717667	761115	-	717666	TRUE
15	717672	761115	773193	773195	716605	-	TRUE
16	717672	761117	773193	773195	716605	-	FALSE
17	773193	773195	761128	761126	-	761130	FALSE
18	761128	761126	761141	761138	718205	-	FALSE
19	761141	761138	761152	761149	718207	761154	FALSE
20	761152	761149	761165	761161	718209	761167	TRUE
21	761165	761161	761177	761174	716606	-	FALSE
22	761177	761174	769701	769703	718212	769705	FALSE
23	769701	769703	761191	761188	-	-	FALSE
24	761191	761188	769772	769773	718213	-	FALSE
25	769772	769773	772857	772859	769774	-	TRUE
26	772857	772859	772872	772874	-	-	FALSE
27	772872	772874	761206	761199	-	774990	FALSE
28	761206	761199	772887	772889	718214	-	FALSE
29	772887	772889	761220	761214	-	-	TRUE
30	761220	761214	765477	770407	718215	717680	FALSE
31	765477	770407	772903	772905	[717679, 717683]	-	FALSE
32	772903	772905	765486	768945	-	761228	TRUE
33	765486	768945	718469	761240	718216	-	FALSE
34	718469	761240	772917	772919	715972	-	FALSE
35	772917	772919	717692	761242	-	717691	FALSE
36	717692	761242	772953	772955	-	-	FALSE

9.2.4. PEMS LOOP HEALTH SUMMARY

The team gathered 92 days of loop health information spanning the period from 10/1/14 to 12/31/14. These were put into an Excel spreadsheet that can be found on the Connected Corridors website [12], and is shown in condensed form in Figure 8-4. This data revealed the following:

- There are 11 stations whose average health was below 50%.
- There are 58 stations with perfect health during the observed time period.
- The average health of the site is around 88%.

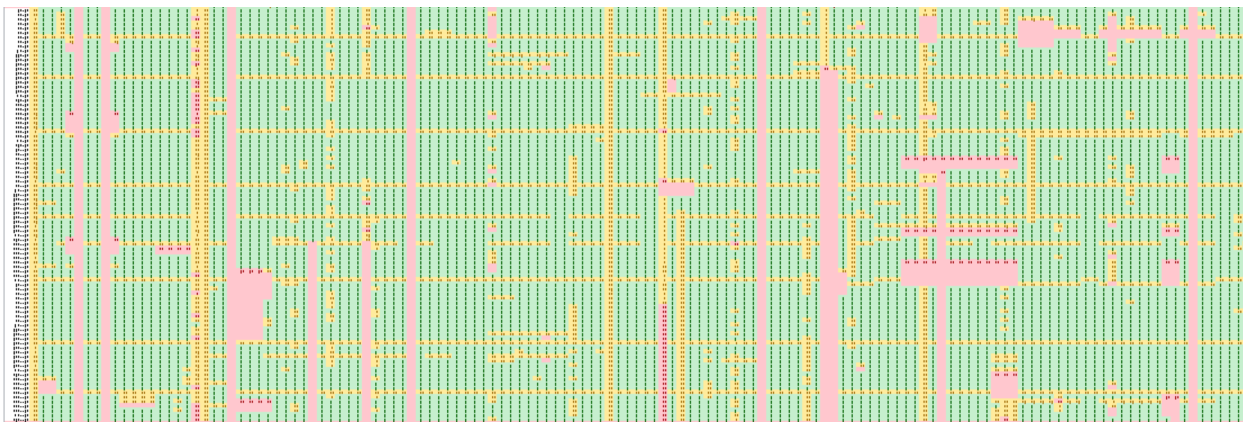


Figure 9-4: PeMS health diagnostics table

9.2.5. FREEWAY DIAGRAM

By inspecting the aerial and street-level photographs, the team found the following facts about I-210E.

- There are 11 HOV gates.
- 14 on-ramps and off-ramps have no detection or partial detection.
- Two mainline stations do not include the auxiliary lane.
- There are 6 lane drops and lane adds.

These items are collected in a diagram that can be found on the Connected Corridors website [13].

9.2.6. FLOW BALANCE

The matrix of flow balance errors obtained for I-210E is provided in Table 8-5. Error values below 5% are considered acceptable. Error values between 5% and 10% merit attention and are shaded in yellow. Values above 10% indicate a vehicle-counting problem in one or more of the stations related to the segment. The table shows that there are 14 segments on I-210 East with significant flow balance errors. For these, a more detailed analysis is provided in the next section.

Table 8-5: Flow balance for I-210E

i	$e_{am}(i)$	$e_{pm}(i)$	$e(i)$	$\bar{e}_{am}(i)$	$\bar{e}_{pm}(i)$	$\bar{e}(i)$
1	-3.3	-3.6	3.4	3.5	3.6	3.6
2	7.4	6.4	6.9	7.4	6.4	6.9
3	-1.1	-6.6	3.8	4.1	6.6	5.3
4	-2.5	-7.4	4.9	2.6	8.0	5.3
5	26.1	24.3	25.2	26.1	24.3	25.2
6	4.1	3.4	3.8	4.1	3.9	4.0
7	-2.9	-3.0	2.9	2.9	3.4	3.2
8	-2.4	-0.8	1.6	3.0	2.5	2.8
9	-2.8	1.2	2.0	2.8	2.2	2.5
10	-3.6	-6.2	4.9	3.7	6.2	4.9
11	-3.4	-3.5	3.4	3.4	3.5	3.4
12	1.7	3.6	2.7	1.7	3.6	2.7
13	-0.9	-1.6	1.2	1.3	2.0	1.6
14	-1.3	-0.8	1.0	1.4	1.0	1.2
15	6.1	2.6	4.3	6.1	2.9	4.5
16	-2.8	-6.0	4.4	2.8	6.0	4.4
17	-2.2	-0.4	1.3	2.4	2.2	2.3
18	-2.6	-1.8	2.2	2.6	2.1	2.4
19	3.3	2.0	2.6	3.7	2.2	2.9
20	-8.6	-7.0	7.8	8.7	7.0	7.8
21	-10.4	-10.0	10.2	10.4	10.0	10.2
22	-14.4	-13.4	13.9	15.9	13.4	14.6
23	-14.8	-18.9	16.9	14.8	18.9	16.9
24	-0.5	3.9	2.2	2.9	4.5	3.7
25	9.1	6.7	7.9	9.1	6.7	7.9
26	0.4	-0.7	0.6	1.2	1.2	1.2
27	1.5	8.5	5.0	6.9	8.5	7.7
28	-2.3	-3.7	3.0	2.3	3.7	3.0
29	-4.3	-3.0	3.6	4.3	3.0	3.6
30	-0.6	0.4	0.5	2.2	1.0	1.6
31	18.3	-17.7	18.0	18.3	19.6	19.0
32	-25.2	12.9	19.0	25.2	15.3	20.2
33	3.2	3.3	3.2	3.2	3.3	3.2
34	-1.8	-2.0	1.9	1.8	2.0	1.9
35	-3.6	-11.2	7.4	3.7	11.2	7.5
36	7.2	14.3	10.7	7.2	14.3	10.7

9.2.7. ANALYSIS

The flow balance errors of Table 8-5 cluster into four main regions of concern:

- Segments 2-5: This is the stretch of SR134E from Figueroa to the I-210 interchange.
- Segments 20-27: The I-605 interchange, from Myrtle St. to the I-605NB on-ramp.
- Segments 31-32: Between Azusa and Citrus.
- Segments 35-36: Grand Ave.

For each segment, the analysis will consider the sign of the flow balance test and the list of bad detectors, and on that basis provide a diagnosis and a list of corrective actions. Underlined phrases indicate the most probable cause of the flow balance error.

9.2.7.1. Segment 2

- Flow balance: <u>Too little entering</u> and/or <u>too much leaving.</u>
- Detection: Bad on-ramp detector.
- Diagnosis: There are two non-mutually excluding possible causes. First, the flows from the Figueroa ramp may be significant, and the lack of detection there may be contributing to the flow imbalance. Second, noting that Segment 3 has the complementary flow balance error, it may also be that the mainline detectors between them are overcounting.
- Corrective action:
    - Fix Figueroa on-ramp station, VDS 716563.
    - Check ML 717601 and HV 763608 for overcounting.

9.2.7.2. Segment 3

- Flow balance: Too much entering and/or <u>too little leaving.</u>
- Detection: Bad Del Mar FR 770172, none to I-210W FR.
- Diagnosis: Significant unmeasured flow to I-210W.
- Corrective action:
    - Find or install detection on the 134E to I-210W connector.

9.2.7.3. Segment 4

- Flow balance: Too much entering and/or <u>too little leaving.</u>
- Detection: None on the Corson FR.
- Diagnosis: The flow to the off-ramp is significant, or the downstream mainline is undercounting. The latter seems like a good option, given the large error in segment 5.

- Corrective action:
  - Gather measurements for the Corson off-ramp.
  - Check mainline stations HV 763614 and ML 717631 for undercounting.

9.2.7.4. Segment 5

- Flow balance: Too little entering and/or too much leaving.
- Detection: Missing OR from Fair Oaks overpass.
- Diagnosis: It is inconceivable that the 25% error for this segment is caused only by the missing on-ramp measurement. There must be, in addition, an error in other supposedly good detectors. Given that the next segment is good, the likely culprits are the upstream mainline detectors and the freeway connector from NB I-710.
- Corrective action:
  - Check mainline stations HV 763614 and ML 717631 for undercounting.
  - Check station FW 768916 for undercounting.

9.2.7.5. Segment 20

- Flow balance: Too much entering and/or too little leaving.
- Detection: Bad incoming mainline detection, no detection on the Buena Vista off-ramp, bad detection on the Mountain off-ramp.
- Diagnosis: The missing ramp flows seem to be dominating the flow balance.
- Corrective action:
  - Fix FR 761167 on Mountain.
  - Gather measurements for the Buena Vista off-ramp.

9.2.7.6. Segment 21

- Flow balance: Too much entering and/or too little leaving.
- Detection: Downstream ML 761177 misses the auxiliary lane.
- Diagnosis: The flow imbalance is caused by the unmeasured auxiliary lane. Aerial photographs show that there is a loop in the lane; however, it is not included in PeMS.
- Corrective action:
  - Add auxiliary lane detection to VDS 761177.

9.2.7.7. Segment 22

- Flow balance: Too much entering and/or too little leaving.
- Detection: Bad detection on exiting HOV lane (HV 769703) and exiting 605 connector (FW 769705). Upstream mainline (VDS 761177) misses the auxiliary lane.
- Diagnosis: The unmeasured flow to SB I-605 causes a significant flow imbalance.
- Corrective action:
  - o Fix I-605SB detection FW 769705.

9.2.7.8. Segment 23

- Flow balance: Too much entering and/or too little leaving.
- Detection: Bad incoming HV 769703, no detection on the Mount Olive off-ramp.
- Diagnosis: Since the Mount Olive off-ramp is probably not taking 17% of the mainline flow, there is likely another source of error here. It is probably an undercounting by the downstream mainline detectors. It is also possible that a significant number of drivers are using the Mount Olive off-ramp/on-ramp to get around congestion. See Figure 8-5.
- Corrective action:
  - o Add detection to the Mount Olive FR.
  - o Check ML 761191 and HV 761188 for undercounting.

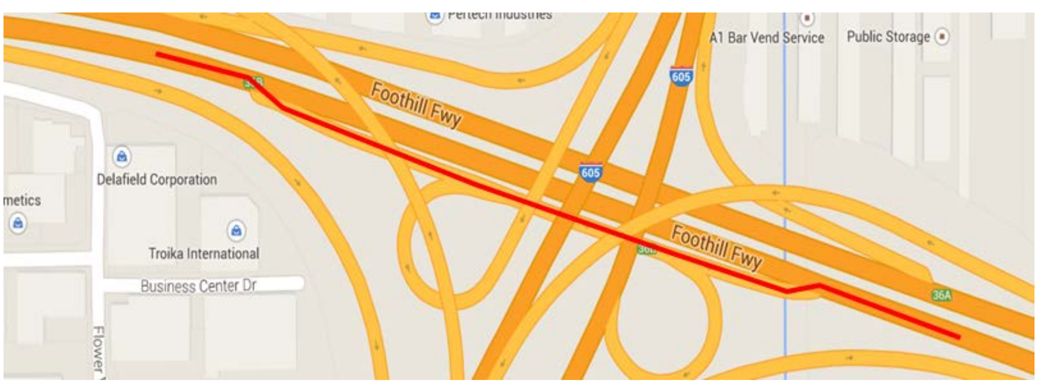


Figure 9-5: The error in segment 23 might be caused by a significant number of drivers taking the red route.

9.2.7.9. Segment 25

- Flow balance: Too little entering and/or too much leaving.
- Detection: Partial I-605 OR measurement, downstream ML 772857 misses the auxiliary lane.

- Diagnosis: The partial measurement of the I-605 OR is a more significant error than the partial measurement of the downstream mainline.
- Corrective action:
    - o Measure flows on the 605NB to 210E connector.

9.2.7.10. Segment 27

- Flow balance: Too little entering and/or too much leaving.
- Detection: Bad upstream ML 772872 and HV 772874. Also, ML 772872 misses the auxiliary lane.
- Diagnosis: Explained by bad upstream measurements.
- Corrective action:
    - o Repair ML 772872 and HV 772874.
    - o Add detection of the auxiliary lane to ML 772872.

9.2.7.11. Segments 31 and 32

These two segments exhibit high and complementary errors, suggesting that the cause lies in the mainline detector station between them. Figure 8-6 shows the mainline flows entering segment 31 (VDS 717684), exiting 31 and entering 32 (VDS 772903), and exiting segment 32 (VDS 765486). The plot clearly shows that the profile of VDS 772903 does not match its neighbors, strongly suggesting a VDS mapping/location error.

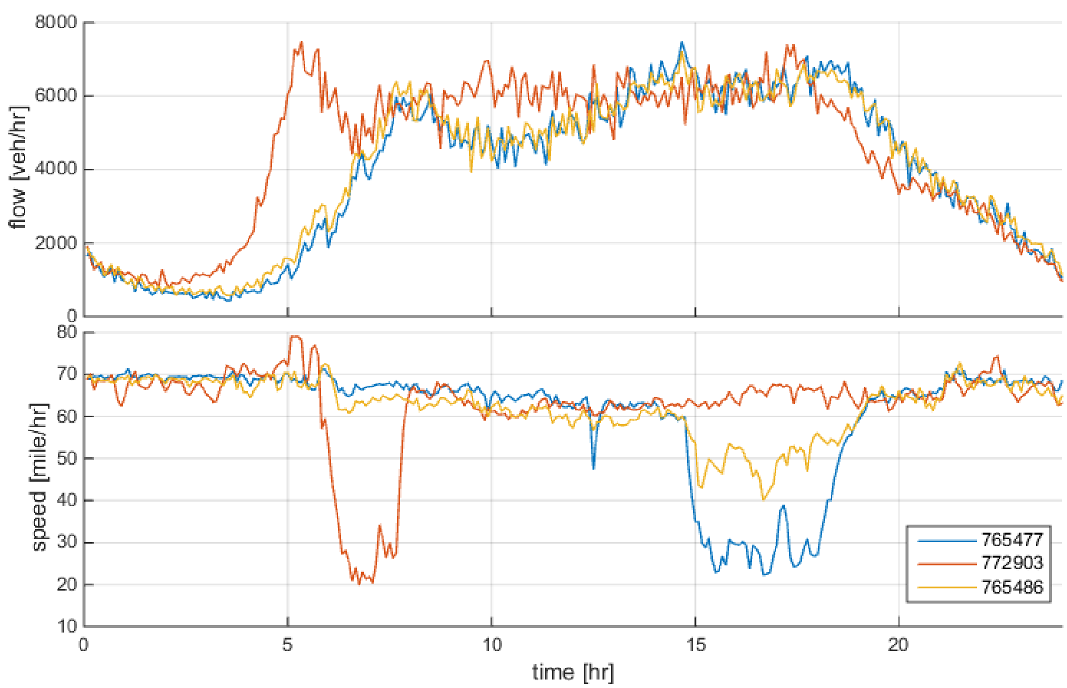


Figure 9-6: Potential VDS location error

9.2.7.12. Segment 35

- Flow balance: Too much entering and/or too little leaving.
- Detection: Bad downstream HOV 761242, partial detection of the Grand Ave. off-ramp.
- Diagnosis: The error decreases when the HOV detector is removed, suggesting that the HOV detector is bad. The partial measurement of the off-ramp also contributes to the error.
- Corrective action:
  - Check and repair HOV 761242.
  - Add full-coverage detection to the Grand Ave. off-ramp.

9.2.7.13. Segment 36

- Flow balance: Too little entering and/or too much leaving.
- Detection: Bad upstream HOV 761242.
- Diagnosis: Explained by the bad HOV detector.
- Corrective action:
  - Check and repair HOV 761242.

9.3. LOOP HEALTH ANALYSIS FOR I-210 WEST

9.3.1. VDS INVENTORY

The I-210 West freeway site covers the same extent as the eastbound site. The full inventory of detector stations can be found in Table 8-6. There are a total of 144 VDSs: 84 mainline stations (42 general purpose, 42 HOV), 30 on-ramp stations, 23 off-ramp stations, and 7 freeway connector stations.

Table 8-6: I-210W loop inventory

Fwy	City	Abs PM	ID	Name	Lanes	Type
SR134-W	Los Angeles	10.643	774014	TOWNSEND	1	HOV
SR134-W	Los Angeles	10.643	774012	TOWNSEND	4	Mainline
SR134-W	Los Angeles	11.473	716562	FIGUEROA	1	On-ramp
SR134-W	Los Angeles	11.473	763612	FIGUEROA	1	HOV
SR134-W	Los Angeles	11.473	717597	FIGUEROA	4	Mainline
SR134-W	Los Angeles	11.473	717596	FIGUEROA	1	Off-ramp
SR134-W	Los Angeles	11.623	774034	COLORADO	1	HOV
SR134-W	Los Angeles	11.623	774037	COLORADO	2	Off-ramp
SR134-W	Los Angeles	11.623	774032	COLORADO	4	Mainline
SR134-W	Pasadena	12.253	717599	SAN RAFAEL	4	Mainline
SR134-W	Pasadena	12.253	763610	SAN RAFAEL	1	HOV
SR134-W	Pasadena	12.253	716564	SAN RAFAEL	1	On-ramp

SR134-W	Pasadena	12.253	717598	SAN RAFAEL	1	Off-ramp
SR134-W	Pasadena	12.763	717603	ORANGE GROVE	5	Mainline
SR134-W	Pasadena	12.763	717604	ORANGE GROVE	1	HOV
SR134-W	Pasadena	12.763	716566	ORANGE GROVE	1	On-ramp
SR134-W	Pasadena	12.883	769301	EB 210 TO WB 134 #2	1	Fwy-Fwy
SR134-W	Pasadena	12.893	769302	NB 710 EXT TO WB 134	1	Fwy-Fwy
I210-W	Pasadena	24.98	769300	WB 210 TO ORANGE GRV	1	Off-ramp
I210-W	Pasadena	25.4	717630	FAIR OAKS 1	4	Mainline
I210-W	Pasadena	25.4	716583	FAIR OAKS 1	1	On-ramp
I210-W	Pasadena	25.4	717632	FAIR OAKS 1	1	HOV
I210-W	Pasadena	25.48	773132	FAIR OAKS OFF	2	Off-ramp
I210-W	Pasadena	25.68	764137	MARENGO	6	Mainline
I210-W	Pasadena	25.68	764135	MARENGO	1	HOV
I210-W	Pasadena	25.68	764349	MARENGO	1	Off-ramp
I210-W	Pasadena	26.12	716586	LAKE 1	1	On-ramp
I210-W	Pasadena	26.12	717634	LAKE 1	5	Mainline
I210-W	Pasadena	26.12	761318	LAKE 1	1	HOV
I210-W	Pasadena	26.47	768920	LAKE 2 - OFF	2	Off-ramp
I210-W	Pasadena	26.8	717637	HILL	5	Mainline
I210-W	Pasadena	26.8	717636	HILL	1	Off-ramp
I210-W	Pasadena	26.8	761322	HILL	1	HOV
I210-W	Pasadena	26.8	716588	HILL	1	On-ramp
I210-W	Pasadena	27.64	764346	ALLEN	2	Off-ramp
I210-W	Pasadena	28.03	716591	ALTADENA	1	On-ramp
I210-W	Pasadena	28.03	717643	ALTADENA	1	HOV
I210-W	Pasadena	28.03	717642	ALTADENA	5	Mainline
I210-W	Pasadena	28.27	716592	SAN GABRIEL	1	On-ramp
I210-W	Pasadena	28.27	717644	SAN GABRIEL	5	Mainline
I210-W	Pasadena	28.27	717645	SAN GABRIEL	1	HOV
I210-W	Pasadena	28.58	768927	SAN GABRIEL OFF	1	Off-ramp
I210-W	Pasadena	29.17	717649	SIERRA MADRE V1	5	Mainline
I210-W	Pasadena	29.17	716594	SIERRA MADRE V1	1	On-ramp
I210-W	Pasadena	29.17	761325	SIERRA MADRE V1	1	HOV
I210-W	Pasadena	29.17	717648	SIERRA MADRE V1	3	Off-ramp
I210-W		29.879	717652	ROSEMEAD 1	1	Off-ramp
I210-W		29.879	717653	ROSEMEAD 1	5	Mainline
I210-W		29.879	761431	ROSEMEAD 1	1	HOV
I210-W		29.879	716596	ROSEMEAD 1	1	On-ramp
I210-W		29.999	717657	ROSEMEAD 2	4	Mainline
I210-W		29.999	717656	ROSEMEAD 2	2	Off-ramp
I210-W		29.999	716597	ROSEMEAD 2	1	On-ramp
I210-W		29.999	761428	ROSEMEAD 2	1	HOV
I210-W	Arcadia	30.139	716599	MICHILLINDA	1	On-ramp
I210-W	Arcadia	30.139	717661	MICHILLINDA	4	Mainline
I210-W	Arcadia	30.139	761327	MICHILLINDA	1	HOV
I210-W	Arcadia	30.689	773179	VAQUERO	4	Mainline
I210-W	Arcadia	30.689	773180	VAQUERO	1	HOV
I210-W	Arcadia	30.779	761329	BALDWIN 1	1	HOV

I210-W	Arcadia	30.779	716601	BALDWIN SB	1	On-ramp
I210-W	Arcadia	30.779	717662	BALDWIN SB	2	Off-ramp
I210-W	Arcadia	30.779	717663	BALDWIN 1	4	Mainline
I210-W	Arcadia	30.999	716602	BALDWIN NB	1	On-ramp
I210-W	Arcadia	30.999	717665	BALDWIN 2	1	HOV
I210-W	Arcadia	30.999	717664	BALDWIN 2	4	Mainline
I210-W	Arcadia	32.019	717669	SANTA ANITA 1	4	Mainline
I210-W	Arcadia	32.019	717670	SANTA ANITA 1	1	HOV
I210-W	Arcadia	32.019	716604	SANTA ANITA SB	1	On-ramp
I210-W	Arcadia	32.019	717668	SANTA ANITA SB	2	Off-ramp
I210-W	Arcadia	32.199	717107	SANTA ANITA NB	1	On-ramp
I210-W	Arcadia	32.199	764146	SANTA ANITA 2	4	Mainline
I210-W	Arcadia	32.199	764144	SANTA ANITA 2	1	HOV
I210-W	Arcadia	32.789	773196	E OF SECOND	1	HOV
I210-W	Arcadia	32.789	773194	E OF SECOND	4	Mainline
I210-W	Monrovia	33.049	761337	HUNTINGTON 1	1	Off-ramp
I210-W	Monrovia	33.049	718206	HUNTINGTON 1	1	On-ramp
I210-W	Monrovia	33.049	761342	HUNTINGTON 1	4	Mainline
I210-W	Monrovia	33.049	761339	HUNTINGTON 1	1	HOV
I210-W	Monrovia	34.049	761353	MYRTLE AV	1	HOV
I210-W	Monrovia	34.049	761350	MYRTLE AV	2	Off-ramp
I210-W	Monrovia	34.049	761356	MYRTLE AV	4	Mainline
I210-W	Monrovia	34.049	718208	MYRTLE AV	1	On-ramp
I210-W	Monrovia	34.899	761366	MOUNTAIN / CENTRAL	1	On-ramp
I210-W	Monrovia	34.899	761363	MOUNTAIN AV	1	HOV
I210-W	Monrovia	34.899	718210	MOUNTAIN AV	4	Mainline
I210-W	Duarte	35.409	761371	BUENA VISTA	1	HOV
I210-W	Duarte	35.409	718211	BUENA VISTA	1	On-ramp
I210-W	Duarte	35.409	761377	BUENA VISTA	1	Off-ramp
I210-W	Duarte	35.409	761374	BUENA VISTA	4	Mainline
I210-W	Duarte	36.089	769704	HIGHLAND	1	HOV
I210-W	Duarte	36.089	769702	HIGHLAND	4	Mainline
I210-W	Duarte	36.089	769706	NB 605 TO WB 210	2	Fwy-Fwy
I210-W	Duarte	36.289	769724	NB 605 TO WB 210 CON	2	On-ramp
I210-W	Duarte	36.289	769723	NB 605 TO WB 210 CON	1	HOV
I210-W	Duarte	36.289	769722	NB 605 TO WB 210 CON	4	Mainline
I210-W	Duarte	36.589	761380	MOUNT OLIVE DR / 605	1	HOV
I210-W	Duarte	36.589	717673	MOUNT OLIVE DR / 605	4	Mainline
I210-W	Duarte	36.589	716881	MOUNT OLIVE DR	1	On-ramp
I210-W	Irwindale	36.889	773207	NB 605 TO EB 210	2	Fwy-Fwy
I210-W	Irwindale	36.889	773205	EB 210 TO MT. OLIVE	1	Fwy-Fwy
I210-W	Irwindale	36.889	773204	NB 605 TO MT. OLIVE	1	Fwy-Fwy
I210-W	Irwindale	36.889	773206	SB 605 FROM WB 210	2	Fwy-Fwy
I210-W	Irwindale	37.389	772858	SAN GABRIEL RIVER	4	Mainline
I210-W	Irwindale	37.389	772860	SAN GABRIEL RIVER	1	HOV
I210-W	Irwindale	37.789	772873	W/O IRWINDALE	4	Mainline
I210-W	Irwindale	37.789	772875	W/O IRWINDALE	1	HOV
I210-W	Irwindale	38.069	717674	IRWINDALE 1	4	Mainline

I210-W	Irwindale	38.069	716607	IRWINDALE SB	1	On-ramp
I210-W	Irwindale	38.069	761382	IRWINDALE 1	1	HOV
I210-W	Irwindale	38.208	761384	IRWINDALE 2	1	HOV
I210-W	Irwindale	38.208	717675	IRWINDALE 2	4	Mainline
I210-W	Irwindale	38.208	716608	IRWINDALE NB	1	On-ramp
I210-W	Irwindale	38.209	768886	IRWINDALE 2	1	Off-ramp
I210-W	Irwindale	38.789	772888	ZACHARY PADILLA	4	Mainline
I210-W	Irwindale	38.789	772890	ZACHARY PADILLA	1	HOV
I210-W	Irwindale	39.159	716609	VERNON	1	On-ramp
I210-W	Irwindale	39.159	717676	VERNON	4	Mainline
I210-W	Irwindale	39.159	717677	VERNON	1	HOV
I210-W	Irwindale	39.339	768726	VERNON	1	Off-ramp
I210-W	Azusa	39.809	761386	AZUSA 1	1	HOV
I210-W	Azusa	39.809	717678	AZUSA 1	4	Mainline
I210-W	Azusa	39.809	716610	AZUSA SB	1	On-ramp
I210-W	Azusa	39.909	717681	AZUSA NB	2	Off-ramp
I210-W	Azusa	39.909	717682	AZUSA 2	4	Mainline
I210-W	Azusa	39.909	761388	AZUSA 2	1	HOV
I210-W	Azusa	39.909	716611	AZUSA NB	1	On-ramp
I210-W	Azusa	40.189	772902	PASADENA AVE	4	Mainline
I210-W	Azusa	40.189	772904	PASADENA AVE	1	HOV
I210-W	Azusa	40.549	761390	CITRUS	1	HOV
I210-W	Azusa	40.549	717685	CITRUS	4	Mainline
I210-W	Azusa	40.549	716612	CITRUS	1	On-ramp
I210-W	Azusa	41.031	767780	CITRUS 2	2	Off-ramp
I210-W	Azusa	41.389	772918	E/B 210-W/O BARRANCA	4	Mainline
I210-W	Azusa	41.389	772920	E/B 210-W/O BARRANCA	1	HOV
I210-W	Azusa	41.789	717687	GRAND 1	1	HOV
I210-W	Azusa	41.789	716613	GRAND SB	1	On-ramp
I210-W	Azusa	41.789	717686	GRAND 1	4	Mainline
I210-W	Glendora	41.915	767704	GRAND	2	Off-ramp
I210-W	Glendora	41.969	717688	GRAND 2	4	Mainline
I210-W	Glendora	41.969	716614	GRAND NB	1	On-ramp
I210-W	Glendora	41.969	717689	GRAND 2	1	HOV
I210-W	Glendora	42.889	772954	BONNIE COVE	4	Mainline
I210-W	Glendora	42.889	772956	BONNIE COVE	1	HOV

9.3.2. AERIAL PHOTOGRAPHY

A set of 128 annotated aerial photographs covering the length of the site, collected from Google Maps, can be found on the Connected Corridors website [14].

9.3.3. FREEWAY SEGMENTATION

The 40 valid mainline/HOV station pairs define 39 freeway segments. Table 8-7 provides information for each of the segments.

Table 8-7: I-210W segments

id	ML in	HOV in	ML out	HOV out	OR	FR	has HOV gate
1	772954	772956	717688	717689		767704	FALSE
2	717688	717689	717686	717687	716614		FALSE
3	717686	717687	772918	772920	716613		FALSE
4	772918	772920	717685	761390		767780	TRUE
5	717685	761390	772902	772904	716612		FALSE
6	772902	772904	717682	761388		717681	FALSE
7	717682	761388	717678	761386	716611		FALSE
8	717678	761386	717676	717677	716610	missing	TRUE
9	717676	717677	772888	772890	716609		FALSE
10	772888	772890	717675	761384		768886	FALSE
11	717675	761384	717674	761382	716608		FALSE
12	717674	761382	772873	772875	716607		FALSE
13	772873	772875	772858	772860			TRUE
14	772858	772860	717673	761380		773206	FALSE
15	717673	761380	769722	769723	716881		FALSE
16	769722	769723	761374	761371	769724	[761377, missing]	TRUE
17	761374	761371	718210	761363	718211		FALSE
18	718210	761363	761356	761353	761366	761350	FALSE
19	761356	761353	761342	761339	718208	761337	TRUE
20	761342	761339	773194	773196	718206		FALSE
21	773194	773196	764146	764144		717668	FALSE
22	764146	764144	717669	717670	717107		FALSE
23	717669	717670	717664	717665	716604	717662	TRUE
24	717664	717665	717663	761329	716602		FALSE
25	717663	761329	773179	773180	716601		FALSE
26	773179	773180	717661	761327		[717652, 717656]	FALSE
27	717661	761327	717657	761428	716599		FALSE
28	717657	761428	717653	761431	716597		FALSE
29	717653	761431	717649	761325	716596	717648	FALSE
30	717649	761325	717644	717645	716594	768927	FALSE
31	717644	717645	717642	717643	716592		TRUE
32	717642	717643	717637	761322	716591	[764346, 717636]	FALSE
33	717637	761322	717634	761318	716588	768920	TRUE
34	717634	761318	764137	764135	716586	764349	FALSE

35	764137	764135	717630	717632		773132 + missing	FALSE
36	717630	717632	717603	717604	[716583, 769301, 769302]	missing	FALSE
37	717603	717604	717599	763610	716566	717598	FALSE
38	717599	763610	717597	763612	716564	717596	FALSE
39	717597	763612	774012	774014	716562		FALSE

9.3.4. PEMS LOOP HEALTH SUMMARY

The same set of days was analyzed for 210 West as for 210 East. These were put into an Excel spreadsheet that can be found on the Connected Corridors website [15] and is shown in condensed form in Figure 8-7.

From this analysis, the following emerged:

- There are 17 stations whose average health was below 50%.
- There are 38 stations with perfect health during the observed time period.
- The average health of the site is around 81%.

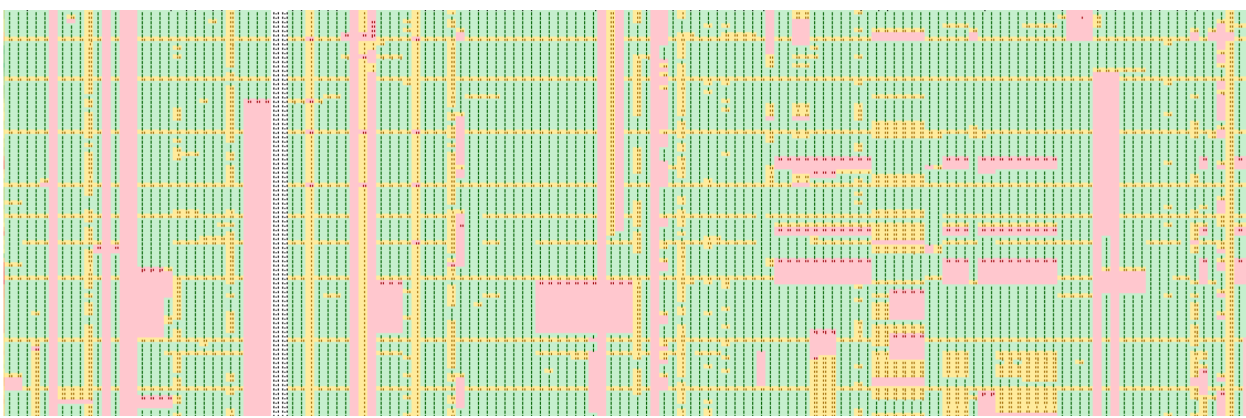


Figure 9-7: PeMS health diagnostics table

9.3.5. FREEWAY DIAGRAM

By inspecting the aerial and street-level photographs, the team found the following facts about I-210W:

- There are 8 HOV gates.
- 12 on-ramps and off-ramps have no detection or partial detection.
- 3 mainline stations do not include the auxiliary lane.
- There are 8 lane drops and lane adds.

These items are collected in a diagram that can be found on the Connected Corridors website [16].

9.3.6. FLOW BALANCE

The matrix of flow balance errors obtained for I-210W is provided in Table 8-8. This table shows that there are 16 segments on I-210W with significant flow balance errors. For these, a more detailed analysis is provided in the next section.

Table 8-8: Flow balance for I-210W

i	$e_{am}(i)$	$e_{pm}(i)$	$e(i)$	$\bar{e}_{am}(i)$	$\bar{e}_{pm}(i)$	$\bar{e}(i)$
1	-4.4	-3.3	3.8	4.4	3.3	3.8
2	6.7	6.0	6.3	6.7	6.0	6.3
3	-10.3	-8.0	9.2	10.3	8.0	9.2
4	0.6	-3.1	1.9	0.6	3.1	1.9
5	35.5	-16.4	26.0	35.5	16.4	26.0
6	-19.5	30.8	25.1	19.5	30.8	25.1
7	19.8	25.6	22.7	19.8	25.6	22.7
8	-16.6	-26.6	21.6	16.6	26.6	21.6
9	2.6	12.1	7.4	2.6	12.1	7.4
10	-2.4	-3.9	3.2	2.4	3.9	3.2
11	2.2	3.0	2.6	2.2	3.0	2.6
12	12.1	15.5	13.8	12.1	15.5	13.8
13	5.2	1.8	3.5	5.2	1.8	3.5
14	-13.2	-13.0	13.1	13.2	13.0	13.1
15	-1.0	0.0	0.5	1.0	0.0	0.5
16	7.5	7.1	7.3	7.5	7.1	7.3
17	-0.7	0.7	0.7	0.7	0.7	0.7
18	0.9	-0.7	0.8	0.9	0.7	0.8
19	1.2	1.4	1.3	1.2	1.4	1.3
20	-2.0	0.3	1.2	2.0	0.3	1.2
21	0.7	-0.5	0.6	0.7	0.5	0.6
22	1.4	0.6	1.0	1.4	0.6	1.0
23	7.1	4.1	5.6	7.1	4.1	5.6
24	20.0	11.2	15.6	20.0	11.2	15.6
25	-12.3	-5.4	8.9	12.3	5.4	8.9
26	8.1	5.5	6.8	8.1	5.5	6.8
27	-11.3	-7.6	9.5	11.3	7.6	9.5
28	2.2	1.4	1.8	2.2	1.4	1.8
29	-5.3	-5.7	5.5	5.3	5.7	5.5
30	17.4	14.9	16.1	17.4	14.9	16.1
31	-13.2	-11.6	12.4	13.2	11.6	12.4
32	-8.8	-5.9	7.4	8.8	5.9	7.4
33	6.3	3.0	4.6	6.3	3.0	4.6
34	-0.2	8.6	4.4	0.2	8.6	4.4
35	20.8	-5.1	13.0	20.8	5.1	13.0
36	-16.5	-9.5	13.0	16.5	9.5	13.0
37	-5.9	-10.0	8.0	5.9	10.0	8.0
38	5.8	8.7	7.3	5.8	8.7	7.3
39	-6.9	-6.3	6.6	6.9	6.3	6.6

9.3.7. ANALYSIS

For each segment, the analysis will consider the sign of the flow balance test and the list of bad detectors, and on that basis provide a diagnosis and a list of corrective actions. Underlined phrases indicate the most probable cause of the flow balance error.

9.3.7.1. Segments 2 and 3

- Flow balance: Too little leaving segment 2 and too little entering segment 3
- Detection: VDS 717686 undercounts.
- Diagnosis: VDS 717686 is in a section with an on-ramp merging lane, but that data is not present in PeMS. Figure 8-8 shows an aerial photograph of the station with the apparently missing loop.
- Corrective action: Install a loop for the acceleration lane if it does not exist. If there is one, then add it to the PeMS configuration.

Figure 9-8: VDV 717686

9.3.7.2. Segments 5 and 6

- Flow balance: The imbalance switches sign for AM to PM.
- Detection: Figure 8-9 shows that VDS 7729902 and 772904 have a different pattern from the rest.
- Diagnosis: The profile differences along with the sign change from AM to PM suggest that these stations are actually on I-210 East.
- Corrective action: Check the freeway assignment of VDSs 7729902 and 772904.

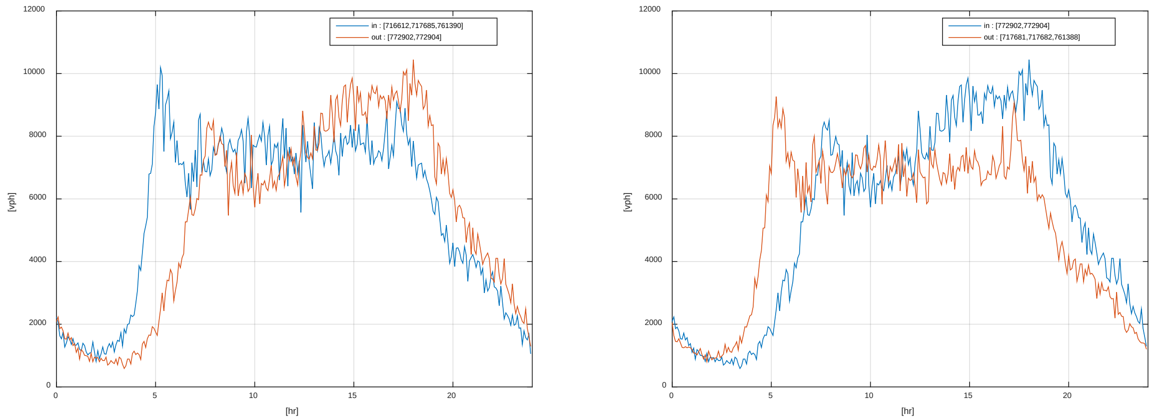


Figure 9-9: Flow balance of segments 5 and 6

9.3.7.3. Segments 7 and 8

- Flow balance: Too little exiting segment 7 and entering segment 8
- Detection: VDS 717678 undercounts
- Diagnosis: Figure 8-10 shows an aerial photograph of VDS 717678. It is located on a section with 4 general purpose lanes and an auxiliary lane (on-ramp acceleration). However, PeMS only provides data for 4 lanes, apparently missing the auxiliary lane.
- Corrective action: Amend the PeMS configuration.

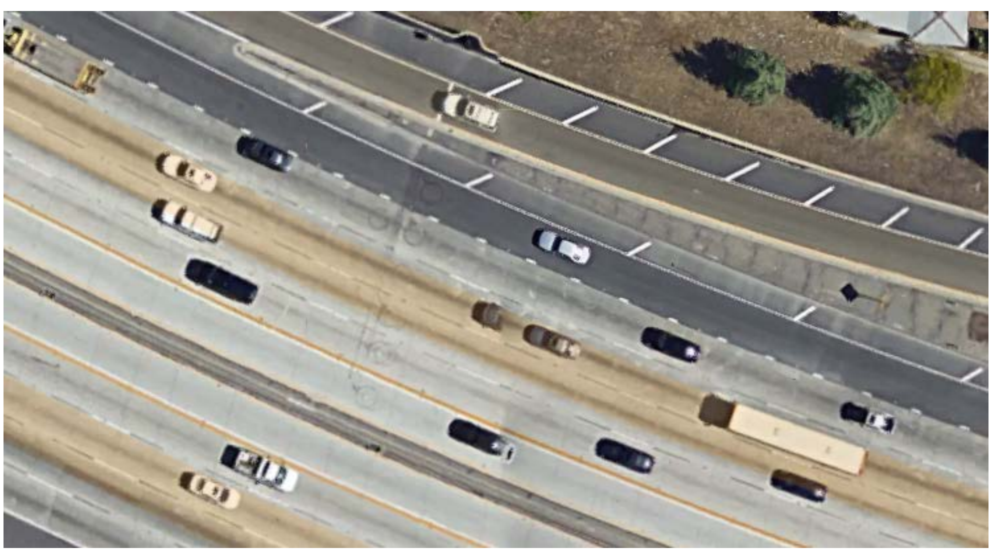


Figure 9-10: I-210W near Azusa Avenue

9.3.7.4. Segment 12

- Flow balance: Too little flow exiting
- Detection: VDS 772873 undercounts
- Diagnosis: VDS 772873 is shown in Figure 8-11. The situation is similar to segments 7 and 8. There is an auxiliary lane which from the photo appears to have detection. However, the number of loops stored in PeMS does not include the extra lane.
- Corrective action: Amend the PeMS configuration.

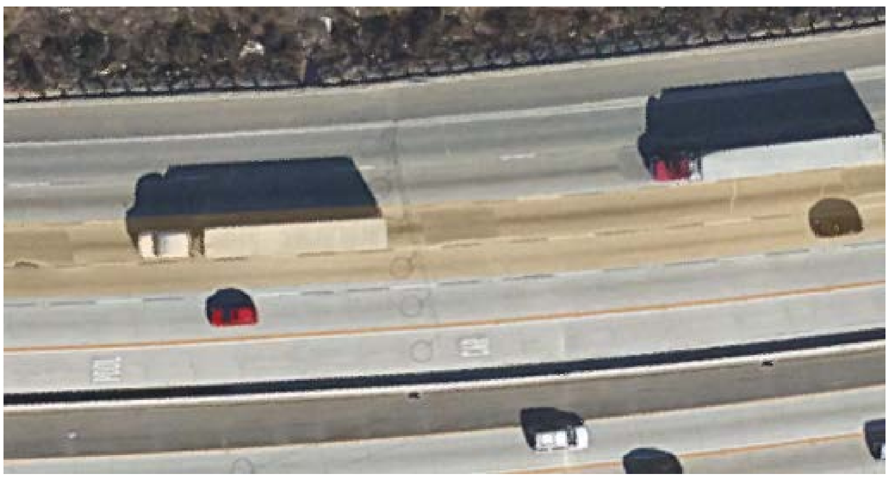


Figure 9-11: VDS 772873

9.3.7.5. Segments 13 and 14

- Flow balance: Too little exiting segment 13 and too little entering segment 14
- Detection: VDS 772858 undercounts
- Diagnosis: VDS 772858 is shown in Figure 8-12. As with VDS 772873 (segment 12), the photo shows 5 lanes (4 general purpose and 1 auxiliary), whereas PeMS only provides 4 lanes of data.
- Corrective action: Amend the PeMS configuration.

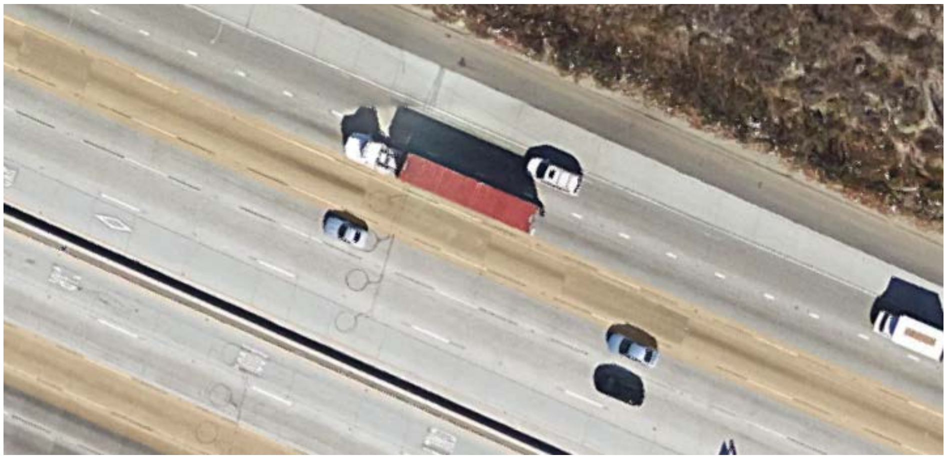


Figure 9-12: VDS 772858

9.3.7.6. Segment 16

- Flow balance: Too little exiting or too little entering.
- Diagnosis: One of the off-ramps near Buena Vista Ave. has not detection. This off-ramp is shown in Figure 8-13. If the volume of traffic on that off-ramp is relatively large, than this would account for the observed error.

Figure 9-13: Missing off-ramp detection

9.3.7.7. Segments 24 and 25

- Flow balance: Too little exiting 24, too little entering 25
- Detection: VDS 761329 and 717663.
- Diagnosis: The stations separating these two segments are bad.
- Corrective action: Test and fix VDSs 761329 and 717663

9.3.7.8. Segments 30 and 31

- Flow balance: Too few leave segment 30 and too few enter segment 31
- Detection: VDS 717644 and 717645.
- Diagnosis: Figure 8-14 shows total inflow and total outflow for segments 30 and 31. It can be noted that the flow imbalances are of a similar magnitude and opposite sign (the blue line exceeds the red in segment 30 by approximately as much the red exceeds the blue in segment 31). This suggests an undercounting error of the mainline detectors.
- Corrective action: Test VDSs 717644 and 717645 for undercounting.

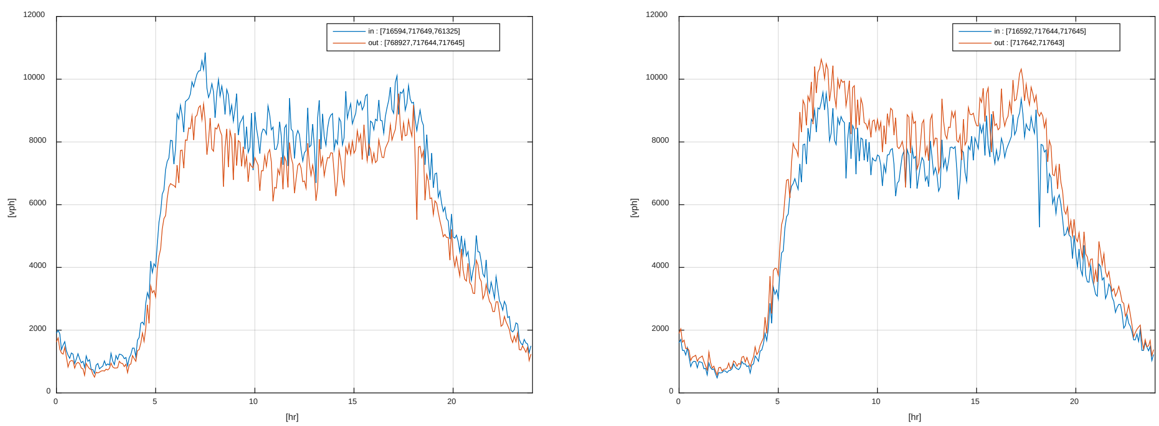


Figure 9-14: Flow imbalance on segments 30 and 31

9.3.7.9. Segment 35

- Flow balance: There is a large flow imbalance in this segment, but its sign is not consistent.
- Detection: This is the segment approaching the SR134W / I210W split. The exact arrangement of detector stations within the segment is not clearly defined in PeMS. In particular, it is not clear whether there is detection on the off-ramp to 710S, nor whether there is direct detection of the freeway interchange toward I-210W. The team made educated guesses for this segment, which require verification and may explain some of the errors.

For 710, VDS 769300 is used – it is also not known whether this is correct.

- Diagnosis: It cannot be determined whether the errors are caused by mistakes in the team's assignment of detectors to pavement, or by flow measurement problems.
- Corrective action: Verify the exact location of detectors on this segment.

9.3.7.10. Segment 36

- Flow balance: Too few vehicles entering.
- Detection: No detection on the two merging freeway connectors shown in Figure 8-15.
- Diagnosis: The deficit of flow entering this section is caused by the lack of measurements on the connector from 210E and NB 710. There are two stations that may be located on these connectors. These are: 769301 and 769302. However both of appear in PeMS to have a "Card off" error.
- Corrective action: Determine what detectors are located on these ramps. Correct detection errors.

Figure 9-15: No detection on connectors from 210E and 710N

9.3.7.11. Segment 37

- Flow balance: Too few vehicles entering.
- Diagnosis: Missing detection on the Orange Grove on-ramp.
- Corrective action: Test and fix the Orange Grove detector station.

9.4. CONCLUSIONS AND RECOMMENDATIONS

9.4.1. HIGH PRIORITY

- Check stations HV 763614 and ML 717631 for undercounting.
- Find or install detection on the SR-134E to I-210W connector.
- Fix I-605SB detection FW 769705.
- Repair measurement of the I-605NB to I-210E connector, VDS 769774. This station has only one lane in PeMS, although the connector has two lanes, and two loop detectors can be seen in aerial photographs.
- Check station FW 768916 for undercounting.
- Fix FR 761167 on Mountain.
- Gather measurements for the Buena Vista off-ramp.
- Add auxiliary lane detection to VDS 761177.
- Add detection to the Mount Olive FR.
- Check ML 761191 and HV 761188 for undercounting.
- The following mainline stations on 210W do not cover all lanes:
  - 717686, 717678, 772873, 772858
- Understand detection on the 210/134 exchange.
- Check and/or fix these mainline stations on 210W:
  - 761329, 717663, 717644, 717645

9.4.2. MEDIUM PRIORITY

- Fix Figueroa on-ramp station, VDS 716563.
- Check ML 717601 and HV 763608 for overcounting.
- Gather measurements for the Corson off-ramp.
- Repair ML 772872 and HV 772874.
- Add detection of the aux lane to ML 772872.
- Check and repair HOV 761242
- Add full-coverage detection to the Grand Ave. off-ramp.
- Check and repair HOV 761242.
- Stations 772902 and 772904 are listed to be on 210W but are apparently on 210E.

10. APPENDIX B: TECHNICAL OVERVIEW OF THE CELL TRANSMISSION MODEL (CTM)

This appendix presents a brief technical explanation of CTM. For a complete description of the model, see [6].

The Cell Transmission Model is a discretized version of the well-known *Lighthill-Whitham-Richards* (LWR) model. The network is discretized into links which are connected via nodes; each link is of size ΔX_i (index i is used to denote a specific link). Time is discretized into steps of length ΔT (index j is used to denote a specific time step). The discretization scheme is known as the Godunov Scheme.

Technical Note: In order to ensure numerical stability, the time and space steps are coupled by the CFL condition:

$$\frac{\Delta T}{\Delta X_i} \leq \frac{1}{v_{\mathrm{ff},i}}$$

where $v_{\mathrm{ff},i}$ denotes the free flow speed for link i according to the fundamental diagram.

10.1. THE FUNDAMENTAL DIAGRAM

For each link i, a fundamental diagram $Q_i(\rho)$ is defined, which relates the flow and the density ρ:

$$Q_i(\rho) = \begin{cases} v_{\mathrm{ff.}i} \cdot \rho & \text{if} \quad \rho \leq \rho_{\mathrm{crit},i} \\ -w_i \cdot \left(\rho - \rho_{\mathrm{jam},i}\right) & \text{if} \quad \text{else} \end{cases}$$

Three parameters are sufficient to specify uniquely a triangular fundamental diagram. The following list describes physical interpretations of parameters that are commonly used.

$v_{\mathrm{ff},i}$	free-flow speed, i.e., speed of traffic in light conditions
$\rho_{\mathrm{crit},i}$	critical density, i.e., density when flow is at capacity
$q_{\mathrm{cap},i} = v_{\mathrm{ff},i} \cdot \rho_{\mathrm{crit},i}$	capacity, i.e., maximum possible flow (also called saturation flow)
w_i	wave speed (in congestion), i.e., speed of shock waves in congestion
$\rho_{\mathrm{jam},i}$	jam density, i.e., density when traffic is standing still

10.2. THE GODUNOV SCHEME FOR A CHAIN OF LINKS

The traffic state in the network is represented by the traffic density ρ_i^j. The following equations show how traffic evolves over a chain of links, i.e., two links are connected by a simple 1-to-1 node. More complicated cases, which are relevant to modeling on-ramps, off-ramps, and intersections, are outlined below. Density evolves over time according to the conservation of vehicles:

$$\rho_i^{j+1} = \rho_i^j - \frac{\Delta T}{\Delta X_i}\left(f_{i\to i+1}^j - f_{i-1\to i}^j\right)$$

Where $f_{i\to i+1}^j$is the flow (or flux) between two neighboring links (index i is increasing with direction of traffic). The flux depends on the demand of the upstream link and the supply of the downstream link:

$$f_{i\to i+1}^j = \min\{d_i^j, s_{i+1}^j\}$$

Demand and supply are defined by the fundamental diagram and the current density:

$$d_i^j = \begin{cases} Q_i(\rho_i^j) & \text{if} \quad \rho_i^j \le \rho_{\text{crit},i} \\ q_{\text{cap},i} & \text{if} \quad \text{else} \end{cases}$$

$$s_i^j = \begin{cases} q_{\text{cap},i} & \text{if} \quad \rho_i^j \le \rho_{\text{crit},i} \\ Q_i(\rho_i^j) & \text{if} \quad \text{else} \end{cases}$$

10.3. THE NODE MODEL

This section briefly outlines how traffic flows when more than two links (or cells) are connected via a node. On freeways, this occurs at on-ramps (2-to-1 nodes) and at off-ramps (1-to-2 nodes), as shown in Figure 9-1:

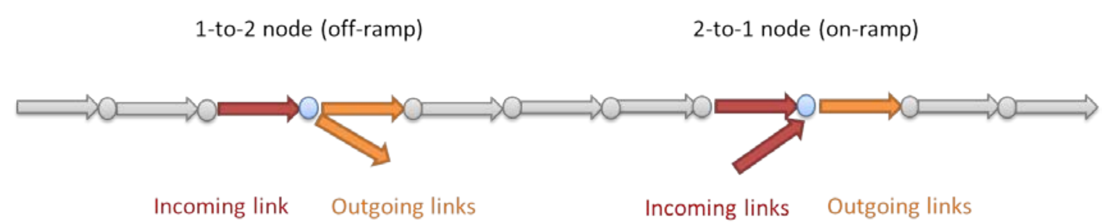


Figure 10-1: Node types at freeway ramps: 2-to-1 and 1-to-2

Two-to-one nodes are used to model merges such as on-ramps. To determine the fluxes at the node, the supply of the outgoing link is distributed to the incoming links according to their capacities. If one in-link's demand is completely served (i.e., its demand is lower than its allocated supply), it provides its excess supply to the other incoming link.

One-to-two nodes are used to model diverges such as off-ramps. The split ratios, or turning ratios, define the fraction of incoming traffic destined to leave the freeway at the off-ramp. To determine the fluxes between the incoming and outgoing links, the demand of the incoming link is distributed according to the specified split ratio. If one of the outgoing links is congested, the flux into the other link is reduced to reflect the (partial) blockage of an off-ramp.

At arterials, the topology is more complicated, which leads to **many-to-many nodes**. The assumptions and ideas of the simple node types can be combined to general nodes. The equations for general nodes are not shown here, but the overall procedure is as follows:

1. Compute supply for each out-link (total amount that can enter each out-link).
2. Index bookkeeping.
3. Compute in-link demands (total amount that wants to leave each in-link).
4. Compute out-link demand (total amount that wants to enter each out-link).
5. Scale in-link demands to satisfy out-link supply.
6. Compute out-flow of in-links.
7. Compute in-flow of out-links.

For further information, see [6].

10.4. SIGNALIZED INTERSECTIONS

Complicated traffic phenomena occur at signalized intersections. To reproduce correct flows, queue spillbacks, and travel times, the simulator contains a model for signalized intersections.

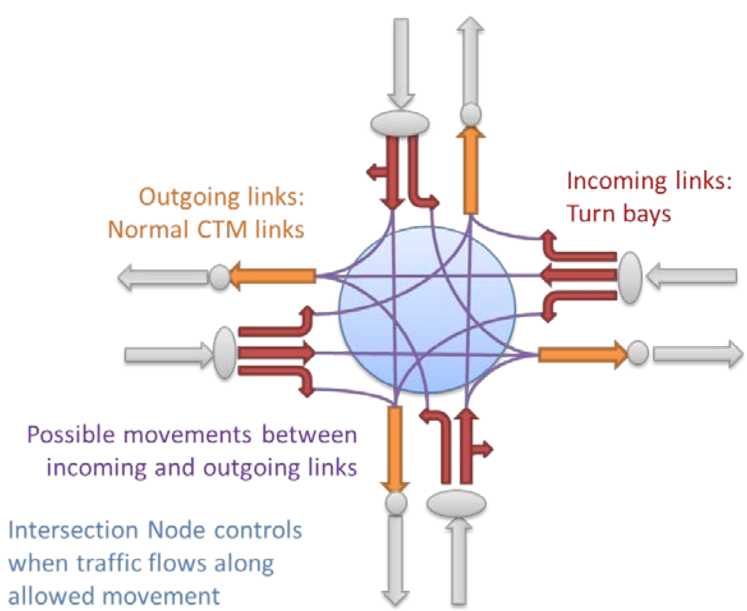


Figure 10-2: Network topology at a typical 4-leg intersection

The network topology at an intersection reflects the possible traffic movements, as illustrated in Figure 9-2. At incoming approaches, each physically existing turnbay is modeled as one or more separate links. Each outgoing egress is modeled as one link. Traffic flow through an intersection is decomposed into multiple streams. Typically, at an intersection with four approaches and three allowed movements per approach (left, through, right), twelve movements are possible. Each of those twelve movements translates into a pair of an incoming link and an outgoing link. When the modeled signal of a link pair is red, no traffic flows between the links. When the signal is green, traffic flows between the links as specified by the Godunov scheme (described in section 9.2).

The simulator is capable of reproducing a fixed-time signal plan, i.e., it repeats the same green-yellow-red sequence in each cycle. It is parameterized by the cycle time and the offset. For each phase, the time step when the signal turns from green to yellow (i.e., force-off time) is specified. Furthermore, yellow clearance and all-red clearance times are specified. To connect the phase with the network, each phase is related to one or more link pairs. The simulation of the traffic signals is accurate to the global simulated time step length ΔT. An example of modeling a specific intersection (Huntington & First) is shown in Figure 9-3:

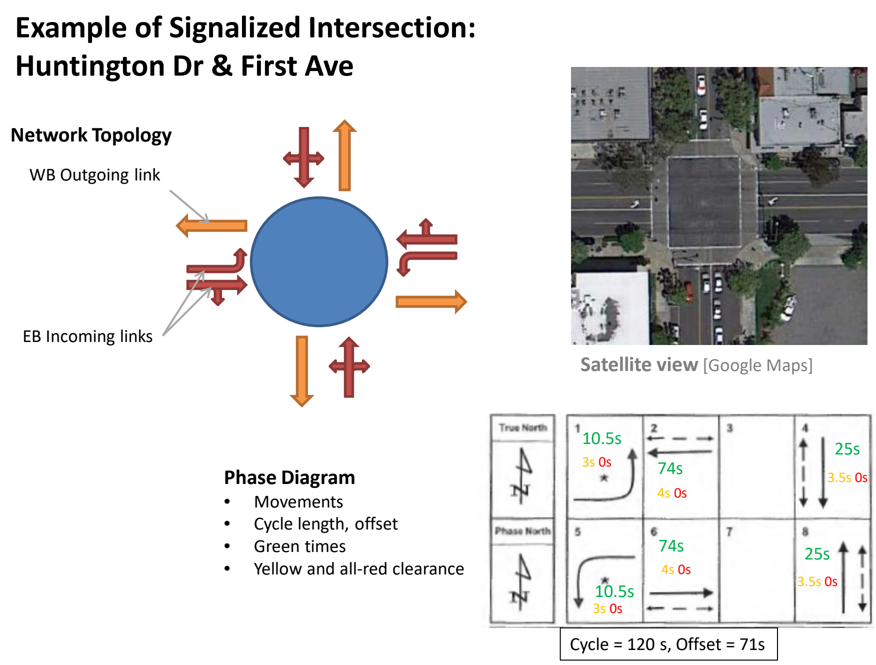


Figure 10-3: Example of a signalized intersection: network topology, satellite view, and phase diagram

Technical note: Since the intersection node is connected to many incoming and outgoing links, the split ratio matrix is relatively large. At a typical 4-leg intersection with turnbays for each movement (i.e., 12 incoming links), the split ratios are defined in a 12-by-4 matrix. Since many movements are not allowed (i.e., turning left from a right turn bay), many entries are zero. Furthermore, a split ratio is also defined at upstream nodes corresponding to the beginning of each turn bay.

Implementation limitations: The 2014 implementation of the signalized intersection model was limited to fixed-time signals with no vehicle actuations. In addition, some movements, such as permitted left-hand turns, were not modeled. Intersection modeling will be expanded in future AMS phases.

10.5. RAMP METERS

The simulator is capable of reproducing the effects of ramp metering. A ramp meter effectively reduces the inflow onto the freeway, which may cause a queue to form on the on-ramp that spills back and potentially affects nearby arterial traffic. The simulator supports fixed-time ramp meters and reactive ramp meters, which adjust the rate according to the traffic state on the freeway.

Although the red and green states are represented directly, it is the average metering rate that is imposed during the simulation, which effectively enforces a cap on the supply function. This behavior is different than that of the intersection signals in which the stop and go (during phases of red and green) is explicitly imposed.

10.6. PERFORMANCE MEASURES

The CTM simulation model can be run to produce measures of traffic flow, speed, and density. From those simulation results, the following performance measures are calculated:

- **Vehicle miles traveled (VMT).** VMT is the total distance traveled by all the vehicles in the specified area and time period. This metric is representative of the demand of vehicles using the network. This value is calculated over individual links (l) and simulation times (t) in the network and then summed over the spatio-temporal region of interest (R). In the following equation, $q_l(t)$ represents the out flow of link l at time t, Δx_l represents the link length, and Δt represents the simulation time step.

$$VMT_l(t) = q_l(t)\Delta x_l \Delta t$$

$$VMT_R = \sum_{l,t \in R} VMT_l(t)$$

- **Vehicle hours traveled (VHT).** VHT is the total time spent by all the vehicles in the specified area and time period. This value is also calculated over individual links (l) and simulation times (t) in the network and then summed over the spatio-temporal region of interest (R). In the following equation, $\rho_l(t)$ represents the density of link l at time t.

$$VHT_l(t) = \rho_l(t)\Delta x_l \Delta t$$

$$VHT_R = \sum_{l,t \in R} VHT_l(t)$$

- **Travel time.** Travel time is the experienced travel time along specified path when entering at time t. This value is first calculated over individual links l at entry time t. Then it is summed over links of a given path, and then averaged over specified time period. The travel time over a link is calculated as follows:

$$T_l(t) = \underset{\tau}{\operatorname{argmax}} \left\{ \sum_{\tau'=0}^{\tau-1} V_l(t+\tau')\Delta t \leq \Delta x_l \right\}$$

- **Delay.** Delay is calculated as extra travel time (compared with free flow speed) over a spatio-temporal region of interest. Similarly, this value is calculated over individual links (l) and simulation times (t) in the network and then summed over the spatio-temporal region of interest (R).

$$D_l(t) = VHT_l(t) - \frac{VMT_l(t)}{V_l}$$

$$D_R = \sum_{l,t \in R} D_l(t)$$

- **Average speed.** The ratio between VMT and VHT equals the average speed for the section length and the simulation time.

$$avgSpeed = \frac{VMT_R}{VHT_R}$$

- **Travel time benefits.** When evaluating travel time benefits associated with a particular intervention, we assume a value of time according to the Cal-B/C Corridor 5.0 defaults.

$$travel\ time\ benefits = [VHT(intervention\ scenario) - VHT(no\ intervention\ scenario)] * value\ of\ time$$

- **Travel time reliability benefits.** Travel time (TT) is reliable when users generally experience what they expect, and do not have to plan extra time for their trips. Travel time reliability can be quantified through several metrics including a buffer-type index or the standard deviation of travel time.

  In this AMS report the 95th percentile travel time is used:

$$travel\ time\ reliability\ benefits = [95^{th}\ percentile\ travel\ time(no\ intervention\ simulation) - 95^{th}\ percentile\ travel\ time(intervention\ simulation)] * value\ of\ time$$

  Since the frequency of incidents is typically more than 5% for this simple analysis, the travel time distribution is binary and the 95th percentile travel time is, in this case, the travel time of the incident scenario, with or without intervention. As the range of models and simulations increases, a more representative collection of travel times will be developed.

- **Vehicle operating cost savings.** The vehicle operating costs depend on VMT and the fuel consumption rate. The fuel consumption rate depends on the speed of the vehicles. This leads to the formula for vehicle operating costs calculation:

$$vehicle\ operating\ costs = VMT * (fuel\ consumption\ rate) * (fuel\ price)$$

$$vehicle\ operating\ cost\ savings = vehicle\ operating\ costs\ (intervention\ simulation) - vehicle\ operating\ costs\ (no\ intervention\ simulation)$$

- **Emission cost savings.** The emission costs depend on VMT and emission rate. This leads to the formula for emissions calculation:

$$\begin{aligned} emissions\ costs = VMT * [&(emission\ rate\ for\ CO) * (emission\ price\ for\ CO) \\ &+ (emission\ rate\ for\ CO_2) * (emission\ price\ for\ CO_2) \\ &+ (emission\ rate\ for\ NO_2) * (emission\ price\ for\ NO_2) \\ &+ (emission\ rate\ for\ PM_{10}) * (emission\ price\ for\ PM_{10}) \\ &+ (emission\ rate\ for\ SO_X) * (emission\ price\ for\ SO_X) \\ &+ (emission\ rate\ for\ VOC) * (emission\ price\ for\ VOC) \end{aligned}$$

$$\begin{aligned} emissions\ cost\ savings = &\ emissions\ costs\ (intervention\ simulation) \\ &- emissions\ costs\ (no\ intervention\ simulation) \end{aligned}$$

The default parameters provided in Cal-B/C Corridor 5.0 were used, as described in section 6.4.

11. APPENDIX C: IDENTIFYING COSTS AND BENEFITS FOR THE CONNECTED CORRIDORS I-210 PILOT

In determining how to perform a cost/benefit analysis for the Connected Corridors I-210 Pilot, the **costs** and **benefits** associated with the project must first be identified. The identification process is discussed in this appendix.

This appendix first identifies cost and benefit categories and then considers multiple strategies for including or excluding costs and benefits. Five strategies are described, principally based on whether a certain cost is or is not allocated to the corridor. For benefits, strategies are based on the ability to accurately measure the underlying corridor characteristics that are used to calculate the monetary benefits.

While there are excellent sources of information on how to conduct cost/benefit evaluations for transportation projects (for instance, http://bca.transportationeconomics.org/), these are more focused on traditional construction projects and not on ITS projects involving highly shared communication and software assets. Having consulted with numerous practitioners, there is no single answer to what costs and benefits should be included in the cost/benefit analysis for the I-210 Pilot. What should be included depends on the audience, the specific reason for performing the cost/benefit analysis, and whether time and or instrumentation permit the measurement of changes in the corridor.

Based on information collected in this AMS study, the following points are proposed for discussion:

- Costs and benefits should be measured only during incidents.
- Costs and benefits evaluations should be based on a before/after comparison of corridor operations.
- Data characterizing costs and benefits after the launch of the Pilot ICM system should ideally be measured after the pilot ICM system has been in operation for one year.
- Simulation and estimation may be used early in the evaluation process. However, without an accurate tally of costs and with the possible variance in measured benefits from simulated benefits, the possibility for significant errors exists.

In addition, this report proposes a preferred strategy for the accounting of costs and benefits:

Costs

Expenditures exclusively on the I-210 corridor, only for items that would never have been undertaken without the need for a centralized decision support system:

1. One-time/Initial
    a. Outreach
    b. Systems engineering
    c. Analysis, modeling, and simulation
    d. Certain software
2. Ongoing/Continuing – 10 year time period
    a. Administrative – Costs of reviewing and updating agreements
    b. Operations – Costs of running the DSS and ensuring underlying models are up to date
    c. Maintenance – Costs of maintaining and upgrading the DSS

Benefits

Transportation benefits associated with the operation of the I-210 Pilot ICM system:

1. Reductions in travel times
2. Reductions in vehicle operating costs
3. Safety improvements
4. Reduction in vehicle emissions
5. Improvements in travel time reliability

These costs and benefits categories do not include community benefits or the costs of any ITS elements. While community benefits are important, they are excluded from consideration due to the difficulty of measuring them accurately. ITS element costs are further excluded based on the fact that they would have been incurred, at some point in the future, whether the I-210 Pilot would have been implemented or not.

11.1. WHAT IS THE COST OF THE CONNECTED CORRIDORS I-210 PILOT?

THE I-210 PILOT AND CORRIDOR MANAGEMENT IN GENERAL

The I-210 Pilot will use centralized management of traffic lights, ramp meters, and traveler information to mitigate traffic congestion on the corridor caused by incidents and events.

This requires the ability to:

1. Collect data on the state of the transportation system (highways, arterials, transit) using detectors (loop, Bluetooth, etc.)
2. Track the state of control elements (signals, meters, and signs)
3. Permit system operators to characterize incidents (location, duration, etc.)
4. Utilize a decision support system to suggest traffic management strategies (selecting a certain timing plan, setting ramp metering rates, informing travelers about incidents, and providing this information to transit and other stakeholders)
5. Recommend these strategies to local/regional TMCs for execution and gain consensus for their adoption
6. Execute the strategies
7. Evaluate the results

The vision for corridor-level management encourages a shift away from less-coordinated traffic management strategies and toward more-coordinated operations. The costs to move a transportation corridor from a lower level of integration to a higher level of integration may vary considerably based on:

1. The existing state of the system
2. The size of the corridor
3. The ability of the system to measure current traffic conditions
4. The sophistication of the decision support system (model versus rule-based, for example)
5. The traffic management strategies chosen
6. The level of performance monitoring desired
7. The degree of automated control chosen by the stakeholders

For the purpose of cost/benefit analysis, some mechanism is needed for allocating the costs of these investments to their respective project or initiative, such as the I-210 Pilot. If possible, only those additional costs needed to enable the implementation of a particular project would be compared to the benefits of that project. A proper cost allocation requires a complete inventory of the costs involved, their incidence, and the performance benefits they make possible.

Between corridors, there will be reusability/sharing of software, organizational structures, and operational components. However, each corridor and major metropolitan area will require site-specific planning, upgrades, and tailoring of existing solutions, organizational structures, and operational processes.

When requesting funding for improved corridor coordination, the ITS elements requested will also be used for improving normal operations. Ramp meters, signals, and CMS signs can and do operate effectively during normal traffic conditions. In fact many, if not all, of the ITS elements needed for coordinated operation would likely be installed in the corridor as part of normal operations and maintenance.

TAXONOMY OF I-210 RELATED COSTS

In order to deliver the I-210 Pilot, funds are being expended to pay for personnel, software, hardware, and support expenses. These expenses can be divided into categories:

1. One-time
    a. Outreach – Establishment of overall stakeholder support for the project. Involves communication, funding establishment, and agreements on charters and memorandums of understanding.
    b. Systems engineering - Project management, requirements definition, systems integration, and deployment
    c. Analysis, modeling, and simulation – Involves building a model of the corridor, defining traffic management strategies for use during an incident, and evaluation of the results
    d. Software and software systems – DSS, ICM, TMC/ATMS upgrades
    e. Infrastructure – Upgrading signal lights, new sensors, better communication, etc.
2. Ongoing
    a. Administrative – Attending meetings, answering questions, reviewing documents, updating agreements
    b. Operations – Operating the DSS and related ICM systems and ensuring the underlying models are up to date
    c. Maintenance – Maintaining and upgrading the infrastructure, the software, and the ITS elements
3. Research – Caltrans has funded and will continue to fund applied research/pilot development on modeling, new data sources, and decision support tools.

A number of these costs are joint costs shared with many projects or initiatives and cannot be allocated to each individually except in an arbitrary way. One way to further refine the categorization of costs is to determine the level of reuse of products that have been delivered or the applied research that can now be brought into practice. Toward this end, this appendix explores five strategies:

1. I-210 Pilot-specific – Only to be used for the I-210 ICM effort
2. Corridor-level – Used within the corridor for more functions than just the ICM efforts
3. Region-level – Utilized within other corridors in the LA region
4. State/Caltrans HQ-level – Utilized state-wide, not including research
5. State/Caltrans HQ-level – Utilized state-wide, including research

There are a number of important questions to consider when determining costs for the I-210:

1. **Multiple use.** If an item was purchased specifically for the I-210 Pilot, will it be used for normal traffic management in addition to its use for incident-related congestion mitigation? This is true for nearly all hardware upgrades. If so, how much of its costs should be allocated to Pilot costs?
2. **Reusability**. Will the item be used on other corridors? This is true for nearly all software. Again, how much of its costs should be allocated to the Pilot costs?
3. **Pre-planned**. Would the item be purchased irrespective of the I-210 Pilot effort? There are many items in this category, including ITS elements. If so, should any of the costs be allocated to the I-210 Pilot?
4. **Pre-existing**. Are needed items already in place? There are many, including existing ITS elements. Should any of these costs be included in the I-210 Pilot cost? This includes costs that have already been incurred and are "sunk" in the sense that they cannot be re-allocated to new uses. They will be incurred regardless of whether these new uses occur or not.

The answers to these questions greatly affect the final cost. Answers are determined by analyzing both the reason that the costs are being requested and the cost incidence (source of funding, cost responsibility, the discounting and amortization approaches, etc.).

In the context of a cost/benefits study, for example, the final ratio may change dramatically depending on how one answers the above questions. This is important because the tendency for these questions to be answered differently is one of the reasons that cost/benefit numbers might not be trusted.

WHY ARE COST ESTIMATES NEEDED?

Costs are generally requested within a larger context. These contexts include:

1. Anticipated costs: Providing the ability to request, acquire, and allocate funding
    a. Future steps in Connected Corridors
    b. As an estimate for other corridors
2. Cost/benefit analysis: Often used to either encourage or discourage future investment in other corridors
3. Cost matching: To help with grants that require a certain amount of funding from other sources
4. Auditing: Tracking overall funding for the Connected Corridors Program as a state-wide effort
5. Gravitas and PR: Demonstrating the serious nature of the project by showing a large amount of funding commitment
6. Initial project approval: Demonstrating that adoption of ICM is not that costly when considered within the normal baseline elements of a corridor
7. Curiosity or general knowledge

A note on funding: Funding originates from different agencies and is allocated based on the priorities of those agencies. A decision to allocate funds to the I-210 Pilot may serve multiple purposes. The purpose used to allocate or justify the funding may include reasons beyond the immediate scope of the I-210 Pilot.

At times, many different items are grouped together in a funding request under a simple, easy-to-present topic (such as the I-210 Pilot). It may be the case that most but not all items in the grouping are directly related to the topic. In this case, when costs estimates for this topic are requested it may be appropriate to include the overall grouped cost. This avoids unneeded confusion.

DETERMINING COSTS FOR THE I-210 PILOT

There is no simple answer to "What is the cost of the Connected Corridors I-210 Pilot?" It depends on the context of the question. Within the context of the question, judgment calls will be made on what deliverables are included in the cost and what percentage of the cost of those deliverables should be used.

Considering the discussion above, the following strategies for determining the cost of the I-210 Pilot (or any corridor management effort) are summarized for further review:

<table>
<tr><th colspan="2">Cost Strategy 1: I-210 Pilot-specific
Only to be used for the I-210 ICM effort. Considering only those items that would never have been undertaken without the need for a centralized decision support system.</th></tr>
<tr><td>Include</td><td>1. One-time/Initial
a. Outreach—This includes the direct charges to write, edit, and manage communication pieces, outreach meetings, etc. It assumes that this effort will not be significantly reused.
b. Systems engineering—This includes the direct charges required to write, edit and review documents. It assumes the documents will not be significantly reused and thus 100% of the costs should be included.
c. Analysis, modeling, and simulation—This includes direct charges to build corridor models, determine traffic management strategies for use during incidents, and evaluation of the results of using these strategies.
d. Software and software systems—Costs for:
• Specific modifications to systems that will not be reused for other purposes within the corridor or on other corridors
• Any systems purchased or built that will not be reused
• Training and delivery that will not be reused
e. Infrastructure—None
2. Ongoing/Continuing – 10 year time period
a. Administrative—Management/Admin costs for maintaining relationships, educating new officials, and updating documents and agreements.
b. Operations—Cost of running DSS (hosting, etc.)
c. Maintenance—Maintenance for the DSS and models</td></tr>
</table>

Exclude	• Review and status meeting times from stakeholders • Any costs associated with selection of this corridor • All infrastructure (ITS, Communication, etc.) upgrades. All hardware upgrades would have been done sooner or later. ➢ **Note**: It would be possible to assign a usage percentage to these costs based on the time (out of 24 hours) these upgrades are used during the application of CC intervention strategies. • All generic or region-wide systems development ➢ **Note**: Again it would be possible to assign a usage percentage based on the time (including all sites and out of 24 hours) these upgrades are used during the application of CC intervention strategies. • All salaries of all personnel not directly related to the included costs above • All research
Used for	• Cost Benefit-Analysis • Costs for other corridors excluding ITS element upgrades

<table>
<tr><th colspan="2">Cost Strategy 2: Corridor-level

Used within the corridor for more functions than just the ICM efforts. Considering support of continuous performance management.</th></tr>
<tr><td>Include</td><td>1. All items above
2. One-time
• Infrastructure:
a. All ITS element upgrades requested as part of the Pilot
o Freeway
o Arterial
o Transit
b. Stakeholder system upgrades only used on this corridor
3. Ongoing
• Operations—Cost of engineers/maintenance personnel focused on performance management
• Maintenance—ITS maintenance costs</td></tr>
<tr><td>Exclude</td><td>• All generic or region-wide systems development
• All salaries of HQ and D7 not directly related to the I-210 corridor
• All research</td></tr>
<tr><td>Used for</td><td>• General questions on “How much have we spent on the I-210 Connected Corridors program focused on performance management as well as incident duration reduction?”
• A very rough estimate of costs for other corridors with ITS upgrades. However, this can vary so much that this estimate may not be useful.</td></tr>
</table>

Cost Strategy 3: Region-level **Used within other corridors in the LA Region.**	
Include	1. All items above 2. One-time • Software and software systems— Region-wide systems development 3. Ongoing • Operations—Salaries for D7 personnel and %of HQ salaries
Exclude	• New systems development at Caltrans HQ • Research
Used for	• Costs of piloting an ICM implementation that can be fanned out across the LA Region • General questions on "How much have we spent on the I-210 Connected Corridors program focused on performance management including all costs permitting this to be fanned out across the LA region?" • A very rough estimate of costs for other regions for the implementation of a performance management culture. However, this can vary so much that this estimate may not useful.

Cost Strategy 4: State/Caltrans HQ-level **Used state-wide, not including research.** Considering funding of the Connected Corridors Program but not on research or TSM&O in general.	
Include	1. All items above 2. One-time • Software and software systems—New systems development at Caltrans. These include Corridor PEMS, TSMSS, ATMS upgrades, etc. Each of these systems will require additional modifications in order to integrate with the overall Connected Corridors architecture. The timetable and costs for these efforts are not yet known. However these upgrades will be used in many corridors and traffic management scenarios. 3. Ongoing • Operations—Salaries for HQ personnel involved in Corridor Management and Performance Management
Exclude	• Research
Used for	• Costs of piloting a Caltrans-led ICM implementation that can be fanned out across the state of California • General questions on "How much have we spent on the I-210 Connected Corridors program focused on performance management including all costs permitting this to be fanned out across the state of California and potentially used by other states?"

<table>
<tr><th colspan="2">Cost Strategy 5: State/Caltrans HQ-level

Used state-wide, including research. Considering funding of the Connected Corridors Program as a holistic approach to TSM&O over the last 10 years.</th></tr>
<tr><td>Include</td><td>1. All items above
2. Research
• Caltrans has invested in basic research related to traffic management. The three most relevant investments are in the areas of Decision Support, new Data Sources, and Data Fusion. These are referred to as the TOPL tools, the Data Task Orders, and the ICM task orders.</td></tr>
<tr><td>Exclude</td><td>• Nothing</td></tr>
<tr><td>Used for</td><td>• “How much have we spent on the overall vision of traffic management?”
• Demonstrating the significant level of commitment that Caltrans has to Corridor Management and to TSM&O</td></tr>
</table>

ADDITIONAL CATEGORIES FOR COSTS

As an addendum, we note that requests are also made for costs categorized by:

- Development phase:
  1) Project Initiation
  2) Planning
  3) Requirements
  4) Development
  5) Deployment
  6) Evaluation
  7) Operations and Maintenance
  8) Retirement

- Funding agencies:
  1) Caltrans HQ (who principally funds PATH, and thus PATH is not included in this list)
  2) Caltrans D7
  3) Metro
  4) Cities
  5) County
  6) Federal
  7) Other

- When funding was allocated:
  1) In the future after the program is completed
  2) In the future but during the program's lifetime
  3) Current – Currently being spent to build deliverables
  4) Past – Allocated previously in the program and already spent
  5) Prior to program inception – Allocated and spent prior to the program's inception (in-place ITS elements, for example)

- Organization receiving the funding:
  1) Interior to the agency providing the funding
  2) Through contract by the agency providing the funding
  3) Through allocation to another agency

11.2. WHAT ARE THE BENEFITS OF THE CONNECTED CORRIDORS I-210 PILOT?

A benefit is defined as a good result of an action. The goal is to determine the benefits of the I-210 Pilot project for the travelers and the community of the I-210 corridor. The benefits of the Connected Corridors Pilot are determined by identifying relevant changes in corridor characteristics that resulted from the I-210 Pilot. Once these changes are identified, a dollar value is assigned to them.

Benefits are divided into broad categories:

1. Reductions in transportation related costs – Transportation Benefits
2. Improvements in economic activity – Economic Impacts
3. Intangible improvements to quality of life – Community or Social Impacts

TRANSPORTATION BENEFITS

For the I-210 Pilot, the focus is on travel time, vehicle operating costs, safety improvements, emission reduction, and travel time reliability. Other items such as noise reduction, savings in parking costs, and the results of induced travel will not be considered in this report.

ECONOMIC IMPACTS

Economic Impacts are the effects a project has on the economy of a given area. It is measured in terms of change in sales, jobs, and taxes. Economic impacts will not be analyzed.

COMMUNITY/SOCIAL IMPACTS

These are effects that a project has on the I-210 Corridor community members and which are not directly related to either transportation costs or economic impacts. They include quality of life issues related to noise, views, community cohesion, etc.

Traditionally, only *transportation benefits* are considered benefits when performing a standard cost/benefit analysis for transportation projects. However, stakeholders have stated that the Pilot is anticipated to provide significant community benefit as well. How to value this is subject to discussion. There is uncertainty regarding what metrics should be applied and how those metrics should be converted to dollar amounts. This appendix recommends that assessment of community impacts be discussed further.

In order to make meaningful comparisons, benefits must be calculated in a manner consistent with the cost strategies described above. For example, if one includes the costs of all ITS upgrades, then the benefits should be measured in relation to any corridor changes that result from these upgrades and not just to changes that are the result of the operation of the Decision Support System during incidents.

DETERMINING BENEFITS FOR THE I-210 PILOT

There is no simple answer to “What is the benefit of the Connected Corridors I-210 Pilot?” It depends on the context of the question. Considering the discussion above, the following strategies for determining the benefits of the I-210 Pilot (or any corridor management effort) are summarized for further review

<table>
<tr><th colspan="2">Benefit Strategy 1: I-210 Pilot-specific
Only to be used for the I-210 ICM effort. Considering only those items that would never have been undertaken without the need for a centralized decision support system.</th></tr>
<tr><td>Include</td><td>• Transportation Benefits—Calculated for changes during incidents where the ICM recommendations were used
  • Reductions in travel times
  • Reductions in vehicle operating costs
  • Safety improvements
  • Reduction in vehicle emissions
  • Improvements in travel time reliability</td></tr>
<tr><td>Exclude</td><td>• Transportation Benefits not specifically associated with operation of the I-210 Pilot ICM system
• Economic Impacts
• Community/Social Impacts</td></tr>
<tr><td>Used for</td><td>• Comparing with costs generated from Strategy 1: I-210 Pilot specific</td></tr>
</table>

<table>
<tr><th colspan="2">Benefit Strategy 2: Corridor-level
Used within the corridor for more functions than just the ICM efforts. Considering support of continuous performance management.</th></tr>
<tr><td>Include</td><td>• Transportation Benefits—Calculated for changes 24/7 in the corridor</td></tr>
<tr><td>Exclude</td><td>• Economic Impacts
• Community/Social Impacts</td></tr>
<tr><td>Used for</td><td>• Comparing with costs generated from Strategy 2: Corridor-level</td></tr>
</table>

Benefit Strategy 3: Region-level **Used within other corridors in the LA Region.**	
Include	• Transportation Benefits—Calculated for changes 24/7 across the LA Region where these components are being used
Exclude	• Economic Impacts • Community/Social Impacts
Used for	• Comparing with costs generated from Strategy 3: Region-level

Benefit Strategy 4: State/Caltrans HQ-level **Used state-wide, not including research.** Considering funding of the Connected Corridors Program but not on research or TSM&O in general	
Include	• Transportation Benefits—Calculated for changes 24/7 across California where these components are being used
Exclude	• Economic Impacts • Community/Social Impacts
Used for	• Comparing with costs generated from Strategy 4: State/Caltrans HQ-level

Benefit Strategy 5: State/Caltrans HQ-level **Used state-wide, including research.** Considering funding of the Connected Corridors Program as a holistic approach to TSM&O over the last 10 years.	
Include	• Transportation Benefits • Economic Impacts • Community/Social Impacts
Exclude	• Nothing
Used for	• Comparing with costs generated from Strategy 5: State/Caltrans HQ-level • It is unclear how to calculate benefits for this holistic an approach

11.3. WHAT COSTS AND BENEFITS SHOULD BE INCLUDED FOR THE I-210 PILOT?

In order to perform a cost/benefit analysis, it is necessary to determine both which costs and which benefits should be included in the analysis. This is not a straightforward decision, as costs and benefits are generally intertwined: the broader the costs, the broader the benefits.

Based on the range of approaches described above and ongoing discussions with practitioners, this appendix recommends a strategy that is I-210 Pilot-specific:

- Considering only those items that would never have been undertaken without the need for a centralized decision support system
- Considering costs and benefits only during incidents

This recommendation is conservative in both the costs and benefits to include.

Costs
1. One-time/Initial a. Outreach b. Systems engineering c. Analysis, modeling, and simulation d. Certain software 2. Ongoing/Continuing – 10 year time period a. Administrative – Costs of reviewing and updating agreements b. Operations – Costs of running the DSS and ensuring underlying models are up to date c. Maintenance – Costs of maintaining and upgrading the DSS
Benefits
Transportation benefits: 1. Reductions in travel times 2. Reductions in vehicle operating costs 3. Safety improvements 4. Reduction in vehicle emissions 5. Improvements in travel time reliability

Comments:

a. This does not include any community benefits. While these exist, it is unclear how to value them.

b. This does not include any costs for ITS element upgrades. While a certain percentage of the overall ITS upgrade costs required by the Connected Corridors decision support system could be included, it is difficult to understand exactly what percentage to use.

c. Some practitioners believe that all ITS element upgrade costs justified as part of this program should be included. However, cost justification does not equate with actual cost allocation to the project for a cost/benefit analysis.

d. This strategy also does not count costs for upgrades to software systems that will be used across multiple corridors. A percentage could be applied here, but that percentage is open to discussion.

e. Overall, it appears that standard transportation-related cost/benefit analysis is not ideally suited for ITS projects. In standard construction, changes to roadway infrastructure are only usable in one location and are available all the time.

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