Analysis, Modeling, and Simulation (AMS) Testbed Development and Evaluation to Support Dynamic Mobility Applications (DMA) and Active Transportation and Demand Management (ATDM) Programs

Evaluation Report for the San Diego Testbed

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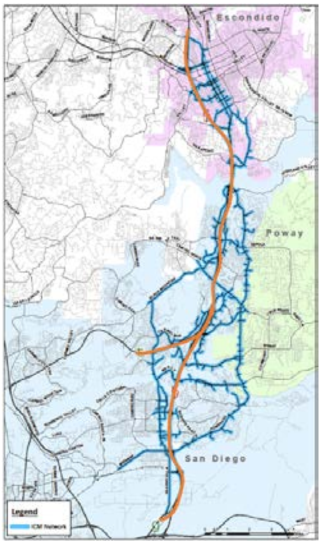

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16. Abstract

The primary objective of this project is to develop multiple simulation testbeds and transportation models to evaluate the impacts of Connected Vehicle Dynamic Mobility Applications (DMA) and Active Transportation and Demand Management (ATDM) strategies. This report documents the evaluations conducted on the San Diego Testbed. The report provides comprehensive documentation of the testbed development as well as the experimental results for the various traffic conditions included in the analysis. These operational conditions were derived from historical data using cluster analysis. The results identify synergistic ATDM and DMA strategies that work well together, and others that may work best when taken individually. Sensitivities of the strategies' impacts to various implementation aspects of the predictive strategies are investigated under different operational conditions.

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Executive Summary

This report documents the evaluation of ATDM strategies and DMA bundles on the San Diego Testbed using the microscopic simulation level in Aimsun, a multi-resolution traffic modeling platform.

Testbed Description

The San Diego Testbed facility comprises of a 22-mile stretch of interstate I-15 freeway and the associated parallel arterials and extends from the interchange with SR 78 in the north to the interchange with SR-163 in the south.

In addition to four or five general-purpose (GP) lanes, the I-15 corridor features two northbound and two southbound express lanes that are free to use for vehicles travelling with two or more passengers in the car, but can be used by single occupancy vehicles for a fee, based on a variable toll price. In addition, it is possible to change the lane configuration of the express lanes with the use of barrier transfer (zipper) vehicles.

The entry to the GP lanes is managed with ramp meters running the San Diego Ramp Metering System (SDRMS) algorithm.

Operational Conditions

For this project, the team selected four operational conditions from a cluster analysis that was conducted as part of the Integrated Corridor Management (ICM) San Diego Evaluation.

Among four AM and five PM clusters in which an incident occurred, an ICM response plan was implemented, and a representative set of real data was available, two AM and two PM clusters where selected:

- AM1: Southbound, Medium Demand, Medium Incident.
- AM2: Southbound, Medium Demand, High Incident.
- PM3: Northbound, Medium Demand, High Incident.
- PM4: Northbound, Medium Demand, Medium Incident.

DMA Applications Evaluated

The two applications that were evaluated in this testbed were:

1. **SPD-HARM** dynamically adjusts and coordinates vehicle speeds to maximize traffic throughput and reduce crashes.
2. **CACC** dynamically and automatically coordinates cruise control speeds among platooning vehicles, coordinates in-platoon vehicle movements, and reduces drag.

The team’s original vision was to evaluate Multi-Modal Intelligent Traffic Signal System (MMITSS) bundle as well, but, the team was unsuccessful in integrating the MMITSS bundle to the San Diego modeling platform and hence the application was not evaluated.

ATDM Strategies Evaluated

Six ATDM strategies are included in this evaluation:

1. **Dynamic Lane Use**, which involves dynamically closing or opening of individual traffic lanes as warranted and providing advanced warning of the closure(s), in order to safely merge traffic into adjoining lanes.
2. **Dynamic Speed Limits**, which adjusts speed limits based on real-time traffic, roadway, and/or weather conditions.
3. **Dynamic Merge Control**, which consists of dynamically managing the entry of vehicles into merge areas with a series of advisory messages approaching the merge point that prepare motorists for an upcoming merge and encouraging or directing a consistent merging behavior.
4. **Predictive Traveler Information**, which involves using a combination of real-time and historical transportation data to predict upcoming travel conditions and convey that information to travelers during pre-trip and en-route stages to influence travel behavior.
5. **Dynamic HOV/Managed Lanes**, which involves dynamically changing the qualifications for driving in a high-occupancy vehicle (HOV) lane(s) or allowing general use of the previously managed lane.
6. **Dynamic Routing**, which uses variable messaging to disseminate information to make better use of roadway capacity by directing motorists to less congested facilities.

Research Questions and Hypotheses

This evaluation answered the following research questions with respect to the DMA applications.

1. Are the DMA applications and bundles more beneficial when implemented in isolation or in combination?
2. What DMA applications, bundles, or combinations of bundles complement or conflict with each other?
3. Under what operational conditions are specific DMA applications the most beneficial?
4. What are the impacts of communication latency on benefits?
5. How effective are the DMA bundles when there are errors or loss in communication?
6. Can new applications that yield transformative benefits be deployed without a commensurate investment in prediction and active management? How cost-effective are DMA bundles when coupled with prediction and active management?
7. At what levels of market penetration of connected vehicle technology do the DMA bundles become effective?
8. What are the impacts of future deployments of the DMA bundles in the near, mid, and long term (varying market penetration)?
9. What are the benefits to participants versus non-participants?

The evaluation also answered the following research questions with respect to the ATDM program.

1. Are ATDM strategies more beneficial when implemented in isolation or in combination?
2. What ATDM strategies or combinations of strategies conflict with each other?
3. Which ATDM strategy or combination of strategies will benefit the most through increased prediction accuracy and under what operational conditions?
4. Are all forms of prediction equally valuable, i.e., which attributes of prediction quality are critical (e.g., length of prediction horizon, prediction accuracy, prediction speed, and geographic area covered by prediction) for each ATDM strategy?

5. Which ATDM strategy or combinations of strategies will be most beneficial under what operational conditions?

Synergies and Conflicts

Combinations of DMA applications, combinations of ATDM strategies, and combinations of DMA applications and ATDM strategies were evaluated under one operational condition to find synergies and conflicts.

Synergy between SPD-HARM and CACC appeared to be minimal: at all penetration rates the effect of SPD-HARM seems to prevail over CACC, even though the vehicles engaged by CACC are not affected by SPD-HARM messages, and in fact it seems to neutralize the benefit in terms of traffic performance that CACC produces when deployed alone.

At low penetration rates the results show some synergy in terms of shockwave reduction; however, at high penetration rates the shockwave reduction is similar to that produced by SPD-HARM alone, and at 50% penetration rate the two DMA applications seem to produce a clear conflict, with lower traffic performance than each application alone, and less shockwave reduction than SPD-HARM alone. The explanation is that at 50% penetration rate CACC platoons are long enough to constitute an impediment for lane-changing of non-connected vehicles, and the addition of SPD-HARM introduces a heterogeneity in the desired speed of non-connected vehicles, which are not affected by SPD-HARM, compared to connected vehicles, which are affected; this increases the desire for non-connected vehicles to overtake connected vehicles, and thus exacerbates the lane-changing issue.

Dynamic Lane Use, Dynamic HOV/Managed Lanes and Dynamic Speed Limits show neither a significant conflict nor a significant synergy. The increase of congestion at the entrances and exits of the HOV lanes due to the increase of demand triggered by Dynamic Lane Use, Dynamic HOV/Managed Lanes is sensed by Dynamic Speed Limits, which extends the congestion over a larger space and longer time in order to avoid abrupt speed changes. This increase of safety is obtained at the expense of throughput and travel time. Dynamic Lane Use and Dynamic HOV/Managed Lanes alone would produce better traffic performance, at the expense of safety. Dynamic Speed Limits alone would produce an increase of safety, but with a more pronounced reduction of throughput.

Dynamic Merge Control and Dynamic HOV/Managed Lanes show a synergy: Dynamic HOV/Managed Lanes compensate the slightly negative effect in terms of traffic performance caused by Dynamic Merge Control. In other words, if Dynamic Merge Control is activated to reduce queueing on the ramp coming into the merge, Dynamic HOV/Managed Lanes would compensate its slightly negative impact on throughput.

Dynamic Merge Control, Dynamic HOV/Managed Lanes and Dynamic Routing show also a synergy: Dynamic HOV/Managed Lanes and Dynamic Routing compensate the slightly negative effect in terms of traffic performance caused by Dynamic Merge Control. Again, if Dynamic Merge Control is activated, Dynamic HOV/Managed Lanes and Dynamic Routing would compensate its slightly negative impact on throughput.

SPD-HARM and Dynamic Merge Control show also a synergy: the benefit in terms of SPD-HARM alone in terms of shockwave reduction are not affected by Dynamic Merge Control, and the throughput reduction caused by Dynamic Merge Control is compensated by SPD-HARM. Again, if Dynamic Merge Control is activated, SPD-HARM would compensate its slightly negative impact on throughput.

SPD-HARM and Dynamic Speed Limits show a synergy in terms of safety improvement: with low penetration rates of connected vehicles, the number of vehicles affected by SPD-HARM is reduced, and the activation of an ATDM strategy that targets non-connected vehicles allows producing a higher shockwave reduction. As the penetration rate of connected vehicles approaches 90%, the contribution of Dynamic Speed Limits gets less significant, though still positive.

SPD-HARM and Predictive Traveler Information don't show good synergy if predictions are made without taking into account what speeds SPD-HARM will suggest, and SPD-HARM operates without knowing what rerouting has been triggered by predictive travel time information. It is however expected that a tighter integration between them, with some interchange of information, would solve the conflict identified in this analysis.

Operational Conditions with Most Benefits

Each DMA application and ATDM strategy was evaluated in isolation under four different operational condition. The performance measures obtained in the simulations was compared with the baseline case, in which no DMA applications nor ATDM strategies are active. The benefits of DMA applications and ATDM strategies appeared to depend on the congestion level.

SPD-HARM generally does not produce significant benefits in terms of traffic performance, but a benefit in terms of safety. Its effectiveness is more evident in congested situations, when it can be appreciated already at lower penetration rates, while when the congestion is low, high penetration rates are required to produce a reduction of shockwaves. The benefit in terms of safety comes at the cost of a slight increase of travel time under all operational conditions.

CACC is more effective in congested situations, where it can produce a significant increase of throughput and reduction of travel time, even at lower penetration rates. When congestion is low, at 50% penetration rate even a slight reduction of traffic performance can be observed, because CACC platoons may cause an obstacle for non-connected vehicle that want to change lane.

The analysis of the simulations with CACC suggested the following observations:

- Most CACC algorithms available today only deal with car-following in a single lane and with an already formed platoon:
    - Care should be taken in selecting the parameters of the CACC algorithm (for example, the gain coefficients of the controller logic, the target headway, the update frequency), as only some combinations produce a stable car-following regime.
- To produce tangible benefits in real-world conditions, CACC algorithms should deal also with other aspects of vehicle movement:
    - Managing the transition (vehicle joining or leaving the platoon) is key to avoid instabilities.
    - Managing the vehicle distribution across multiple lanes is key with multiple reserved lanes (higher penetration rates).
    - Managing the length of the platoon is key with mixed traffic, to prevent blocking non-connected vehicles.
    - Managing the lane changing is key to allow connected vehicles take the exit they need to take and to prevent blocking non-connected vehicles.

Dynamic Lane Use and Dynamic HOV/Managed Lanes are effective only in congested situations. Additionally, the location of incidents and bottlenecks may reduce the effectiveness of this ATDM strategy, because if the congestion caused by them affects the access points to the HOV lanes, vehicles have difficulty in reaching the additional lane that allows bypassing the bottlenecks.

Dynamic Speed Limits reduce the speed change between consecutive road segments, at the expense of reducing the overall speed along the corridor. With little congestion, the impact in terms of increase of delay is negligible, while as congestion increases, the increase of delay increases, too, and is coupled with a slight decrease of throughput.

Dynamic Merge Control facilitates the entrance from SR-78, at the expense of penalizing traffic coming from the northern boundary of the I-15 corridor in the southbound direction. When the I-15 traffic is lower than that entering from SR-78, this strategy has a positive overall impact on the corridor, because it reduces conflicts at the merge.

Predictive Traveler Information with Dynamic Routing is more effective with higher demand and with more severe incidents. The benefit is evident if we focus on the I-15 corridor, while if we adopt a network-wide perspective, we can notice that in some operational condition the positive impact on the speed along the I-15 corridor is in fact counterbalanced by an overall slight increase of travel time because or rerouting along the arterials.

Communication Latency and Errors

The impact of latency and message loss on SPD-HARM was evaluated under one operational condition. Two values of latency (1 and 3 seconds) and two values of message loss (10% and 20%) were tested. The results obtained were compared with those produced under perfect communication conditions to assess the impact of these communication issues.

SPD-HARM doesn’t seem to be sensitive to latency: at all penetration rates, even a latency of 3 seconds doesn’t alter the performance of this DMA application. However, it is sensitive to packet loss at lower penetration rates of connected vehicles: at the highest penetration rate, even 20% message loss doesn’t alter the performance of this DMA application because the number of vehicles receiving SPD-HARM message is high; at 25% penetration rate instead, the effect of just a 10% message loss can already be perceived, while at 50% penetration rate, only 20% message loss can impact the shockwave reduction.

Prediction

To assess the benefit of prediction for DMA applications, SPD-HARM and Predictive Traveler Information were run concurrently, though as two independent applications with no interchange of information between them, under one operational condition. Thus, with low penetration rates of connected vehicles, the shockwave reduction is limited, and the increase of throughput reduced compared to SPD-HARM alone. As the penetration rate of connected vehicles approaches 90%, the gain in terms of shockwave reduction doesn’t increase as quickly as with SPD-HARM alone, but the travel time increases significantly more.

It can be concluded that a tighter integration between Predictive Traveler Information and DMA application, with some interchange of information, would produce significantly better results, by allowing the prediction of shockwaves and the dissemination of anticipatory speed harmonization messages, rather than reactive.

To assess the benefit of prediction for ATDM strategies, a Predictive Traveler Information framework with response plans based on the activation of ATDM strategies in an anticipatory rather than reactive fashion was simulated under four operational conditions. In this specific testbed, predictions do not increase the effectiveness of ATDM strategies, but they can be valuable to determine whether and when those strategies should be activated, rather than relying on a fixed schedule or on a trigger that reacts to the congestion when it is already formed.

Deployment Readiness and Policy

The simulations to evaluate the impact of DMA applications were run with three penetration rates (25%, 50% and 90%). All applications targeting connected vehicles produce higher benefits as the penetration rate increases; the more congested is the traffic condition, the lower is the penetration rate that starts showing some benefit.

SPD-HARM starts being effective in terms of shockwave reduction at 25% penetration rate, especially when the traffic is dense, while CACC requires penetration rates higher than 50% to have a positive impact on the traffic performance. At the same time, the 50% penetration rate for CACC proved to be the most critical, as with an even mixture of connected and non-connected vehicles, lane changing problems caused by compact CACC platoons on non-connected vehicles will expectedly increase the congestion around on and off-ramps and weavings.

SPD-HARM benefits both participant and non-participants. If the penetration rate is high enough and there is congestion: under these conditions, even if just a portion of the vehicles receives the messages and adapt its speed, then the rest of the traffic is also forced to adapt to their speed, and therefore the shockwave reduction benefits all vehicles.

CACC mostly benefits participants, which can keep shorter headways, and hence experience less congestion thanks to the increase of throughput, and higher safety, thanks to the anticipatory effect of speed reduction through the platoon. Indirect benefits for non-participants may be expected, as the increase of throughput and thus reduction of congestion implies a better travel speed for all vehicles, but are more difficult to assess, as the increase of throughput in a corridor may attract additional traffic.

It should be noted that 50% penetration rate for CACC is expected to be the most delicate situation, especially in case CACC platoons are forced to use a subset of the lanes, but these lanes are open also to non-connected vehicles. In this situation, the formation of long platoons may cause an obstacle for lane-changing of non-connected vehicles, which are forced to reduce the speed to wait for a suitable gap, causing a disruption for all traffic.

Chapter 1. Introduction

The United States Department of Transportation (USDOT) initiated the Active Transportation and Demand Management (ATDM) and the Dynamic Mobility Applications (DMA) programs to achieve transformative mobility, safety, and environmental benefits through enhanced, performance-driven operational practices in surface transportation systems management. To explore a potential transformation in the transportation system's performance, both programs require an Analysis, Modeling, and Simulation (AMS) capability. Effective and reliable AMS Testbeds provide valuable mechanisms to address this shared need by providing a laboratory to refine and integrate research concepts in virtual computer-based simulation environments prior to field deployments.

The foundational work conducted for the DMA and ATDM programs revealed several technical risks associated with developing an AMS Testbed which can facilitate detailed evaluation of the DMA and ATDM concepts. Therefore, rather than developing a single testbed, it is desirable to identify a portfolio of AMS Testbeds to (1) capture a wider range of geographic, environmental and operational conditions under which to examine most appropriate ATDM and DMA strategy bundles; (2) add robustness to the analysis results; and (3) mitigate the risks posed by a single testbed approach. Consequently, the testbed selection process resulted in the selection of six testbeds to form a diversified portfolio to achieve rigorous DMA bundle and ATDM strategy evaluation. They are: San Mateo, Pasadena, Dallas, Phoenix, San Diego and Chicago Testbeds. The primary purpose of this report is to document the evaluation conducted on the **San Diego** Testbed.

The San Diego Testbed was used to test several ATDM strategies and DMA bundles considering a proactive network management approach that adopts simulation-based prediction capabilities. Six different ATDM strategies and two DMA applications were evaluated for this Testbed. The ATDM strategies analyzed include Dynamic Lane Use, Dynamic Speed Limits, Dynamic Merge Control, Predictive Traveler Information, Dynamic HOV/Managed Lanes, and Dynamic Routing. The DMA application tested consists of the Intelligent Network Flow Optimization (INFLO) bundle's Dynamic Speed Harmonization (SPD-HARM) and Cooperative Adaptive Cruise Control (CACC). The Multi-Modal Intelligent Traffic Signal Systems (MMITSS) bundle which was originally intended to be evaluated was not included in this evaluation due to technical issues that prevented a full integration of the bundle with this testbed. The Testbed is developed using the microscopic simulation level in Aimsun, a multi-resolution traffic modeling platform.

1.1 Report Overview

This report includes an Executive Summary and twelve chapters as follows:

1. Chapter 1 – Introduction: Presents the report overview and objectives.
2. Chapter 2 – Testbed Description: Presents the regional characteristics of the Testbed (e.g., geographic characteristic) and the proposed modeling framework.
3. Chapter 3 – Operational Conditions and Calibration: Identifies the proposed operational conditions that will be used by the Testbed. This chapter also details the performance of the baseline scenarios under different operational conditions.
4. Chapter 4 – Applications and Strategies Modeled: Describes the ATDM strategies and DMA applications to be evaluated and proposes performance measurement for strategies evaluation.
5. Chapter 5 – Research Questions and Hypotheses: Lists the DMA and ATDM research questions answered by the San Diego Testbed and details respective hypotheses from the Analysis Plan.

6. Chapter 6 – DMA Application Modeling Details: Describes how DMA applications are modeled.
7. Chapter 7 – ATDM Strategy Modeling Details: Details how ATDM strategies are modeled.
8. Chapter 8 – Synergies and Conflicts: Describes the analysis approach and results for the research questions related to the Synergies and Conflicts between DMA applications, ATDM strategies, and combinations of DMA applications and ATDM strategies
9. Chapter 9 – Operational Conditions with Most Benefit: Describes the analysis approach and results for the research questions related to the Operational Conditions with Most Benefit for individual DMA applications and ATDM strategies.
10. Chapter 10 – Communication Latency and Errors: Describes the analysis approach and results for the research questions related to the Communication Latency and Errors for DMA applications.
11. Chapter 11 – Prediction and Active Management: Describes the analysis approach and results for the research questions related to the Prediction and Active Management.
12. Chapter 12 – Deployment Readiness and Policy: Describes the analysis approach and results for the research questions related to the Deployment Readiness and Policy
13. Chapter 13 – Conclusions: Concludes the evaluation report.

Chapter 2. Testbed Description

This chapter describes the San Diego Testbed in detail, including the network's geographic details and the modeling framework.

2.1 Network

The San Diego Testbed facility comprises of a 22-mile stretch of interstate I-15 and associated parallel arterials and extends from the interchange with SR 78 in the north to the interchange with SR-163 in the south as shown in Figure 2-1.

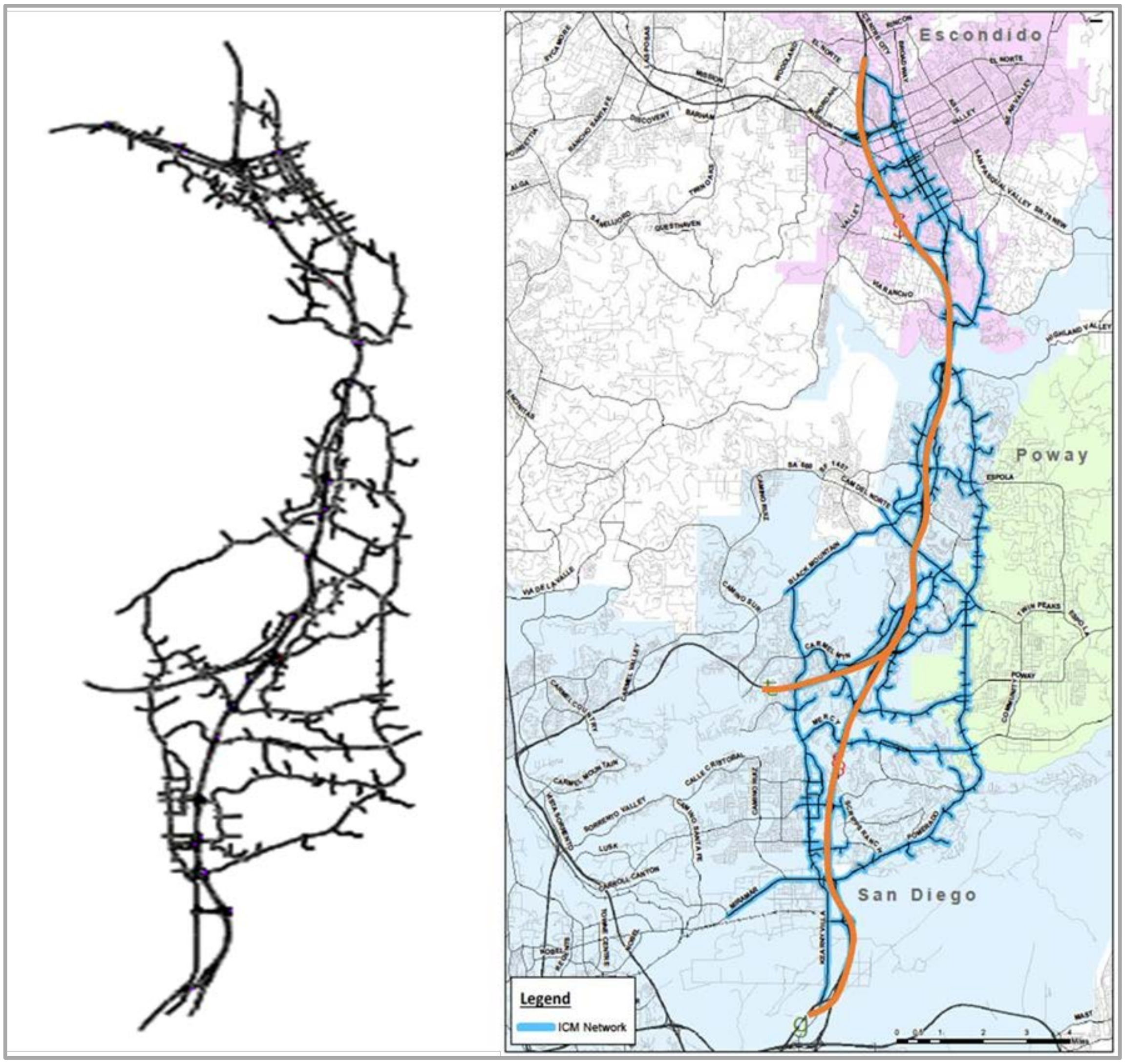


Figure 2-1: Map of the Extracted Network of San Diego

The current I-15 corridor operates with both general-purpose (GP) lanes and four express lanes from the Beethoven Drive DAR to the southern extent of the model. These lanes currently run with two northbound lanes and two southbound lanes and are free to vehicles travelling with two or more passengers in the car (High-Occupancy Vehicles, or HOVs); they also allow Single Occupancy Vehicles (SOV) to use the lanes for a fee, using a variable toll price scheme making them High Occupancy Tolled (HOT) lanes. In addition, it is possible to change the lane configuration of the express lanes with the use of barrier transfer (zipper) vehicles and the Reversible Lane Changing System (RLCS).

The entry to the GP lanes is managed during the morning and evening peak hours throughout the corridor by the Ramp Metering Information System (RMIS) that has localized ramp meters running the San Diego Ramp Metering System (SDRMS) algorithm.

Along the arterials there are two corridors, which are running a Traffic Light Synchronization Program (TLSP) that allows for the use of a more responsive coordinated directional approach to manage the traffic in the peak directions. The TLSP corridors use an algorithm to step through the available timing plans to apply the appropriate plan for the corridor to handle the level of flow.

2.2 Overall Modeling Framework

The San Diego Testbed was developed based on the modularized structure for all AMS Testbeds as shown in Figure 2-2. Note that each block represents one module, and the arrows denote the data and information flow between these modules. The system elements are organized in a modularized structure for easy updates and upgrades.

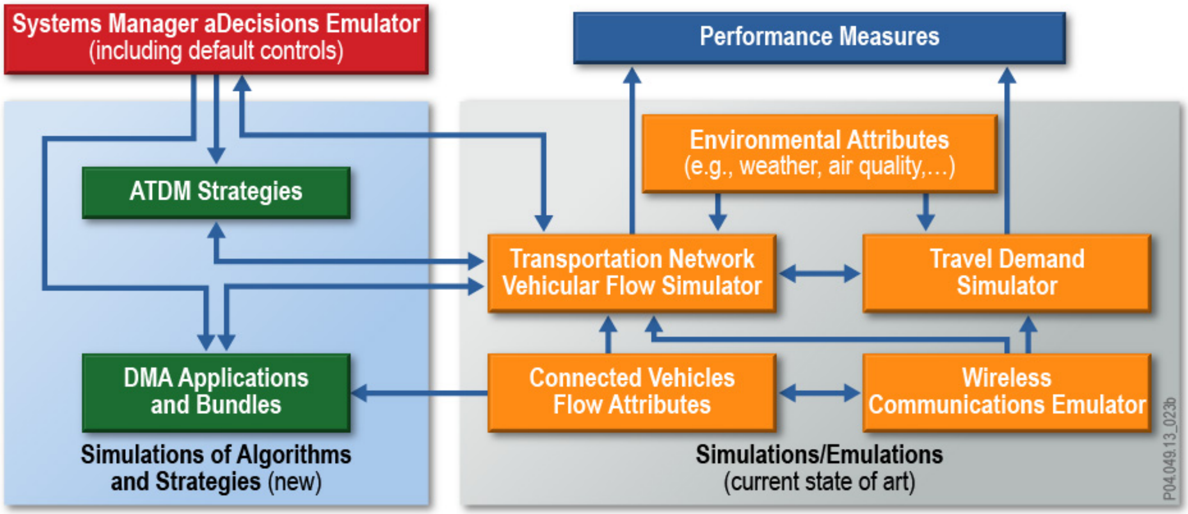
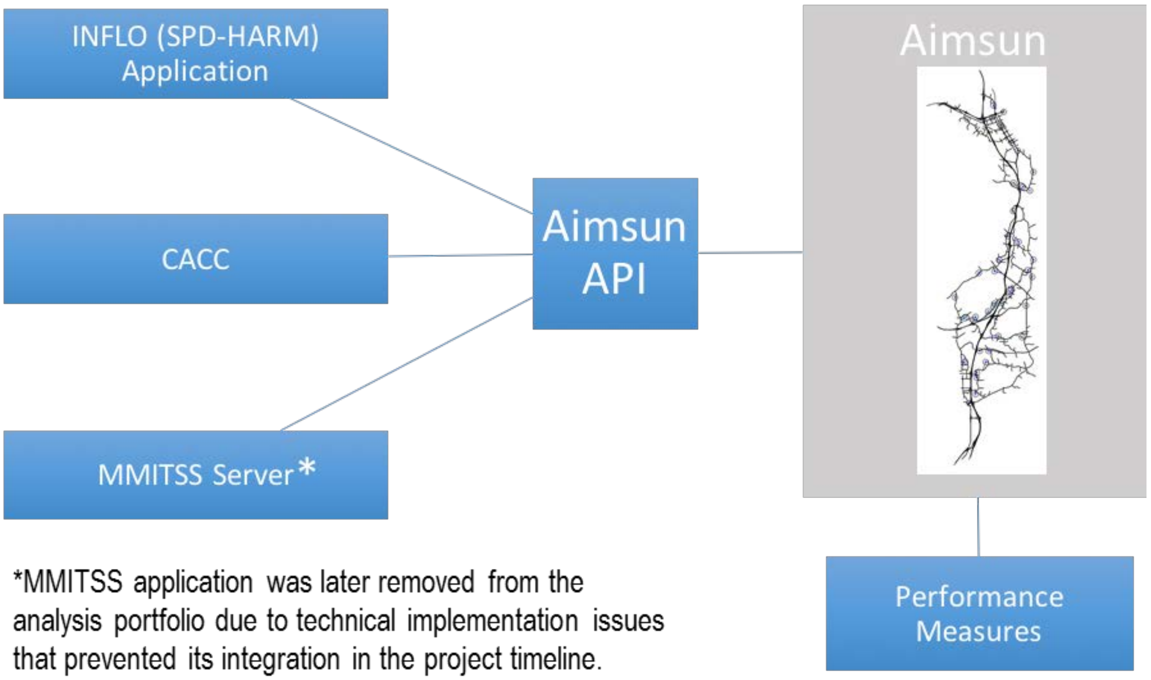


Figure 2-2: Generic Modeling Framework

Figure 2-3 Illustrates the specific modeling framework for the San Diego testbed. The emulation of DMA applications relied on external software components that were interfaced with the traffic simulation via Advanced Programming Interface (API), while ATDM strategies could be emulated using the standard Traffic Management functionality provided by Aimsun.



*MMITSS application was later removed from the analysis portfolio due to technical implementation issues that prevented its integration in the project timeline.

Figure 2-3: San Diego Testbed Modeling Framework

2.2.1 Traffic Simulation Tool

The traffic simulation tool that was used for the San Diego Testbed is Aimsun, developed by TSS-Transport Simulation Systems. Aimsun is a multi-resolution traffic modelling platform that includes macroscopic, mesoscopic, microscopic and hybrid mesoscopic-microscopic modelling engines. The microscopic simulator is the one used for the San Diego Testbed.

Aimsun features an Advanced Programming Interface (API) that allows implementing processes that during the simulation read outputs and implement changes to the infrastructure (signals, ramp meters, lane closures, etc.), or interfacing Aimsun with external processes. The API was used to model:

- ITS devices that are already operational in the corridor: San Diego Ramp Metering System (SDRMS), Congestion Pricing System (CPS), Changeable Express Lane System (CELS)
- Interfaces with external DMA applications and bundles: details on how these interfaces were implemented are provided in Chapter 6.

ATDM strategies were modeled using the standard Traffic Management functionality provided by the software, which allows to code changes affecting the infrastructure (e.g. lane closure, turn closure, change of speed limit) or the vehicle behavior (e.g. forced turn, forced re-routing) at specific times or when a triggering condition occurs during the simulation. Details on how these strategies were implemented are provided in Chapter 7.

Chapter 3. Operational Conditions and Calibration

3.1 Operational Conditions

For this project, the team identified and used four operational conditions that represented the testbeds traffic conditions. The operational conditions were identified from the results of a cluster analysis that was performed as part of the ICM Demonstration Evaluation project. The detailed approach of the cluster analysis and the selection of operational conditions are presented in the “San Diego Testbed Analysis Plan” document (FHWA-JPO-16-375)[1].

The analysis was primarily focused on analyzing incidents within the corridor occurring during the AM peak hours (from 5 AM to 10 AM) or the PM peak hours (from 2 PM to 7 PM) where the ICM system developed and deployed a response plan. As the I-15 corridor is a North/South corridor serving daily commuters to and from downtown San Diego, the analysis focused on the AM Southbound and the PM Northbound datasets.

Among four AM and five PM clusters in which an incident occurred, an ICM response plan was implemented, and a representative set of real data was available, two AM and two PM clusters where selected to represent operational conditions for the San Diego Testbed. Table 3-1 provides a description of these clusters.

Table 3-1: Selected Operational Scenarios for the San Diego Testbed

	AM1	AM2	PM3	PM4
Representative day	05/27/15	02/09/15	06/30/15	07/07/14
Operational Condition	Southbound (AM) +Medium Demand + Medium Incident	Southbound (AM) +Medium Demand + High Incident	Northbound (PM) +Medium Demand + High Incident	Northbound (PM) +Medium Demand + Medium Incident
VPH	6201	6348	9034	8870
Total Cluster Delay (min)	49.88	108.03	99.72	63.25
Number of Incidents/Period	1.9	3.7	5.5	2.1

To calibrate the base model for each operational condition, one representative day was selected from each cluster such that the temporal traffic flow profile for the day is closest to the centroid of the cluster it belongs to. The selected representative days are also shown in Table 3-1.

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[1] Booz Allen Hamilton, Analysis, Modeling and Simulation (AMS) Testbed Development and Evaluation to Support Dynamic Mobility Applications (DMA) and Active Transportation and Demand Management (ATDM) Programs: San Diego Testbed Analysis Plan, USDOT Document FHWA-JPO-16-375, Accessed at: https://ntl.bts.gov/lib/61000/61100/61113/FHWA-JPO-16-375.pdf

3.2 Baseline Calibration

The "Post ICM Evaluation" model, which was calibrated based on the representative day dataset, was used as base to model the four operational conditions. For the representative day within each cluster scenario, the same traffic demand (AM or PM peak for the typical day) was loaded on the network, and the time, location, scope and duration of the incident was coded on top of the base network, as well as the response plan deployed by ICM. Each model was then fine-tuned to fit the calibration criteria by comparing with the real data set for the specific day of the cluster. The detailed approach and results of the calibration process are presented in the "San Diego Testbed Calibration Report" document (FHWA-JPO-16-382)[2].

Table 3-2 presents the details on baseline performance of the network under different operational conditions in terms of average travel time, average stop time and average trip distance. It also shows the generated vehicles according to the calibrated demand profiles.

Table 3-2: Baseline Scenarios under Different Operational Conditions

	OC 1 (AM1)	OC 2 (AM2)	OC 3 (PM3)	OC 4 (PM4)
Vehicle Miles Travelled (mi)	2,320,947	2,304,353	2,518,604	2,302,897
Total Vehicle Travel Time (h)	61,946	61,509	76,531	57,547
Total Passenger Travel Time (h)	78,635	78,853	99,052	75,856
VMT/VHT (mi/h)	37.47	37.46	32.91	40.02
Total demand (veh)	335,913	337,476	417,671	350,066

3.2.1 Operational Condition 1 (AM1)

The first operational condition (AM1) covers from 6 AM to 10 AM and includes higher than recurrent congestion from 8:34 AM to 8:53 AM on I-15 right after the entrance from of SR-78 in the southbound direction **(**Figure 3-1**).**

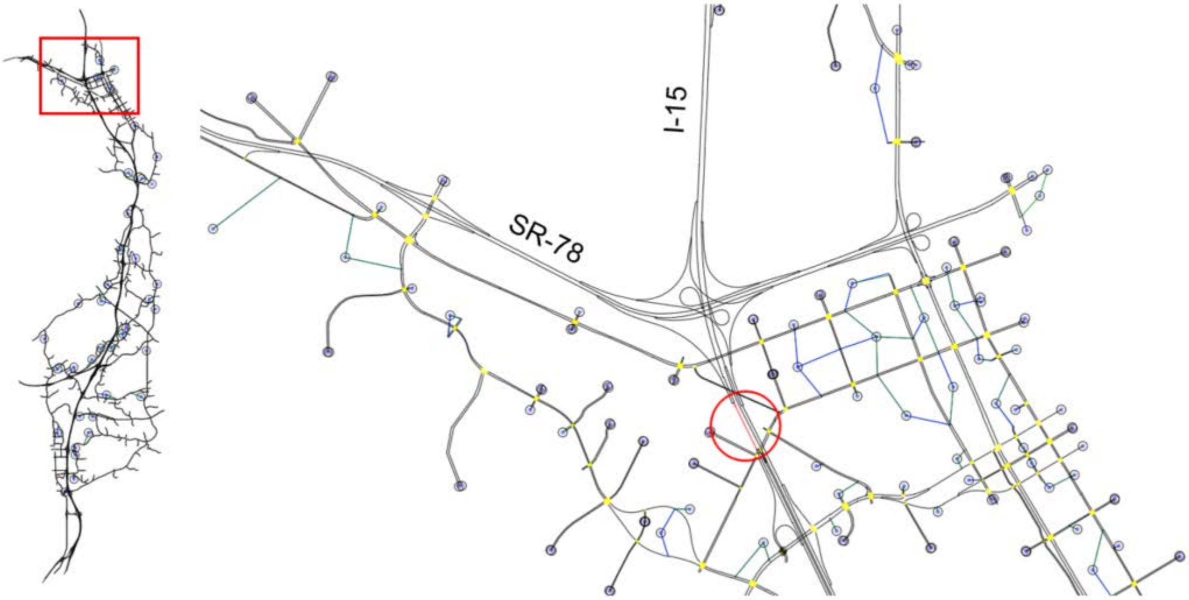

Figure 3-1: Location of the congestion event in scenario AM1

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[2] Booz Allen Hamilton, Analysis, Modeling and Simulation (AMS) Testbed Development and Evaluation to Support Dynamic Mobility Applications (DMA) and Active Transportation and Demand Management (ATDM) Programs: San Diego Testbed Calibration Report, USDOT Document FHWA-JPO-16-382, Accessed at: https://ntl.bts.gov/lib/61000/61800/61819/FHWA-JPO-16-382.pdf

The response plan that was applied includes two diversion routes triggered via VMSs (Figure 3-2): vehicles coming from I-15 go towards SR-78 eastbound, exit at Centre City Parkway and reenter I-15 at West Valley Parkway; vehicles coming from SR-78 continue along SR-78 eastbound, exit SR-78 at Centre City Parkway and reenter I-15 at West Valley Parkway. The rerouting is supported with a change of signal plans along the arterials to accommodate the increase of traffic along the diversion route, and an increase of the metering throughput at West Valley Parkway southbound on-ramp.

Figure 3-2: Diversion routes applied in scenario AM1

The traffic demand loaded on the network totals 335,913 vehicles distributed in 15-minute time slices over 4 hours according to the departure profile depicted in Figure 3-3.

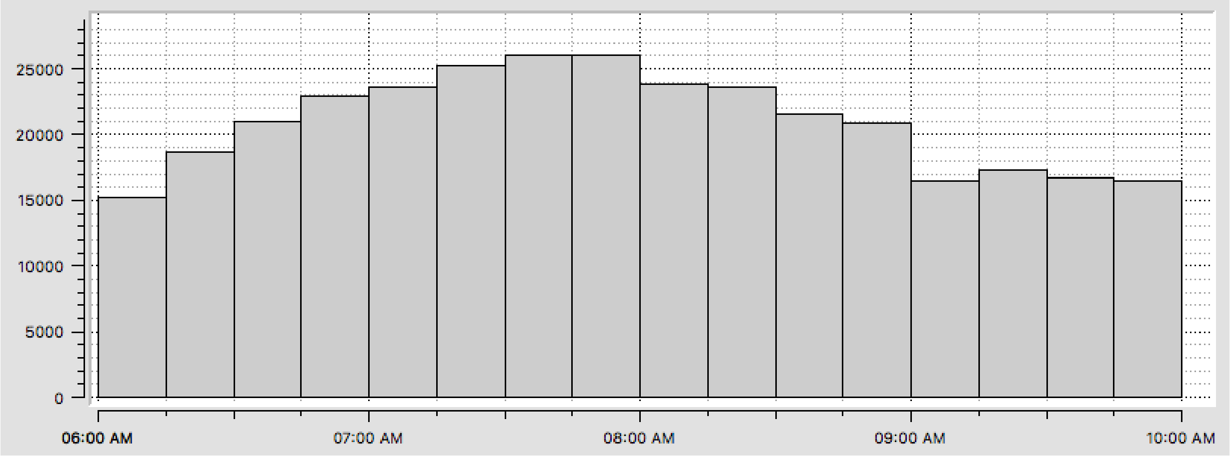

Figure 3-3: Departure time profile in scenario AM1

3.2.2 Operational Condition 2 (AM2)

The second operational condition (AM2) covers from 6 AM to 10 AM and includes a congestion event from 7:49 AM to 8:54 AM on I-15 downstream of the exit to 9th Ave in the southbound direction **(**Figure 3-4**).**

Figure 3-4: Location of the congestion event in scenario AM2

The response plan that was applied includes two diversion routes triggered via VMSs **(**Figure 3-5**):** vehicles coming from I-15 go towards SR-78 eastbound, exit at Centre City Parkway and reenter I-15 at 9th Ave; Vehicles coming from SR-78 continue along SR-78 eastbound, exit at Centre City Parkway and reenter I-15 at 9th Ave. The rerouting is supported with a change of signal plans along the arterials to accommodate the increase of traffic along the diversion route, and an increase of the metering throughput at 9th Ave southbound on-ramp.

Figure 3-5: Diversion routes applied in scenario AM2

The traffic demand loaded on the network totals 337,476 vehicles distributed in 15-minute time slices over 4 hours according to the departure profile depicted in Figure 3-8**.**

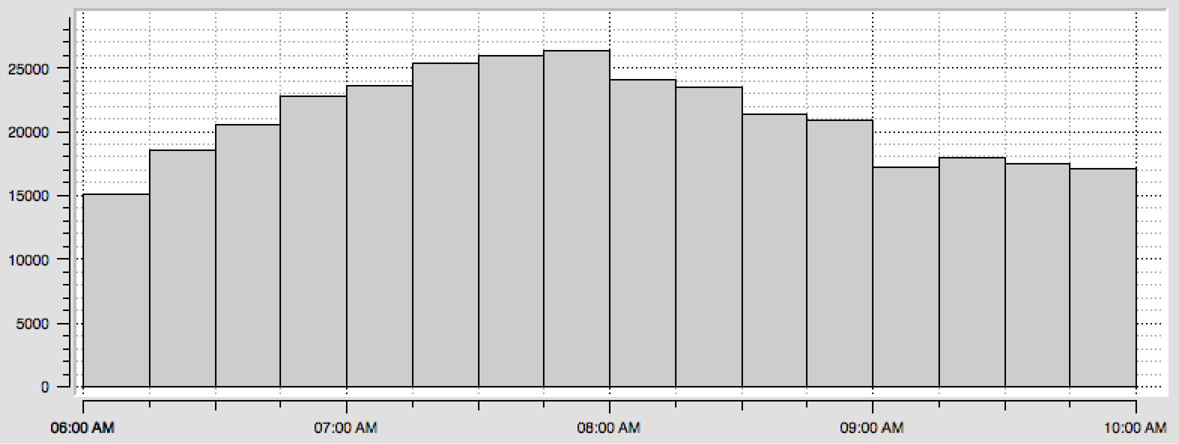

Figure 3-6: Departure time profile in scenario AM2

3.2.3 Operational Condition 3 (PM3)

The third operational condition (PM3) covers from 2 PM to 6 PM and includes a blockage from 2:30 PM to 3:56 PM on the rightmost lane of I15 downstream of the exit to Rancho Bernardo Road in the northbound direction **(**Figure 3-7**).**

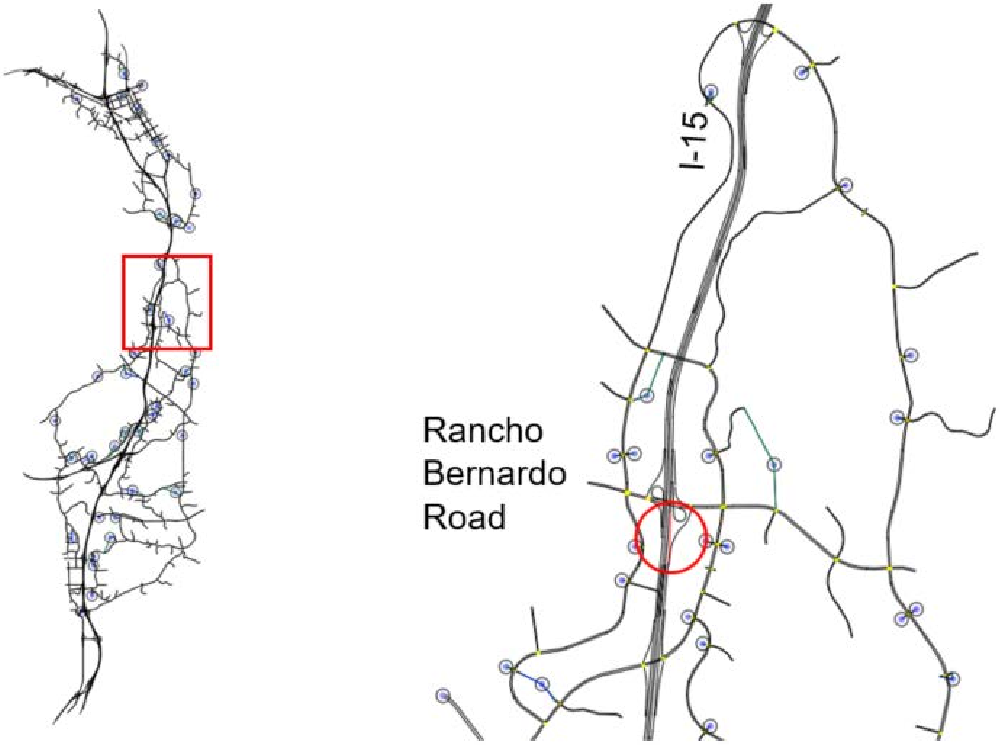

Figure 3-7: Location of the blockage event in scenario PM3

The response plan that was applied includes a diversion route triggered via VMSs **(**Figure 3-8**):** vehicles exit I-15 at Ted Williams and reenter at Pomerado Road. The rerouting is supported with a change of signal plans along the arterials to accommodate the increase of traffic along the diversion route, and an increase of the metering throughput at Pomerado Road northbound on-ramp.

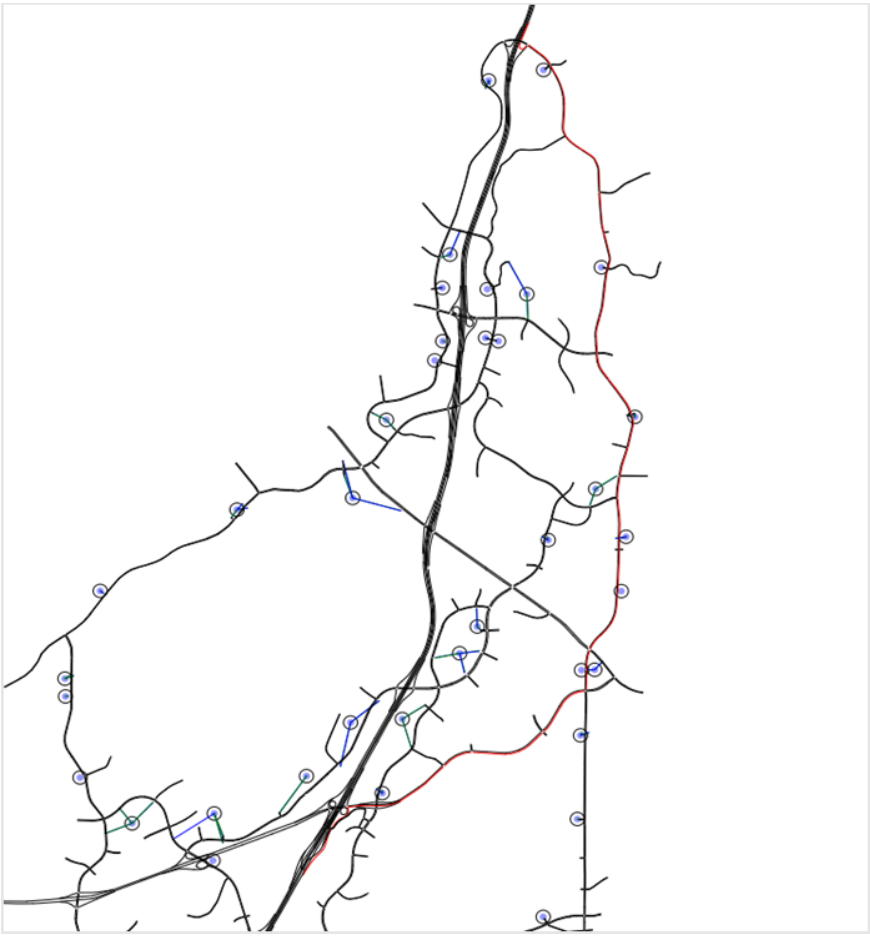

Figure 3-8: Diversion route applied in scenario PM3

The traffic demand loaded on the network totals 417,671 vehicles distributed in 15-minute time slices over 4 hours according to the departure profile depicted in Figure 3-9**.**

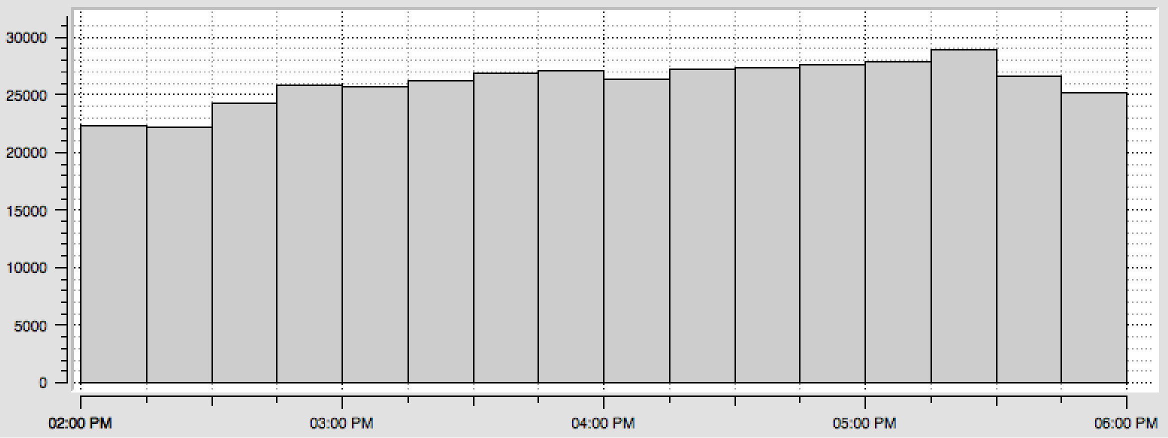

Figure 3-9: Departure time profile in scenario PM3

3.2.4 Operational Condition 4 (PM4)

The fourth operational condition (PM4) covers from 4 PM to 8 PM and includes a complete closure from 5:30 PM to 5:32 PM of the ramp going from I-15 northbound to SR-78 westbound, followed by a blockage of the rightmost lane only from 5:32 PM to 6:00 PM **(**Figure 3-10**).**

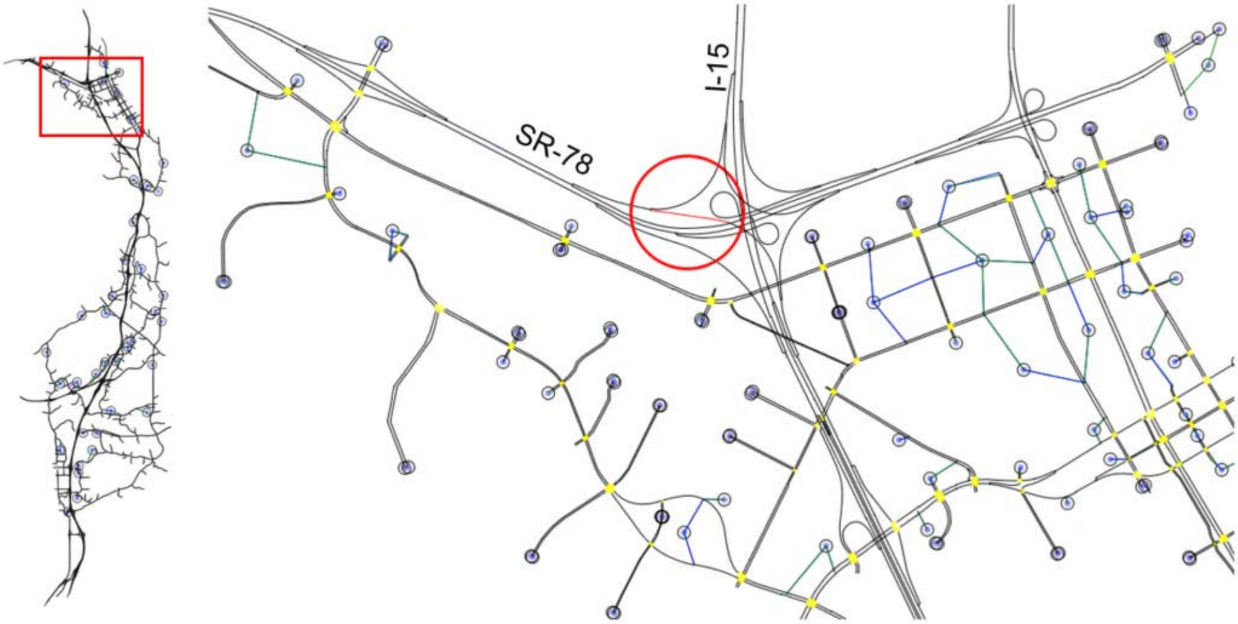

Figure 3-10: Location of the blockage event in scenario PM4

The response plan that was applied includes a diversion route for vehicles going to SR-78 westbound from I-15 northbound triggered via VMSs **(**Figure 3-11): they exit I-15 at 9th Ave and enter SR-78 at Centre City Parkway. The rerouting is supported with a change of signal plans along the arterials to accommodate the increase of traffic along the diversion route.

Figure 3-11: Diversion route applied in scenario PM4

The traffic demand loaded on the network totals 350,066 vehicles distributed in 15-minute time slices over 4 hours according to the departure profile depicted in Figure 3-12**.**

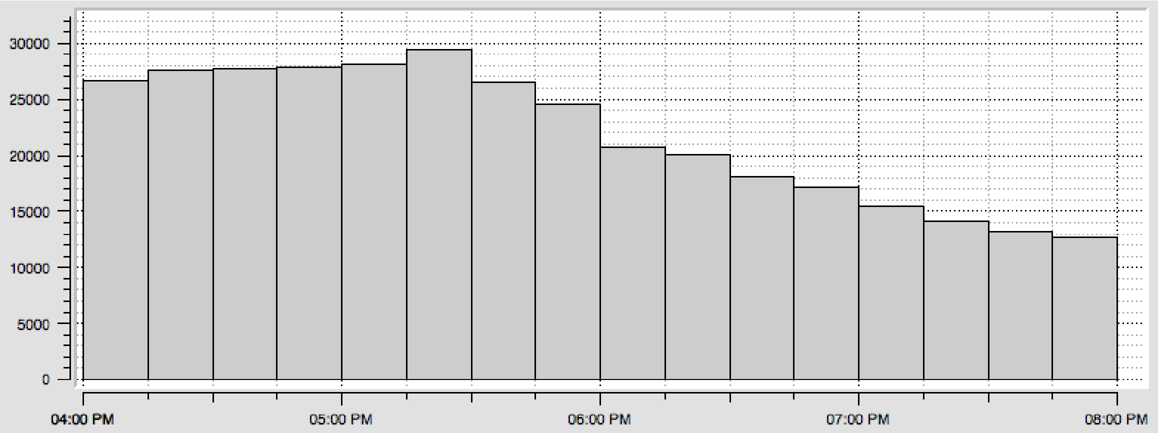

Figure 3-12: Departure time profile in scenario PM4

Chapter 4. Applications and Strategies Modeled

This chapter describes the DMA and ATDM applications that are evaluated in the San Diego Testbed.

4.1 DMA Applications

Two DMA application bundles, namely, INFLO (Intelligent Network Flow Optimization) and MMITSS (Multi-modal Intelligent Traffic Signal Systems) were originally envisioned to be integrated with the San Diego testbed. However, MMITSS application was not integrated owing to technical issues.

4.1.1 INFLO

The INFLO[3] bundle consists of three different applications:

7. **Q-WARN** provides a vehicle operator with sufficient warning of an impending queue backup, thereby minimizing the occurrence and impact of traffic queues by using CV technologies, including vehicle-to-infrastructure (V2I) and vehicle-to-vehicle (V2V) communications
8. **SPD-HARM** dynamically adjusts and coordinates vehicle speeds in order to maximize traffic throughput and reduce crashes. By reducing speed variability among vehicles, traffic throughput is improved, flow breakdown formation is delayed or even eliminated, and the number and severity of collisions are reduced
9. **CACC** dynamically and automatically coordinates cruise control speeds among platooning vehicles, coordinates in-platoon vehicle movements, and reduces drag

The three applications within the INFLO bundle[4] are cross-functional as described in Figure 4-1.

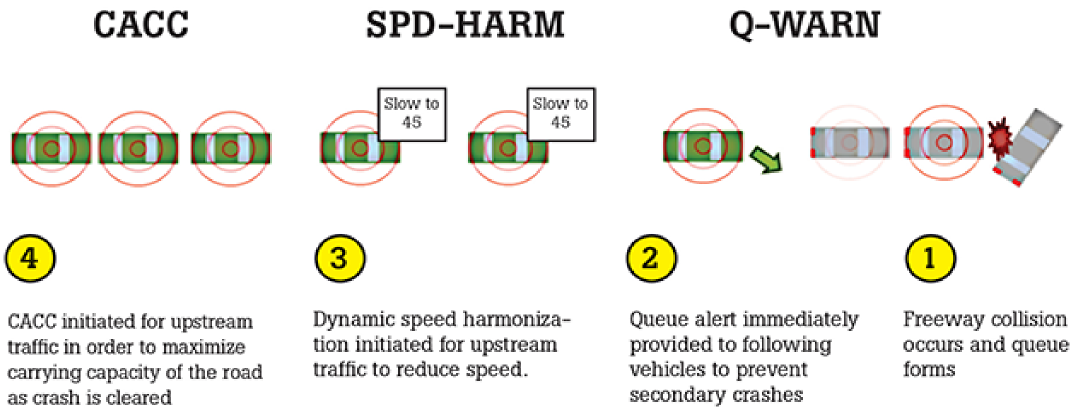

Figure 4-1: INFLO Applications Working Together [Source: TTI]

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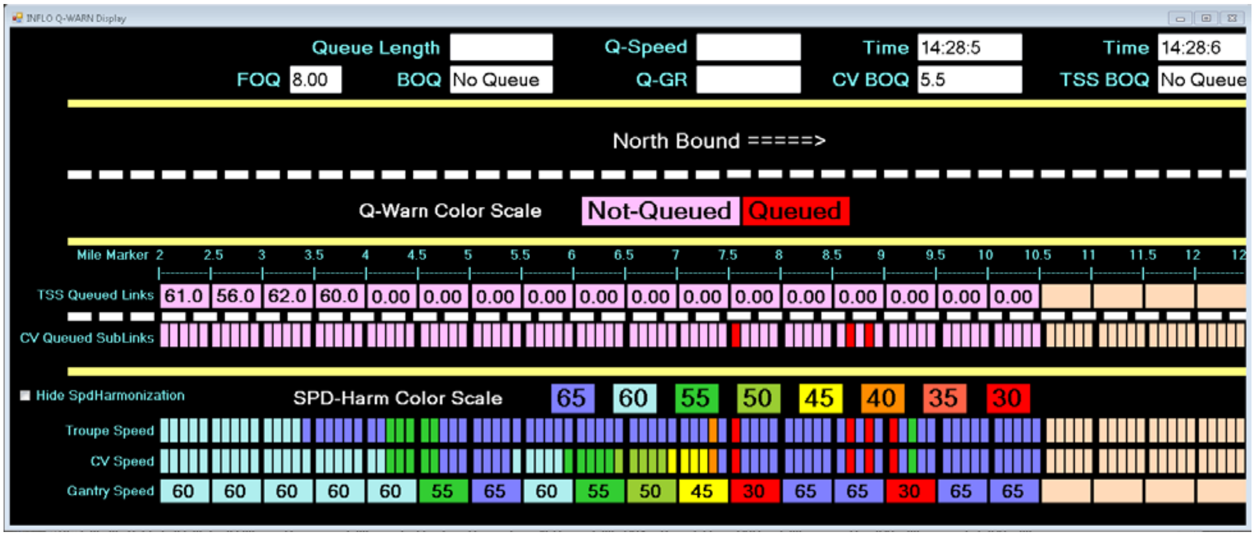
[3] Science Applications International Corporation (SAIC), Concept Development and Needs Identification for Intelligent Network Flow Optimization (INFLO), FHWA-JPO-13-012, Accessed at: http://ntl.bts.gov/lib/42000/42300/42325/FHWA-JPO-13-012_Final_Pkg_v2.pdf

[4] Battelle, Intelligent Network Flow Optimization (INFLO) Prototype: Seattle Small-scale Demonstration, FHWA-JPO-15-223, Accessed at: http://ntl.bts.gov/lib/56000/56200/56240/FHWA-JPO-15-223.pdf

Of these, SPD-HARM application was implemented as a Windows application (Figure 4-2) developed by the Texas Transportation Institute for the DMA Impacts Assessment project[5]. Details on how the application was interfaced with Aimsun are provided in Chapter 6.1.

CACC application was also implemented in Aimsun and details of the implementation are described in Chapter 6.2.



Queue Length
FOQ 8.00
BOQ No Queue
Q-Speed
Q-GR
Time 14:28:5
CV BOQ 5.5
Time 14:28:6
TSS BOQ No Queue

Mile Marker 2 2.5 3 3.5 4 4.5 5 5.5 6 6.5 7 7.5 8 8.5 9 9.5 10 10.5 11 11.5 12 12

TSS Queued Links 61.0 56.0 62.0 60.0 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00

Gantry Speed 60 60 60 60 60 55 65 60 55 50 45 30 65 65 30 65 65

Figure 4-2: Screenshot of Q-WARN and SPD-HARM Application Developed by TTI

4.1.2 MMITSS

MMITSS is a next-generation traffic signal system that seeks to provide a comprehensive traffic information framework to service all modes of transportation. Figure 4-3 shows an example of the MMITSS application framework where different entities at a signalized intersection could interact using CV technology. MMITSS consists of five different applications which all are prototyped together as a single application by the University of Arizona as a Software-in-the-Loop system.

The five applications are described below; each is implemented in a Linux-based Docker container.

1. **I-SIG** aims at maximizing the throughput of passenger vehicles and minimizing the delay of priority vehicles under saturated conditions and minimizing the total weighted delay during under-saturated conditions.
2. **TSP** allows transit agencies to manage bus service by adding the capability to grant buses priority.
3. **PED-SIG** integrates information from roadside or intersection sensors and new forms of data from pedestrian-carried mobile devices.
4. **PREEMPT** will integrate with V2V and V2I communication systems in preempting signal phases for emergency vehicles.
5. **FSP** provides signal priority near freight facilities based on current and projected freight movements.

The original analysis plan included MMITSS application to be modeled as part of the San Diego Testbed. However, several technical challenges arose during the course of integration of MMITSS into the full

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[5] Texas Transportation Institute, Report on Dynamic Speed Harmonization and Queue Warning Algorithm Design, FHWA-JPO-14-168, Accessed at: http://ntl.bts.gov/lib/54000/54800/54895/FHWA-JPO-14-168.pdf

testbed. To this end, the application was dropped from evaluation to keep the project timeline and budget intact. Details on how the application was planned to be interfaced with Aimsun simulation are provided in Chapter 6.3.

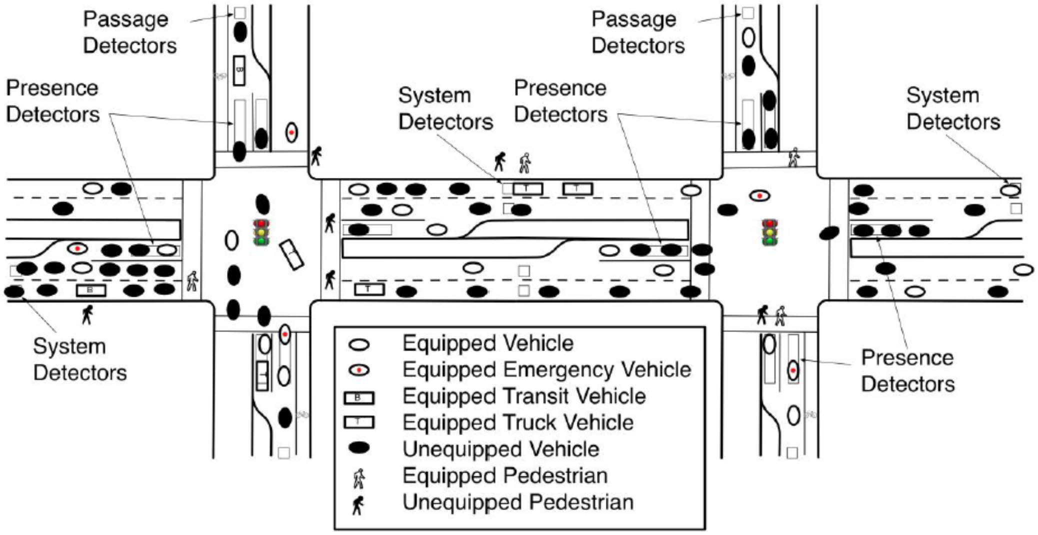

Figure 4-3: Illustration of the MMITSS Concept[6] [Source: University of Arizona]

4.2 ATDM Strategies

Six ATDM strategies are included in this evaluation:

- Dynamic Lane Use
- Dynamic Speed Limits
- Dynamic Merge Control
- Predictive Traveler Information
- Dynamic HOV/Managed Lanes
- Dynamic Routing

4.2.1 Dynamic Lane Use

This strategy involves dynamically closing or opening of individual traffic lanes as warranted and providing advance warning of the closure(s) (typically through dynamic lane control signs), in order to safely merge traffic into adjoining lanes. In an ATDM approach, as the network is continuously monitored, real-time incident and congestion data is used to control the lane use ahead of the lane closure(s) and dynamically manage the location to reduce rear-end and other secondary crashes.

Details on how this strategy was modeled in Aimsun are provided in Chapter 7.1.1.

4.2.2 Dynamic Speed Limits

This strategy adjusts speed limits based on real-time traffic, roadway, and/or weather conditions. Dynamic speed limits can either be enforceable (regulatory) speed limits or recommended speed advisories, and they can be applied to an entire roadway segment or individual lanes. In an ATDM approach, real-time

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[6] Virginia Tech Transportation Institute, Multi-Modal Intelligent, Traffic Signal Systems Impact Assessment, Accessed at: http://ntl.bts.gov/lib/55000/55700/55710/MMITSS_IA_REPORT_0811_v1.4.pdf

and anticipated traffic conditions are used to adjust the speed limits dynamically to meet an agency's goals/objectives for safety, mobility, or environmental impacts.

Details on how this strategy was modeled in Aimsun are provided in Chapter 7.1.2.

4.2.3 Dynamic Merge Control

This strategy (also known as dynamic late merge or dynamic early merge) consists of dynamically managing the entry of vehicles into merge areas with a series of advisory messages (e.g., displayed on a dynamic message sign [DMS] or lane control sign) approaching the merge point that prepare motorists for an upcoming merge and encouraging or directing a consistent merging behavior. Applied conditionally during congested (or near congested) conditions, dynamic merge control can help create or maintain safe merging gaps and reduce shockwaves upstream of merge points. In an ATDM approach, conditions on the mainline lanes and ramps approaching merge areas are continuously monitored and the dynamic merge system will be activated dynamically based on real-time and anticipated congestion conditions.

Details on how this strategy was modeled in Aimsun are provided in Chapter 7.1.3.

4.2.4 Predictive Traveler Information

This strategy involves using a combination of real-time and historical transportation data to predict upcoming travel conditions and convey that information to travelers pre-trip and en-route (such as in advance of strategic route choice locations) in an effort to influence travel behavior. In an ATDM approach, predictive traveler information is incorporated into a variety of traveler information mechanisms (e.g., multi-modal trip planning systems, 511 systems, dynamic message signs) to allow travelers to make better informed choices.

Details on how this strategy was modeled in Aimsun are provided in Chapter 7.2.1.

4.2.5 Dynamic HOV/Managed Lanes

This strategy involves dynamically changing the qualifications for driving in a high-occupancy vehicle (HOV) lane(s). HOV lanes (also known as carpool lanes or diamond lanes) are restricted traffic lanes reserved at peak travel times or longer for exclusive use of vehicles with a driver and one or more passengers, including carpools, vanpools and transit buses. The normal minimum occupancy level is 2 or 3 occupants. Many agencies exempt other vehicles, including motorcycles, charter buses, emergency and law enforcement vehicles, low emission vehicles, and/or single-occupancy vehicles paying a toll. In an ATDM approach, the HOV lane qualifications are dynamically changed based on real-time or anticipated conditions on both the HOV and general purpose lanes. Qualifications that can potentially be dynamically adjusted include the number of occupants (e.g., from 2 to 3 occupants), the hours of operation, and the exemptions (e.g., change from typical HOV operation to buses only). Alternatively, the HOV restrictions could be dynamically removed allowing general use of the previously managed lane.

Details on how this strategy was modeled in Aimsun are provided in Chapter 7.2.2.

4.2.6 Dynamic Routing

This strategy uses variable destination messaging to disseminate information to make better use of roadway capacity by directing motorists to less congested facilities. These messages could be posted on dynamic message signs in advance of major routing decisions. In an ATDM approach, real-time and anticipated conditions can be used to provide route guidance and distribute the traffic spatially to improve overall system performance.

Details on how this strategy was modeled in Aimsun are provided in Chapter 7.2.3.

4.3 Performance Measures

The performance measures quantify the achievement of DMA/ATDM program objectives in the following categories:

- Overall performance measures
- DMA-Specific
- ATDM-Specific

4.3.1 Overall Performance Measures

Several performance measures have been identified to evaluate the DMA and ATDM applications under this project. The overall performance measures are assessed over the entire network (i.e. including arterials) and can be used to summarize the impact of the application/strategy on the overall mobility of the corridor. The overall performance measures considered are:

1. **Vehicle Miles Travelled (VMT):** The total distance travelled by all vehicles in the simulation.

2. **Total Vehicle Travel Time**: The total travel time experienced by all vehicles in the simulation. It is equivalent to Vehicle Hours Traveled (VHT).

3. **Total Passenger Travel Time:** The total travel time experienced by passengers on board of all vehicles in the simulation. For each vehicle, the passenger travel time is computed from the vehicle travel time by assuming the average passenger occupancy of different vehicle types at: 1.0 for SOVs, 2.3 for HOVs, 1.5 for trucks and 25 for buses.

4. **Harmonic Average Speed (VMT/VHT):** The ratio between Vehicle Miles Travelled and Total Vehicle Travel Time. It is equal to the harmonic average speed of all vehicles in the simulation.

Additionally, for each simulation a speed contour plot showing the measured speed at 15 minute intervals along the different segments of the general-purpose lanes of I-15 was produced and compared with the baseline case. This allows a visual assessment of the locations with congestion, how far the congestion propagates and how long it lasts. The plot is produced only for the peak direction in each Operational Condition (southbound for AM1 and AM2, northbound for PM3 and PM4).

4.3.2 DMA-Specific

While overall performance measures are valued across the different applications/strategies, additional performance measures are defined to evaluate the Q-WARN and SPD-HARM bundle of applications part of INFLO. These additional performance measures, which are consistent with the impacts assessment performed by Kittelson and Associates[7] and with the other testbeds for DMA evaluation, are defined as follows:

1. **95th Percentile Spatial Speed Drop:** Shockwaves were quantified by calculating the speed difference between adjacent 0.1mi segments for each 20s time period, and taking the 95th percentile throughout the simulation:

   $$W_{(\mathrm{i},\mathrm{i}+1,h)} = Max[0,(V_{(i,t,n)} - V_{(i+1,t,n)})]_{t\in h,n\in N}$$

   where:

   - *i* is the segment

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[7] Kittelson and Associates, Impacts Assessment of Dynamic Speed Harmonization with Queue Warning Accessed at: http://ntl.bts.gov/lib/55000/55300/55307/Impact_Assesment_Report_Final_2015.pdf

    - *t* is the time period

2. **95th Percentile Temporal Speed Drop**: Shockwaves were also quantified by calculating the speed difference between consecutive 20s time periods for the each 0.1mi segment, and taking the 95th percentile throughout the simulation:

   $$W_{(\mathrm{i},h)} = Max[0,(V_{(i,t,n)} - V_{(i,t+1,n)})]_{t \in h, n \in N}$$

   where:

    - *i* is the segment
    - *t* is the time period

The DMA-specific performance measures were assessed only along the I-15 corridor in the direction in which the application is implemented (southbound for Operational Condition 1 and 2, and northbound for Operational Condition 3 and 4) by post-processing the log file[8] produced by the Q-WARN and SPD-HARM bundle of applications.

4.3.3 ATDM-Specific

The different options evaluated with Predictive Traveler Information are compared based on a specific performance measure:

1. **Average Delay Time Around the Incident:** Average delay time experienced by vehicles travelling within 5 miles upstream and downstream of the location of the incident.

The Predictive Traveler Information framework runs multiple simulations with different rerouting options (for Predictive Traveler Information with Dynamic Routing) or with different ATDM strategies (for Predictive Traveler Information with ATDM strategies) in parallel, calculates this indicator for each run, and selects the one that produces the minimum delay around the incident location. In other words, this indicator has only been used to select the best strategy, and not to assess the overall performance of the strategy, for which the measures defined in Section 4.3.1 were used.

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[8] The speed for segment *i* at time *t* is read from the CVAvgSpd field in the CVDataProcessor log file, which provides the average speed of connected vehicles.

Chapter 5. Research Questions and Hypotheses

The San Diego Testbed analysis focused on the DMA and ATDM applications evaluation. This chapter details the analysis hypotheses to address the research questions for the San Diego Testbed.

5.1 DMA Research Questions

The DMA applications analyzed and evaluated using the San Diego testbed are discussed in Chapter 4. Table 5-1 presents the DMA research questions and associated hypotheses. Twelve DMA-related research questions are answered through the San Diego evaluation.

Table 5-1: DMA Research Questions and Corresponding Hypotheses

ID	DMA Research Question	Preliminary Hypothesis
II	**Synergies and Conflicts**	
2	Are the DMA applications and bundles more beneficial when implemented in isolation or in combination?	DMA bundles that are synergistic will be more beneficial when implemented in combination than in isolation.
3	What DMA applications, bundles, or combinations of bundles complement or conflict with each other?	Certain DMA applications, bundles, or combinations of bundles will complement each other resulting in increased benefits, while others will conflict with each other resulting in no benefits or reduced benefits.
III	**Operational Conditions with Most Benefit**	
7	Under what operational conditions are specific DMA applications the most beneficial?	A DMA application will yield the highest benefits only under certain operational conditions. For example, on non-incident days, SPD-HARM will have limited impact.
VI	**Communications Latency and Errors**	
16	What are the impacts of communication latency on benefits?	Applications such as CACC rely on low-latency communication, whereas application such as SPD-HARM could work with higher-than-one-second latency.
17	How effective are the DMA bundles when there are errors or loss in communication?	The effectiveness of DMA bundles will be reduced by errors and loss in communication.
VIII	**Prediction and Active Management**	
20	Can new applications that yield transformative benefits be deployed without a commensurate investment in prediction and active management (reduced control latency)? How cost-effective are DMA bundles when coupled with prediction and active management?	DMA bundles (Queue Warning and Speed Harmonization) will be most cost-effective only when coupled with prediction and active management.
IX	**Deployment Readiness**	

ID	DMA Research Question	Preliminary Hypothesis
22	At what levels of market penetration of connected vehicle technology do the DMA bundles (collectively or independently) become effective?	As market penetration increases, the applications will perform better, but it is anticipated that 50 percent market penetration will provide most of the benefits, beyond which the increase in benefits will taper off.
23	What are the impacts of future deployments of the DMA bundles in the near, mid, and long term (varying market penetration, RSE deployment density, and other connected vehicle assumptions)?	Bundles that influence tactical driver decision-making and depend on emerging localized low-latency messaging concepts, e.g., MMITSS, Q-WARN and SPD-HARM, will yield measureable localized benefits under near-term deployment assumptions, but limited system-level impacts until market penetration of connected vehicle technology reaches bundle-specific thresholds.
X	**Policy**	
29	What are the benefits to participants versus non-participants?	Applications such as MMITSS will yield more benefits for participants whereas applications such as INFLO will benefit both participants and non-participants

5.2 ATDM Research Questions

The ATDM strategies analyzed and evaluated using the San Diego testbed are discussed in Chapter 4. Table 5-2 presents the ATDM research questions and the corresponding hypotheses. Eight ATDM-related research questions are answered using the San Diego Evaluation.

Table 5-2: ATDM Research Questions and Corresponding Hypotheses

ID	ATDM Research Question	Preliminary Hypothesis
I	**Synergies and Conflicts**	
1	Are ATDM strategies more beneficial when implemented in isolation or in combination (e.g., combinations of ATM, ADM, or APM strategies)?	ATDM strategies that are synergistic (e.g., ADM, APM, ATM) will be more beneficial when implemented in combination than in isolation.
3	What ATDM strategies or combinations of strategies conflict with each other?	Certain ATDM strategies will conflict with each other, resulting in no benefits or reduced benefits.
II	**Prediction Accuracy**	
4	Which ATDM strategy or combination of strategies will benefit the most through increased prediction accuracy and under what operational conditions?	Improvements in prediction accuracy will yield higher benefits for certain ATDM strategies and combinations of strategies than for others. An ATDM strategy or combinations of strategies will yield the most benefits with improvements in prediction accuracy only under certain operational conditions.
5	Are all forms of prediction equally valuable, i.e., which attributes of prediction quality are critical (e.g., length of prediction horizon, prediction accuracy, prediction speed, and geographic	Increased prediction accuracy is more critical for certain ATDM strategies over others, with certain attributes (e.g., length of prediction horizon, prediction accuracy, prediction speed,

ID	ATDM Research Question	Preliminary Hypothesis
	area covered by prediction) for each ATDM strategy?	and geographic area covered by prediction) of prediction quality being most critical.
IV	**Operational Conditions with Most Benefit**	
8	Which ATDM strategy or combinations of strategies will be most beneficial for certain modes and under what operational conditions?	Certain ATDM strategies and combinations of strategies will yield the highest benefits under certain operational conditions.

Chapter 6. DMA Application Modeling Details

This chapter describes how DMA applications have been interfaced with Aimsun to be evaluated in the San Diego Testbed.

6.1 INFLO Speed Harmonization (SPD-HARM)

SPD-HARM was applied along the whole I-15 corridor, in the peak direction (southbound for AM1 and AM2, northbound for PM3 and PM4), and only on the general-purpose lanes.

The application was implemented as a Windows application developed by the Texas Transportation Institute. The original application was interfaced with the Vissim traffic simulator as part of the assessment of the impacts of the Speed Harmonization and Queue Warning on the US 101 freeway corridor in San Mateo[9] and in the DMA evaluation in the San Mateo Testbed[10]; this implementation is available in the USDOT Open Source Portal (OSADP) portal as INFLO-SIM. A similar implementation was made for the San Diego Testbed.

The project team implemented this application bundle using the API functionality of Aimsun. The high-level logic of the interface with the INFLO application is shown in Figure 6-1. This interface performs the following tasks every 20s of simulated time:

- It pauses the traffic simulation.
- It reads the speed, volume and occupancy aggregated over the last 20s for all detection stations in the corridor and writes them into the TME_TSSData_Input table of the INFLO database.
- It reads the current location and instantaneous speed of all connected vehicles and writes them into the TME_CVData_Input table of the INFLO database.
- It notifies the INFLO applications that a new set of data is available by writing a synch file.
- It waits for eight seconds for INFLO do perform its computations.
- It reads from the TMEOutput_SPDHARMMessage_CV table the speed to assign to connected vehicles in each 0.1mi sublink.
- It applies these speeds using the Speed Change traffic management action.

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[9] Kittelson and Associates, Impacts Assessment of Dynamic Speed Harmonization with Queue Warning Accessed at: http://ntl.bts.gov/lib/55000/55300/55307/Impact_Assesment_Report_Final_2015.pdf

[10] Booz Allen Hamilton, Analysis, Modeling and Simulation (AMS) Testbed Development and Evaluation to Support Dynamic Mobility Applications (DMA) and Active Transportation and Demand Management (ATDM) Programs: DMA Evaluation Report, USDOT Document FHWA-JPO-16-383, August 2017.

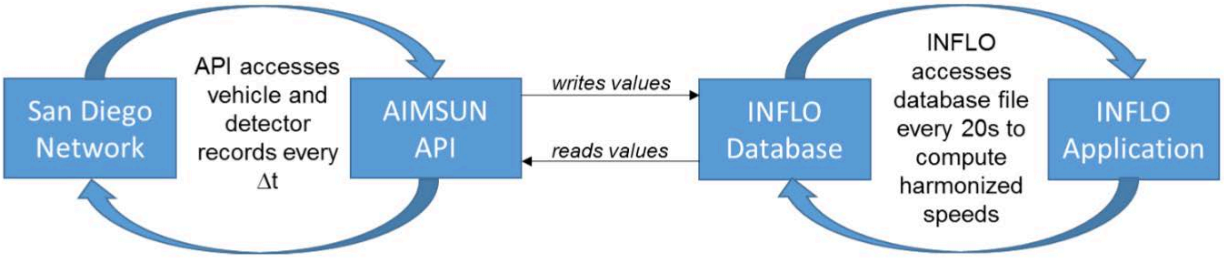

Figure 6-1: Interface between INFLO and Aimsun

It should be noted that we modeled Q-WARN purely as 100% compliance of the connected vehicles to SPD-HARM speed advisories. This is in line with what was done in the San Mateo assessment[11]. The interface allows optionally to introduce latency and packet loss in the communication between the connected vehicles and the INFLO application; details on how these communication issues are modelled are provided in 6.4.

6.2 INFLO Cooperative Adaptive Cruise Control (CACC)

The project team implemented the INFLO CACC algorithm in Aimsun for the San Diego testbed. An adaptation to Aimsun of the CACC application available in the USDOT Open Source Portal (OSADP) as CACC-VISSIM was utilized for this purpose. The CACC algorithm is based on the report "Design and evaluation of an Integrated Full-Range Speed Assistant", prepared by TNO in 2007[12].

As per the algorithm, the CACC is only applied to vehicles that meet the following conditions:

- It's a CACC vehicle
- It's not in an on-ramp lane
- It's not trying to reach a valid lane in its path (e.g. moving towards an exit ramp)
- It's in a reserved lane for CACC vehicles

CACC modifies the car-following and lane-changing behavior of the vehicle; CACC vehicles not meeting the conditions above apply the default Aimsun Car-Following and Lane-Changing models. Reserved CACC lanes were created along the general-purpose section of I-15 in the peak direction (southbound for AM1 and AM2, northbound for PM3 and PM4).

6.2.1 Car-Following Logic

The TNO's report presents three different Car-Following implementations. All of them have been implemented in Aimsun and the user can select which one to use.

- CACC considers a single predecessor to compute the acceleration to apply

$$a_d = k_3 a + k_2 e_v + k_1 e_x, \quad k_1, k_2, k_3 > 0.$$

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[11] "The compliance of the connected vehicles with SPD-HARM speed advisories was assumed to be 100%. Q-WARN advisories were assumed to have no effect on driver behavior. (These advisories are not intended to affect tactical behavior. The advisories are not lane specific and are intended to come long before the driver sees the actual queue.)" at page 109 in Kittelson and Associates, Impacts Assessment of Dynamic Speed Harmonization with Queue Warning Accessed at: http://ntl.bts.gov/lib/55000/55300/55307/Impact_Assesment_Report_Final_2015.pdf

[12] Bart van Arem et al., Design and evaluation of an Integrated Full-Range Speed Assistant, Accessed at http://publications.tno.nl/publication/34623299/0wxA9h/D-R0280-B.pdf

- CACC1 computes the acceleration considering that of N preceding vehicles and applies the minimum value

$$a_{d,n} = \min(a_{d,n,n-1}, \ldots, a_{d,n,1})$$

- CACC2 computes the acceleration based on the speed and space difference with respect to the immediate preceding vehicle and the speed difference with respect to the preceding N vehicles

$$a_{d,n} = (k_2 e_{v,n-1} + k_1 e_{x,n-1}) + \left(\frac{k_2}{n-2} \sum_{i=1}^{n-2} e_{v,i} \right)$$

The resulting acceleration is converted into a speed that the Aimsun vehicle will apply for the next simulation step, provided it doesn't exceed the Maximum Desired Speed of the vehicle (which is equal to the speed limit of the road section multiplied by the speed acceptance factor of the vehicle, which represents the compliance of each vehicle to the speed limit).

Neither of the algorithms sets a limit to the platoon size: a platoon ends when the following vehicle is non-connected, or disengages CACC in preparation to leaving the reserved lanes to take an off-ramp.

The third algorithm (CACC2) was selected for this testbed since it was described to be the best performing in terms of headway.

The gain coefficients k_1 and k_2 were set to 0.1 and 0.58, respectively; the number of preceding vehicles taken into account was set to 5 within a maximum distance of 100 m, and the target headway was set to 5 m. Preliminary tests showed that this combination of values produced stable platoons.

When CACC is activated, the vehicle is forced to comply strictly with the speed limit, and its reaction time at stop (the longer reaction time applied when the vehicle reaches a stopped condition) is reduced to be equal to the reaction time (0.85 s), to remove the effect of distraction and imperfect perception of the movement of the leader.

6.2.2 Lane-Changing Logic

The TNO's report does not provide any Lane-Changing logic. The team added the following lane changing logic to promote the formation of platoons:

- If the leader is a CACC vehicle, the CACC vehicle will stay in the leader's lane unless it's forced to move to another lane to make the next turn in its path (e.g., to take a freeway exit).
- If the leader is not a CACC vehicle, the CACC vehicle will look on the adjacent reserved lanes to the left and to the right for a potential CACC vehicle leader. If found, the CACC vehicle will try to change to the potential leader's lane, waiting for a suitable gap.

Preliminary tests with different reserved lane configurations and different penetration rates showed that this lane-changing logic was beneficial only with low penetration rates (<25%). With low penetration rates, the probability for a connected vehicle to have already as leader another connected vehicle is limited, therefore it should be forced to change lane to find a suitable leader and engage CACC. When the penetration rate increases, this logic tends to promote the formation of long platoons in a single lane, rather than achieving an optimal distribution among the lanes, thus creating artificial bottlenecks.

Since the modeled scenarios covered penetration rates of 25%, 50% and 90%, the lane-changing logic to promote the formation of platoons was disabled in all simulations. However, there is still a mechanism to consolidate CACC vehicles, as along I-15 they are forced to use one of the reserved lanes (the two leftmost lanes with 25% penetration and the three leftmost lanes with 50% and 90% penetration).

Another situation in which a CACC vehicle must change lanes is when it must move to the rightmost lane to take an exit. When the vehicle enters Zone 2 for the exit turn[13], we disable CACC car-following, and the vehicle starts applying the default Aimsun Car-Following and Lane-Changing models. We conducted initial tests in which we postponed the CACC deactivation to Zone 3, closer to the exit turn, but the exiting CACC vehicle reacted too abruptly, causing a speed drop for the whole CACC platoon.

6.2.3 CACC Lane Configurations

The project team conducted a sensitivity analysis to evaluate the optimal number of lanes to open for CACC operations under different penetration rates.

The tests consisted of running the AM2 cluster scenario with different CACC penetration rates and different lane configurations on I-15 (keeping in mind there are five general purpose lanes):

- CACC vehicles must use the leftmost lane.
- CACC vehicles must use one of the two leftmost lanes.
- CACC vehicles must use one of the three leftmost lanes.

The highest penetration rate (90%) was not considered in this analysis, because since almost all traffic consists of CACC, CACC operations should be allowed on all available lanes. In all cases, the usage of the CACC lanes is not exclusive to CACC vehicles, but allowed also to non-CACC vehicles (which have access to any of the lanes). We compared the throughput by lane at a location in which the lane selection is stable, i.e. far enough from entrances or exits (Table 6-1).

Table 6-1: Throughput comparison with different penetration rates and lane configurations for CACC

	Total	CACC Vehicles	Non CACC Vehicles
10%, 1 lane	5,880	354	5,526
10%, 2 lanes	5,994	418	5,576
10%, 3 lanes	5,904	428	5,476
25%, 2 lanes	5,852	971	4,881
25%, 3 lanes	6,648	1,071	5,577
50%, 2 lanes	6,211	1,466	4,745
50%, 3 lanes	6,430	1,726	4,704
Reference (AM2)	5,608	-	5,608

The analysis produced the following recommendations:

- With a single lane for CACC vehicles, a CACC vehicle may have a leader that is a non-CACC vehicle, and would not be able to overtake it (as it's not allowed to leave the CACC reserved lane). In other words, with a single lane the probability of forming a CACC platoon or not doesn't

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[13] Every turn has three different user-defined areas of influence:
- Zone 1: the turn doesn't affect lane selection, a lane-change is motivated only by overtaking.
- Zone 2: this is a transitional situation in which vehicles that have to change lane in order to make a turn either try to get into the desired lane if there is a gap adjacent to them or they can keep moving and use a gap downstream.
- Zone 3: the vehicle now urgently needs to join a lane that allows it to follow its path, waiting for gaps upstream and reducing speed if necessary, even coming to a complete stop while waiting for a suitable gap.

depend on the CACC logic, but purely on the density of non-CACC vehicles in the CACC reserved lane (which depends on the demand).

- With two lanes for CACC vehicles, a CACC vehicle following a non-CACC vehicle would look for a CACC leader to follow in the adjacent lanes and change lane if found. This increases the probability of forming platoons of closely-spaced vehicles and hence the throughput.
- With more than two lanes for CACC vehicles (or, more in general, when the number of CACC lanes becomes close to the total number of lanes) platoons are easier to form, but they become more dispersed, and may even make more difficult for non-CACC vehicles to change lane and overtake, hence the benefit in terms of throughput is achieved only with higher penetration rates.

These led to the following lane configurations adopted for the traffic simulations:

- With 25% penetration rate, CACC vehicles must use the three leftmost lanes.
- With 50% penetration rate, CACC vehicles must use the three leftmost lanes.
- With 90% penetration rate, CACC vehicles have access to all five lanes.

6.3 Multi-Modal Intelligent Traffic Signal System

The MMITSS system is a software in the loop system (SILS) that interfaces with NTCIP-compliant signal controllers. To interface with a traffic simulator, the traffic simulator must integrate either a full NTCIP compliant signal controller emulator interfaced with the simulator (like the Econolite ASC/3) or a wrapper for the simple signal controller integrated in the simulator. Since the first option was not available with Aimsun, nor was it obtainable in the project timeline, the second option was selected.

The system needs to acquire both vehicle data and infrastructure data.

The project team implemented via API an interface between Aimsun and the MMITSS system that performs the following every simulation step:

- Read the state of all connected vehicles approaching the intersection, generate Basic Safety Message (BSM) packets and send them to MMITSS.
- Read the state of the current phase and detector data and send them to MMITSS.
- Read from MMITSS any command (hold, force-off, omit or call) and implement it in the simulated controller.

However, the project team was able to successfully install MMITSS on a local computer. The MMITSS system runs inside a software container, called Docker, that is hosted in a Linux machine. However, the project team was not able to establish a network communication with MMITSS from outside of the Docker, which was required to interface with Aimsun. Consequently, this bundle of DMA applications was not evaluated as a part of the San Diego Testbed.

6.4 Trajectory Conversion Algorithm

The Trajectory Conversion Algorithm (TCA) tool is aimed at generating, from a traffic simulation, standard messages broadcasted by connected vehicles, such as Probe Data Messages (PDMs), Basic Safety Messages (BSMs), ITS Spot messages, and/or European Cooperative Awareness Messages (CAMs). The tool produces a log file with the content of these message as well as their transmission and reception time (considering latency) for the messages that have not been dropped (considering packet loss).

The project team implemented in Aimsun using the API functionality an interface for the TCA tool like the one already available in the in the USDOT Open Source Portal (OSADP) for Vissim and Paramics. The San Diego Testbed Analysis Plan envisioned the use of the TCA tool to test the impact of latency and packet loss on Q-WARN and SPD-HARM. However, this usage would require changes for the tool, as it does not send out the messages while the simulation is running and it does not interface with the INFLO application.

For this reason, we decided to model latency and packet loss by directly modifying the database communication process between Aimsun and the INFLO application. Specifically, in the Aimsun API interface with the INFLO application:

- Latency has been implemented as follows:
    - From Aimsun to INFLO, no latency is possible as INFLO waits for Aimsun to write the synch file before trying to process the data, and Aimsun waits for INFLO to finish the computations before resuming the traffic simulation.
    - From INFLO to Aimsun, as a delay in assigning the calculated speed to connected vehicles.
- Packet loss has been implemented as follows:
    - From Aimsun to INFLO, by skipping some records when writing into the database the current speed of connected vehicles.
    - From INFLO to Aimsun, by making some connected vehicles not comply with the speed calculated by SPD-HARM.

Chapter 7. ATDM Strategy Modeling Details

This chapter describes how ATDM strategies have been implemented in Aimsun to be evaluated in the San Diego Testbed.

7.1 Active Traffic Management Strategies

The three ATM strategies implemented in the San Diego testbed are Dynamic Lane Use, Dynamic Speed Limits and Dynamic Merge Control.

7.1.1 Dynamic Lane Use

This strategy involves dynamically closing or opening of individual traffic lanes as warranted and providing advance warning of the closure(s) (typically through dynamic lane control signs), in order to safely merge traffic into adjoining lanes.

The I-15 corridor doesn’t have additional general-purpose lanes to open to traffic if needed, however it features a total of four express lanes with a movable barrier, which normally operate in a 2 northbound and 2 southbound lane configuration. The Changeable Express Lane System (CELS) allows modifying the lane configuration to 1 northbound and 3 southbound or 3 northbound and 1 southbound lanes. Therefore, the project team decided to model this ATM strategy by altering the configuration of the express lanes, which strictly speaking is Dynamic Lane Reversal.

This was implemented in Aimsun using the Traffic Management functionality. A change from the standard 2 northbound and 2 southbound lane configuration to 1 northbound and 3 southbound lanes for Operational Conditions 1 and 2 (AM) or 3 northbound and 1 southbound lanes for Operational Conditions 3 and 4 (PM) is performed using this system. The configuration is generally activated throughout the simulation and is generally coupled with Dynamic HOV/Managed Lanes to promote the usage of the additional HOT lane.

7.1.2 Dynamic Speed Limits

This strategy adjusts speed limits based on real-time traffic, roadway, and/or weather conditions. Dynamic speed limits can either be enforceable (regulatory) speed limits or recommended speed advisories, and they can be applied to an entire roadway segment or individual lanes. This was implemented in Aimsun using the variable speed limit algorithm ACISA-1 (Algorismes de Control I Senyalització Automàtics – 1) designed by ACISA (Aeronaval de Construcciones e Instalaciones) in 2009 for the C-31 and C-32 motorways accessing Barcelona.

The corridor (I-15 mainline) is divided into segments, where each segment is defined as the stretch between an entrance ramp and the next exit ramp, or between an exit ramp and the next entrance ramp.

The logic to set the speed of each segment is the following:

- Every 5 minutes, starting from the last segment downstream, calculate an average of the speed measured by all the active detectors on top of sections belonging to the segment, weighted with the count; then round up to the closest multiple of 5 mph.

- Apply the segment a speed limit equal to the minimum between the average speed as computed above and average speed of the segment immediately downstream plus 5 mph. If the value is greater or equal to the general speed limit, do not apply any variable speed limit.

The rounding by excess ensures that the logic doesn't produce any wind-down effect, in which a speed limit is applied, then because vehicles are complying with it and possibly driving a bit slower, a lower speed gets calculated for the next time interval with no reason.

7.1.3 Dynamic Merge Control

This strategy (also known as dynamic late merge or dynamic early merge) consists of dynamically managing the entry of vehicles into merge areas with a series of advisory messages (e.g., displayed on a dynamic message sign [DMS] or lane control sign) approaching the merge point that prepare motorists for an upcoming merge and encouraging or directing a consistent merging behavior. Applied conditionally during congested (or near congested) conditions, dynamic merge control can help create or maintain safe merging gaps and reduce shockwaves upstream of merge points. The San Diego Association of Governments (SANDAG) has identified a single location where the Dynamic Merge Control could potentially be deployed: the entrance of SR-78 into I-15.

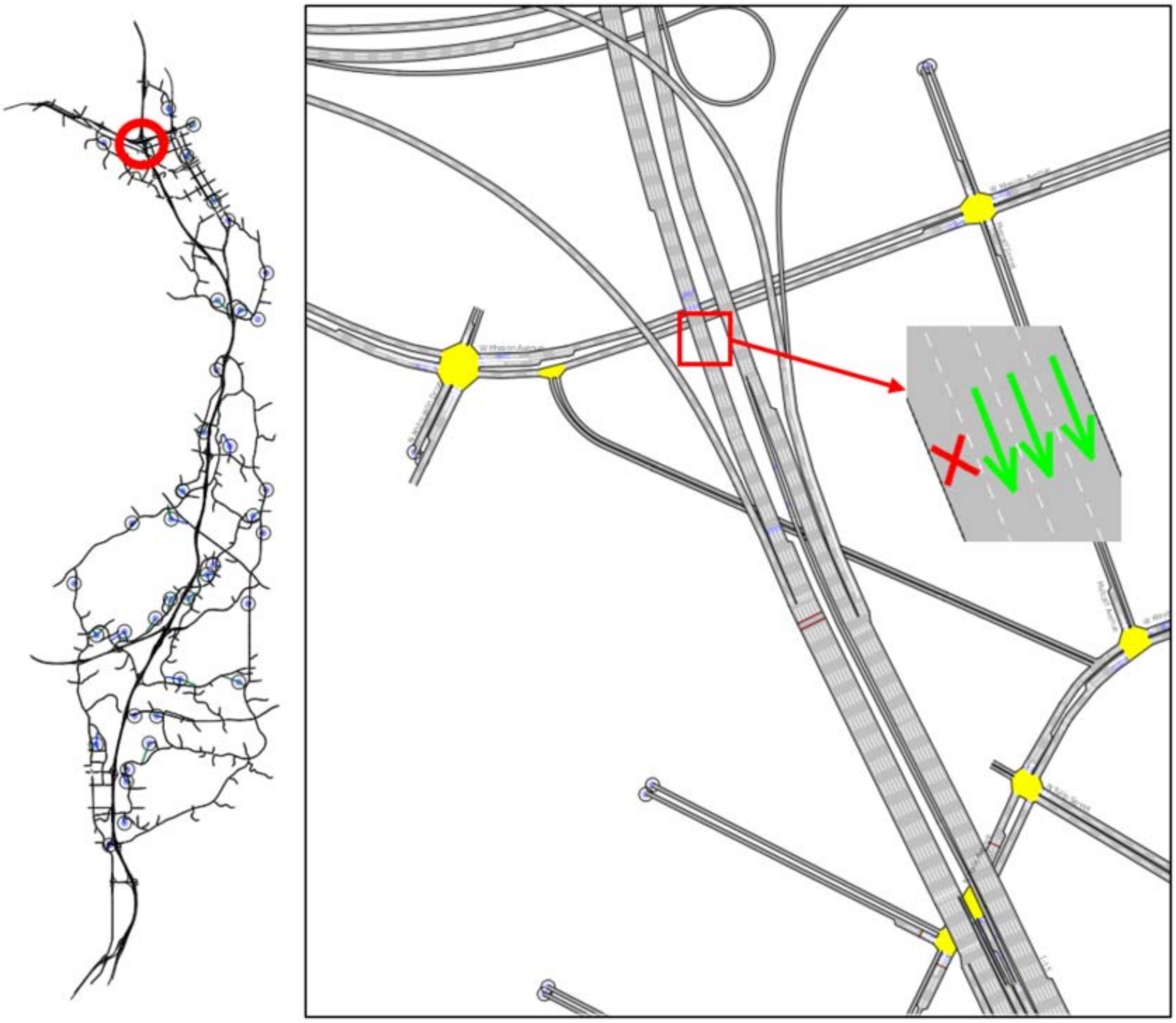

Figure 7-1: Location of Dynamic Merge Control

This was implemented in Aimsun using the Traffic Management functionality. The activation of a closure of the rightmost lane on I-15 upstream of the entrance is triggered when the occupancy of the ramp from SR-78 exceeds 80% and turned off when the occupancy goes below 80%. Sensitivity tests were performed to find a triggering density value that best balanced between the need of facilitating the merge from SR-78 and, at the same time, not penalizing excessively the traffic coming from I-15, which is always close to capacity during the AM peak period; 80% occupancy was found to be a good indicator for spikes of demand coming from SR-78, which can potentially create a queue spillback on SR-78 itself.

Since only one location has been identified, and it is in the southbound direction, this strategy has been tested only under the first two Operational Conditions.

7.2 Active Demand Management Strategies

The three ADM strategies implemented and evaluated in the San Diego Testbed are Predictive Traveler Information, Dynamic HOV/Managed Lanes and Dynamic Routing strategies. Their modeling approach is provided below.

7.2.1 Predictive Traveler Information

This strategy involves using a combination of real-time and historical transportation data to predict upcoming travel conditions and convey that information to travelers before and during their trips to influence travel behavior. The I-15 corridor features an Integrated Corridor Management (ICM) application that constantly produces predicted travel time information and provides a simulation-based Decision Support System (DSS) to evaluate the best response plans to apply when an unexpected incident occurs.

The project team implemented a testing framework that consists in having an off-line version of the I-15 ICM Aimsun Online system connected to a virtual reality simulation instead of a real-time detection data feed (Figure 7-2).

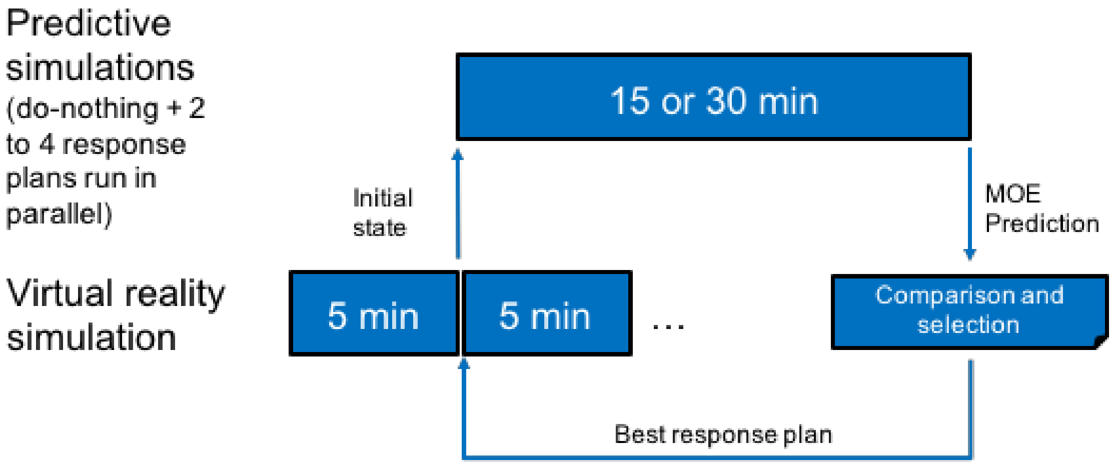

Figure 7-2: Testing framework for the Predictive Traveler Information strategy

Starting from 10 or 25 min before the incident occurring in each scenario, the virtual reality simulation pauses every 5 minutes and sends the current simulation state to the Aimsun Online instance. The Aimsun Online instance performs a simulation-based prediction, at 15 or 30 min, for alternative options: do-nothing and a fixed set of response plans (whose number and specification depends on the scenario).

At the end of this parallel simulation runs, the Aimsun Online instance reads the delay time within 5 miles upstream and downstream of the incident, and picks the response plan that produces the lowest result (or the do-nothing). The virtual reality simulation applies this response plan and advances for other 5 min, when it repeats the process described above.

A comparison with the architecture of the real I-15 ICM system shows two simplifications:

- In the real system, the data taken from reality are real-time counts, while in this testing framework the predictive simulations are fed with a full snapshot of the state of the vehicles in the virtual reality simulation.
- The real system includes a comprehensive set of response plans designed to deal with a broad range of incidents and features a business rules engine capable of selecting which response plans are most suitable for a given event.

Taking from reality real-time counts, and configuring the demand for the predictive simulations with a procedure involving pattern matching, analytic predictions, demand selection from a library and real-time dynamic demand adjustment, requires a significant warm-up period and therefore cannot work with a virtual reality simulation that covers only four hours. For this reason, in the proposed testing framework both the virtual reality simulation and the predictive simulations access the same Aimsun model document file, where the demand and the incident are already defined, and the data taken by the predictive simulations from the virtual reality simulation is a full snapshot of the state of the vehicles.

Since the business rules engine in the ICM system is provided by a component developed by a third party and external to the Aimsun Online modules, TSS has no access to this functionality. For this reason, the testing framework doesn’t include a business rules engine and always tests a predefined set of response plans for each Operational Condition. We consider that both simplifications are acceptable for this evaluation and do not invalidate the results of the analysis, because the testing framework must deal with four specific Operational Conditions with fixed and predefined traffic demand and incidents, rather than with any conditions throughout the year and any incidents, like the real ICM system. In these four Operational Conditions, the testing framework should produce similar results to those of the real system.

It’s worth noting that each Operational Condition has a response plan that was applied during the incident, on the real-deployment day. In the Predictive Traveler Information simulations, the do-nothing case will deactivate the response plan that was originally applied.

7.2.2 Dynamic HOV/Managed Lanes

The HOV lanes on the I-15 corridor feature a Congestion Pricing System (CPS) that updates the cost of accessing the HOV lanes for SOVs based on the current congestion level. This was implemented in Aimsun using the Traffic Management functionality. A “free-to-all” scenario, in which SOVs[14] have free access to the HOV lanes was emulated for this strategy. The free access is granted in the southbound direction for Operational Conditions 1 and 2 (AM) and in the northbound direction for Operational Conditions 3 and 4 (PM).

7.2.3 Dynamic Routing

Dynamic Routing provides a set of alternative routes for the vehicles to avoid the area affected by the incident in each operational condition. These alternative routes are evaluated either with Predictive Traveler Information as a set of alternative response plans evaluated in parallel, or with current travel times, when no predictions are available.

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[14] The demand is segmented into HOVs (which have always free access to HOV lanes), SOV-toll (which are SOVs that may be willing to pay to get access to HOV lanes) and SOV-no-toll (which are SOVs that are never willing to pay to get access to HOV lanes). The “free-to-all” scenario makes all SOV-toll and 20% of the SOV-no-toll consider the option to use the HOV lanes (for free).

7.2.3.1 *Operational Condition 1*

The Dynamic Routing options are based on two diversion routes, one for vehicles coming from I-15 and one for vehicles coming from SR-78, and two percentages of vehicles following them, 3% and 6%. They produce a total of six response plans to test (plus the do-nothing): activating only one diversion route or both, and affecting 3% or 6% of the vehicles.

In the first rerouting option, vehicles coming from I-15 go towards SR-78 eastbound, exit SR-78 at Centre City Parkway and reenter I-15 at West Valley Parkway (Figure 7-3). In the second rerouting option, vehicles coming from SR-78 exit at Nordahl Road, follow Auto Parkway and reenter I-15 at 9th Ave. These diversion routes are complemented by change of signal plans at the signalized intersections along the routes (9 signals and 5 signals respectively), and by an increase of the metering rate at West Valley Parkway and 9th Ave southbound entrances on I-15.

Figure 7-3: The two rerouting options for Operational Condition 1

7.2.3.2 *Operational Condition 2*

The Dynamic Routing options are based on two diversion routes, one for vehicles coming from I-15 and one for vehicles coming from SR-78, and two percentages of vehicles following them, 3% and 6%. They produce a total of six response plans to test (plus the do-nothing): activating only one diversion route or both, and affecting 3% or 6% of the vehicles.

In the first rerouting option, vehicles coming from I-15 go towards SR-78 eastbound, exit SR-78 at Centre City Parkway and reenter I-15 at 9th Ave (Figure 7-4). In the second rerouting option, vehicles coming from SR-78 exit at Nordahl Road, follow Auto Parkway and reenter I-15 at 9th Ave. These diversion routes are complemented by change of signal plans at the signalized intersections along the routes (10 signals and 5 signals respectively), and by an increase of the metering rate at 9th Ave southbound entrance on I-15.

Figure 7-4: The two rerouting option for Operational Condition 2

7.2.3.3 Operational Condition 3

The Dynamic Routing options are based on three diversion routes for 3% of the vehicles traveling northbound on I-15. They produce a total of four response plans to test (plus the do-nothing): activating only one diversion route or the three concurrently.

In one diversion route vehicles exit at Bernardo Center Drive and reenter at Rancho Bernardo Road. In another diversion route vehicles exit at Camino del Norte and reenter at Rancho Bernardo Road. In the last diversion route vehicles exit at Carmel Mountain and reenter at Rancho Bernardo Road (Figure 7-5). These diversion routes are complemented by change of signal plans at the signalized intersections along the routes (6 signals, 6 signals and 5 signals respectively), and by an increase of the metering rate at Rancho Bernardo northbound entrance on I-15.

Figure 7-5: The three rerouting options for Operational Condition 3

7.2.3.4 Operational Condition 4

The Dynamic Routing options are based on two diversion routes for 3% of the vehicles traveling northbound on I-15 towards SR-78 westbound. They produce a total of three response plans to test (plus the do-nothing): activating only one diversion route or both concurrently.

In one diversion route vehicles exit I-15 at 9th Ave and enter SR-78 at Centre City Parkway. In the other diversion route vehicles exit I-15 at 9th Ave and enter SR-78 at Nordahl Road (Figure 7-6). These diversion routes are complemented by change of signal plans at the signalized intersections along the routes (9 signals and 8 signals respectively), and by an increase of the metering rate at Centre City Parkway and Nordahl Road westbound entrances on SR-78.

Figure 7-6: The two rerouting options for Operational Condition 4

Chapter 8. Synergies and Conflicts

This chapter documents the research findings regarding the synergies and conflicts among different DMA applications and ATDM strategies. It also refers to possible benefits in using the DMA applications and ATDM strategies in combination and isolation.

8.1 Research Questions

The following research questions are answered using this analysis:

1. Are the DMA applications and bundles more beneficial when implemented in isolation or in combination?
2. What DMA applications, bundles, or combinations of bundles complement or conflict with each other?
3. Are the ATDM strategies more beneficial when implemented in isolation or in combination?
4. What ATDM strategies or combinations of strategies conflict with each other?

In order to analyze these questions, the following list of hypotheses was made:

1. DMA bundles that are synergistic will be more beneficial when implemented in combination than in isolation.
2. Certain DMA applications, bundles, or combinations of bundles will complement each other resulting in increased benefits, while others will conflict with each other resulting in no benefits or reduced benefits.
3. ATDM strategies that are synergistic will be more beneficial when implemented in combination than in isolation.
4. Certain ATDM strategies will be in conflict with each other, resulting in no benefits or reduced benefits.

8.2 Analysis Approach

Operational condition 1 was used to evaluate combinations of DMA applications, combinations of ATDM strategies, and combinations of DMA applications and ATDM strategies to find synergies and conflicts. Specifically, the scenarios that have been evaluated are:

- Combinations of DMA applications:
  - SPD-HARM and CACC
- Combinations of ATDM strategies:
  - Dynamic Lane Use, Dynamic HOV/Managed Lanes and Dynamic Speed Limits
  - Dynamic Merge Control and Dynamic HOV/Managed Lanes
  - Dynamic Merge Control, Dynamic HOV/Managed Lanes and Dynamic Routing
- Combinations of DMA applications and ATDM strategies:
  - SPD-HARM and Dynamic Merge Control
  - SPD-HARM and Dynamic Speed Limits
  - SPD-HARM and Predictive Traveler Information

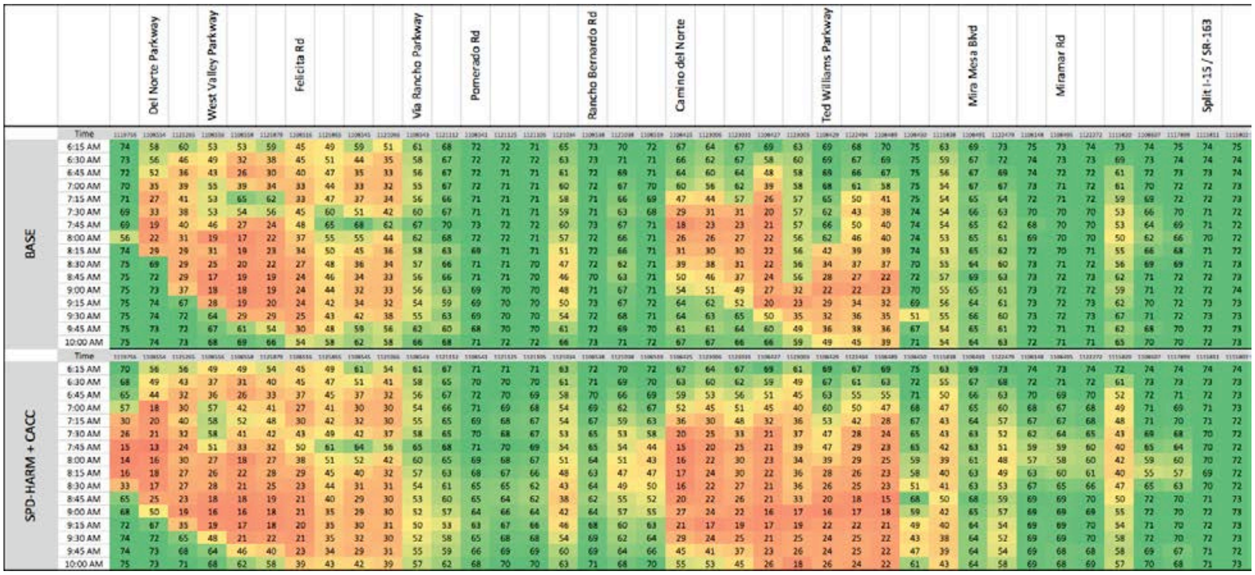
Simulations were conducted activating concurrently DMA applications and/or ATDM strategies, modeled as described in Chapters 6 and 7. The performance measures obtained in these simulations have been compared both with the baseline case, in which no DMA applications nor ATDM strategies are active, and with the results of the scenarios in which an individual DMA application or ATDM strategy is active.

In all these evaluations, for DMA application that are based on connected vehicles (SPD-HARM and CACC) perfect communication was assumed. The impact of communication issues on the effectiveness of these applications in combination has not been evaluated.

8.2.1 SPD-HARM and CACC

SPD-HARM and CACC are part of the INFLO bundle. Simulations were performed with SPD-HARM (see 6.1) and CACC (see 6.2) concurrently active with different penetration rates of connected vehicles. A first set of simulations was run making all connected vehicles comply with SPD-HARM messages. The results showed a significant reduction of speed and throughput network-wide, thus suggesting that SPD-HARM neutralized the benefit of CACC. In order to reduce the conflict between SPD-HARM and CACC, a second set of simulations was run in which the SPD-HARM messages were disseminated only to connected vehicles not engaged in a CACC platoon (i.e. connected vehicles that are not the leader nor the follower of other connected vehicles).

A comparison of the speed contour on I-15 in the southbound direction in the AM peak with the baseline conditions shows that at lower penetration rates SPD-HARM produces a “dilution” of the congestion over space and time (Figure 8-1, Figure 8-2 and Figure 8-3). This effect is lower both at the lowest penetration rate, when there are less vehicles affected, but also at the highest penetration rates, where most connected vehicles are engaged in CACC platoons, so they are not affected by SPD-HARM.



			Del Norte Parkway		West Valley Parkway			Felicita Rd				Via Rancho Parkway		Pomerado Rd				Rancho Bernardo Rd			Camino del Norte					Ted Williams Parkway					Mira Mesa Blvd			Miramar Rd					Split I-15 / SR-163	
	Time	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
BASE	6:15 AM	74	58	60	53	53	59	45	49	59	51	61	68	72	72	71	65	73	70	72	67	64	67	69	63	69	68	70	75	63	69	73	75	73	74	73	74	75	74	75
	6:30 AM	73	56	46	49	32	38	45	51	44	35	58	67	72	72	72	63	73	71	71	66	62	67	58	60	69	67	69	75	59	67	72	74	73	73	69	73	74	74	74
	6:45 AM	72	52	36	43	26	30	40	47	35	33	56	67	72	71	71	61	72	69	71	64	60	64	48	58	69	66	67	75	56	67	69	74	72	72	61	72	73	73	74
	7:00 AM	70	35	39	55	39	34	33	44	33	32	55	67	72	71	71	60	72	67	70	60	56	62	39	58	68	61	58	75	54	67	67	73	71	72	61	70	72	72	73
	7:15 AM	71	27	41	53	65	62	33	47	37	34	56	66	71	71	71	58	71	66	69	47	44	57	26	57	65	50	41	75	54	65	64	72	71	72	59	69	72	72	73
	7:30 AM	69	33	38	53	54	56	45	60	51	42	60	67	71	71	71	59	71	63	68	29	31	31	20	57	62	43	38	74	54	66	63	70	70	70	53	66	70	71	72
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	8:00 AM	56	22	31	19	17	22	37	55	55	44	62	68	72	72	71	57	72	66	71	26	26	27	22	56	62	46	40	74	53	65	61	69	70	70	50	62	66	70	72
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	10:00 AM	75	73	71	68	62	58	39	43	42	39	57	62	68	70	70	63	71	68	70	55	53	45	26	18	26	24	22	61	43	64	58	69	68	69	57	70	68	71	73

Figure 8-1: Speed contour with CACC and SPD-HARM with 25% penetration rate compared with the baseline case

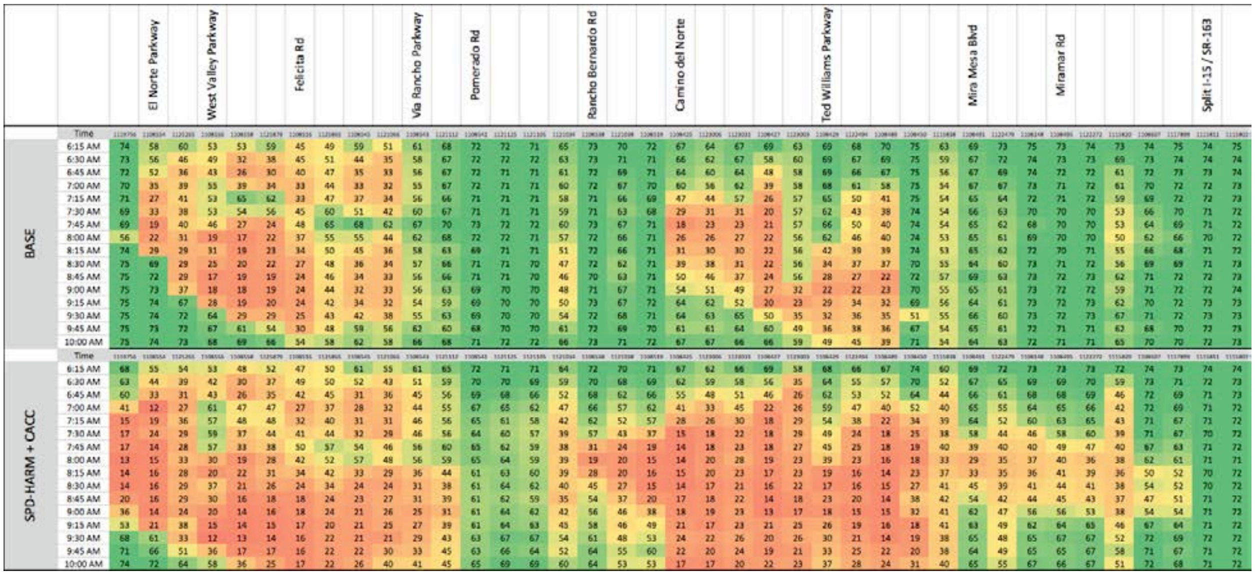


Figure 8-2: Speed contour with CACC and SPD-HARM with 50% penetration rate compared with the baseline case

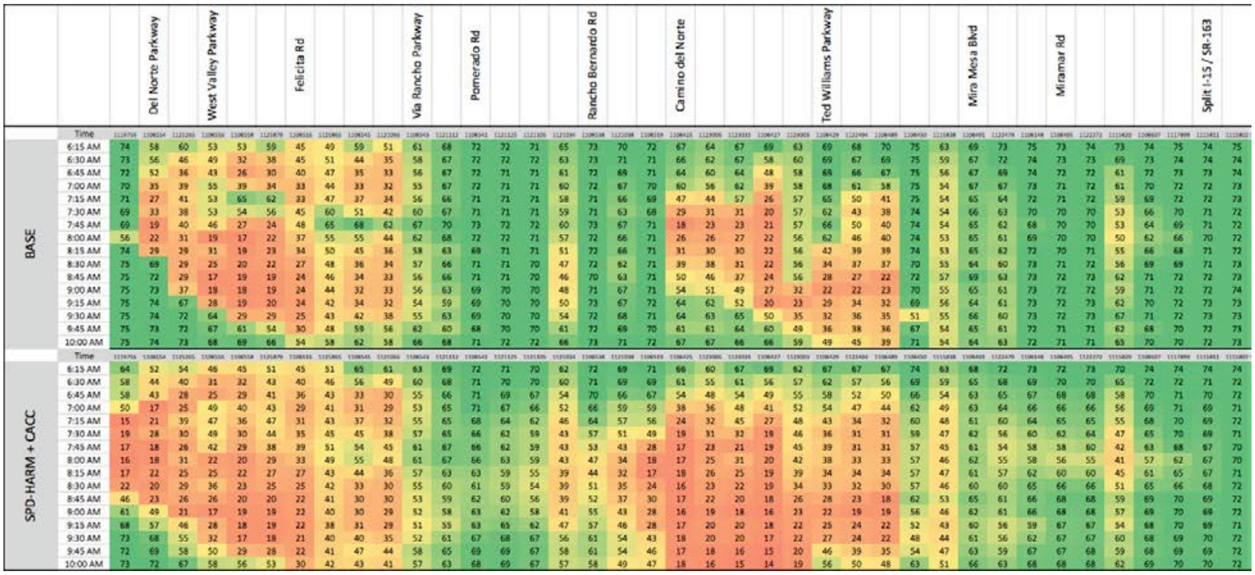


Figure 8-3: Speed contour with CACC and SPD-HARM with 90% penetration rate compared with the baseline case

If we compare network-wide traffic performance measures with CACC and SPD-HARM with different penetration rates concurrently active with the baseline condition and with the case of only CACC or only SPD-HARM active (Table 8-1 and Figure 8-4), we can notice that at the lowest and at the highest penetration rates the results are similar to the situation with SPD-HARM only. However, at 50% penetration rate, the combined result shows a significant increase of travel time, higher than with SPD-HARM alone, not accompanied with a reduction of shockwaves as high as with SPD-HARM alone. The results with SPD-HARM alone are consistent with those obtained in the San Mateo testbed.

Table 8-1: Performance measures with SPD-HARM and CACC compared with the baseline case and with the activation of individual ATDM strategies and DMA applications

Network Statistics	Base	SPD-HARM + CACC 25%	Difference	SPD-HARM 25%	Difference	CACC 25%	Difference
Vehicle Miles Traveled (mi)	2,320,947	2,331,287	0.4%	2,340,587	0.8%	2,336,549	0.7%
Total Travel Time (h)	61,946	64,927	4.8%	64,185	3.6%	61,602	-0.6%
Passenger Hourly Travel Time (h)	78,635	82,263	4.6%	81,499	3.6%	78,375	-0.3%
VMT/VHT (mi/h)	37.47	35.91	-4.2%	36.47	-2.7%	37.93	1.2%
Spatial speed drop (mi/h)	15.0	12.0	-20.0%	12.6	-16.0%		
Temporal speed drop (mi/h)	11.0	9.8	-10.9%	9.8	-10.9%		

Network Statistics	Base	SPD-HARM + CACC 50%	Difference	SPD-HARM 50%	Difference	CACC 50%	Difference
Vehicle Miles Traveled (mi)	2,320,947	2,305,199	-0.7%	2,350,332	1.3%	2,379,451	2.5%
Total Travel Time (h)	61,946	71,069	14.7%	66,744	7.7%	60,803	-1.8%
Passenger Hourly Travel Time (h)	78,635	89,559	13.9%	84,659	7.7%	77,461	-1.5%
VMT/VHT (mi/h)	37.47	32.44	-13.4%	35.21	-6.0%	39.13	4.4%
Spatial speed drop (mi/h)	15.0	12.6	-16.0%	10.4	-30.7%		
Temporal speed drop (mi/h)	11.0	8.0	-27.3%	7.0	-36.4%		

Network Statistics	Base	SPD-HARM + CACC 90%	Difference	SPD-HARM 90%	Difference	CACC 90%	Difference
Vehicle Miles Traveled (mi)	2,320,947	2,349,403	1.2%	2,351,385	1.3%	2,402,310	3.5%
Total Travel Time (h)	61,946	68,163	10.0%	68,997	11.4%	58,358	-5.8%
Passenger Hourly Travel Time (h)	78,635	86,207	9.6%	87,306	11.0%	74,407	-5.4%
VMT/VHT (mi/h)	37.47	34.47	-8.0%	34.08	-9.0%	41.17	9.9%
Spatial speed drop (mi/h)	15.0	10.0	-33.3%	10.0	-33.3%		
Temporal speed drop (mi/h)	11.0	6.2	-43.6%	6.2	-43.6%		

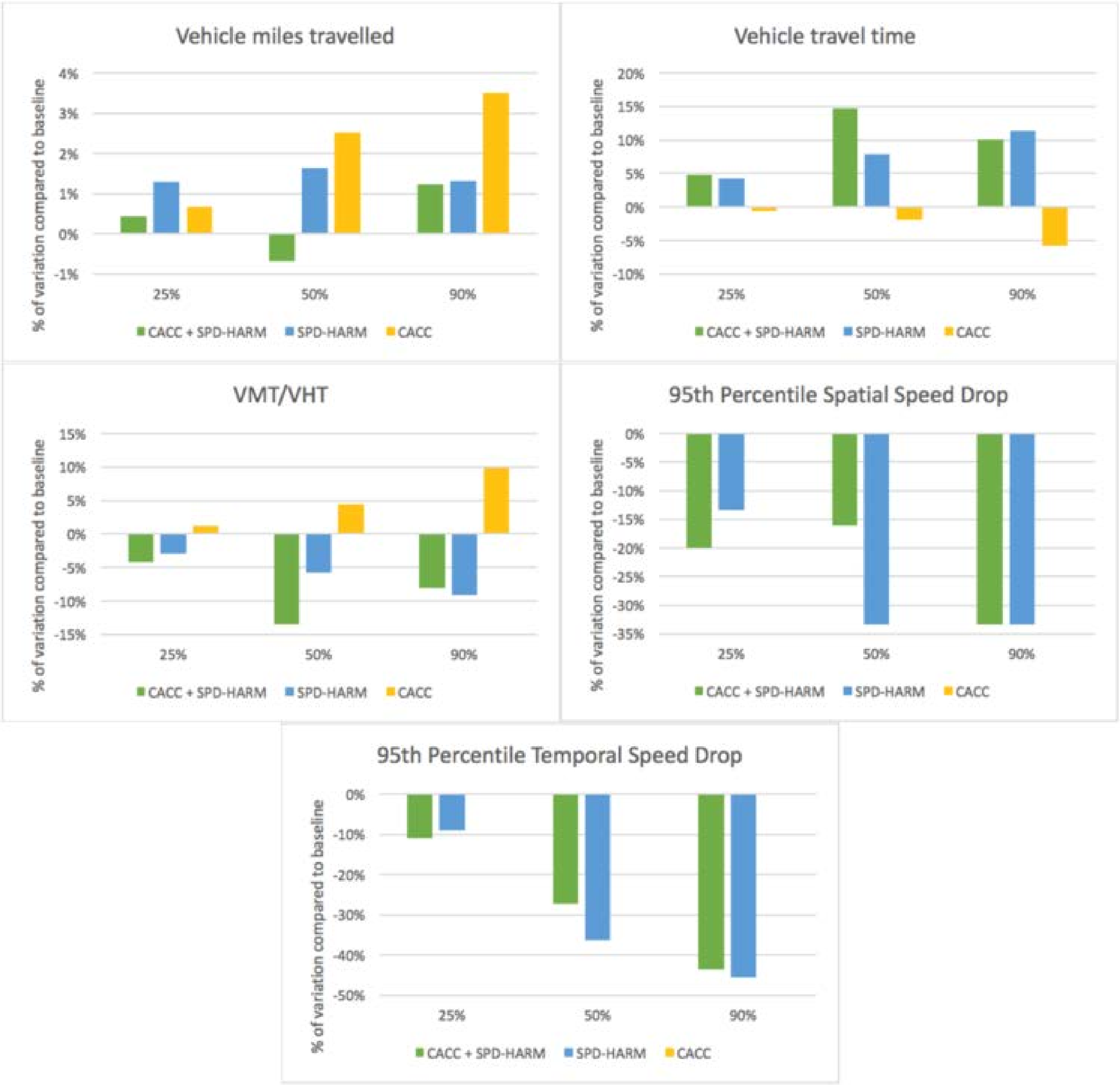


Figure 8-4: Performance measures with CACC and SPD-HARM with different penetration rates compared with the baseline case and with the activation of individual DMA applications

In summary, at all penetration rates the effect of SPD-HARM seems to prevail over CACC, even though the vehicles engaged by CACC are not affected by SPD-HARM messages, and in fact it seems to neutralize the benefit in terms of traffic performance that CACC produces alone. At low penetration rates the results show some synergy in terms of shockwave reduction; however, at high penetration rates the shockwave reduction is similar to that produced by SPD-HARM alone, and at 50% penetration rate the two DMA applications seem to produce the worst conflict, with lower traffic performance than each application alone, and less shockwave reduction than SPD-HARM alone.

Being CACC and SPD-HARM part of the INFLO bundle, the conflict detected at 50% penetration rate was unexpected, and therefore it was further investigated to understand what was the cause. We found that at this penetration rate often long CACC platoons on multiple parallel lanes make lane-changing for non-connected vehicles harder (Figure 8-5). The introduction of SPD-HARM introduces significant heterogeneity in the desired speed of different vehicles: on one side, there are connected vehicles receiving speed advisories, and on the other side, there are non-connected vehicles that want to overtake to drive faster, which increases the lane-changing desired compared to the case without SPD-HARM, and CACC platoons that are not subject to the speed limitation.

The problem is evident only at 50% penetration rate because there is no clear majority: at 25% penetration rate there are less CACC platoons and less vehicles affected by the speed harmonization message, whereas at 90% the number of non-connected vehicles that want to make frequent lane changes is reduced.

In order to find a mitigation for this problem, we evaluated a scenario in which we opened all lanes to CACC platoons, with the rationale that this would create shorter platoons, more distributed across the lanes, and thus reducing the lane-changing problems for non-connected vehicles. The simulations show that this change of policy is indeed effective and the results are similar to the case with SPD-HARM only (Table 8-2).

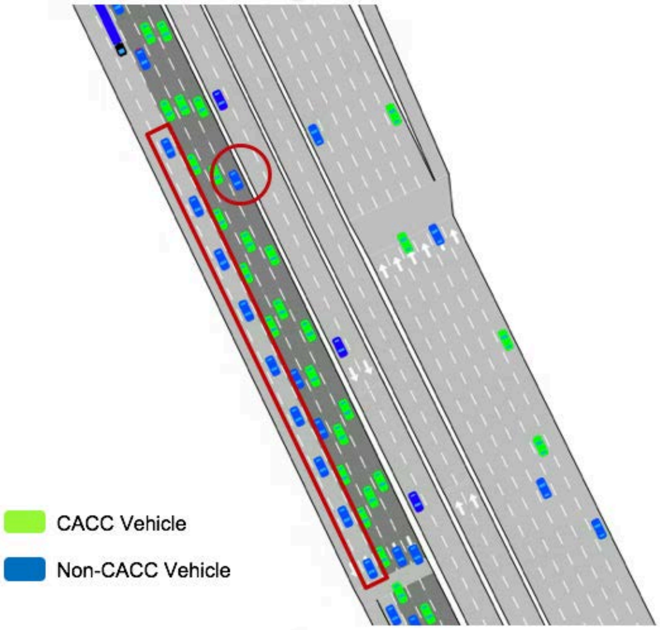


Figure 8-5: Snapshot of the traffic simulation showing the blockage caused to non-connected vehicles by vehicles engaged in a CACC platoon

Table 8-2: Performance measures with different lane configurations for CACC and 50% penetration rate

Network Statistics	Base	SPD-HARM + CACC 50% all lanes	Difference	Scenario 8 50% 3 lanes	Difference	SPD-HARM 50%	Difference	CACC 50%	Difference
Vehicle Miles Traveled (mi)	2,320,947	2,353,280	1.4%	2,305,199	-0.7%	2,358,911	1.6%	2,379,451	2.5%
Total Travel Time (h)	61,946	66,389	7.2%	71,069	14.7%	66,803	7.8%	60,803	-1.8%
Passenger Hourly Travel Time (h)	78,635	84,278	7.2%	89,559	13.9%	84,662	7.7%	77,461	-1.5%
VMT/VHT (mi/h)	37.47	35.45	-5.4%	32.44	-13.4%	35.31	-5.8%	39.13	4.4%
Spatial speed drop (mi/h)	15.0	10.4	-30.7%	12.6	-16.0%	10.4	-30.7%		
Temporal speed drop (mi/h)	11.0	7.0	-36.4%	8.0	-27.3%	7.0	-36.4%		

8.2.2 Dynamic Lane Use, Dynamic HOV/Managed Lanes and Dynamic Speed Limits

A set of simulations was run with a 3+1 configuration of the HOV lanes along I-15 in the southbound direction (see 7.1.1), no toll for SOVs that would use the HOT lanes in the southbound direction (see 7.2.2), and dynamic speed limits sets according to the ACISA-1 algorithm (see 7.1.2).

A comparison of the speed contour on I-15 in the southbound direction with the baseline conditions shows that dynamic speed limits produce a “dilution” of the congestion over space and time (Figure 8-6), which suggests an improvement in safety.

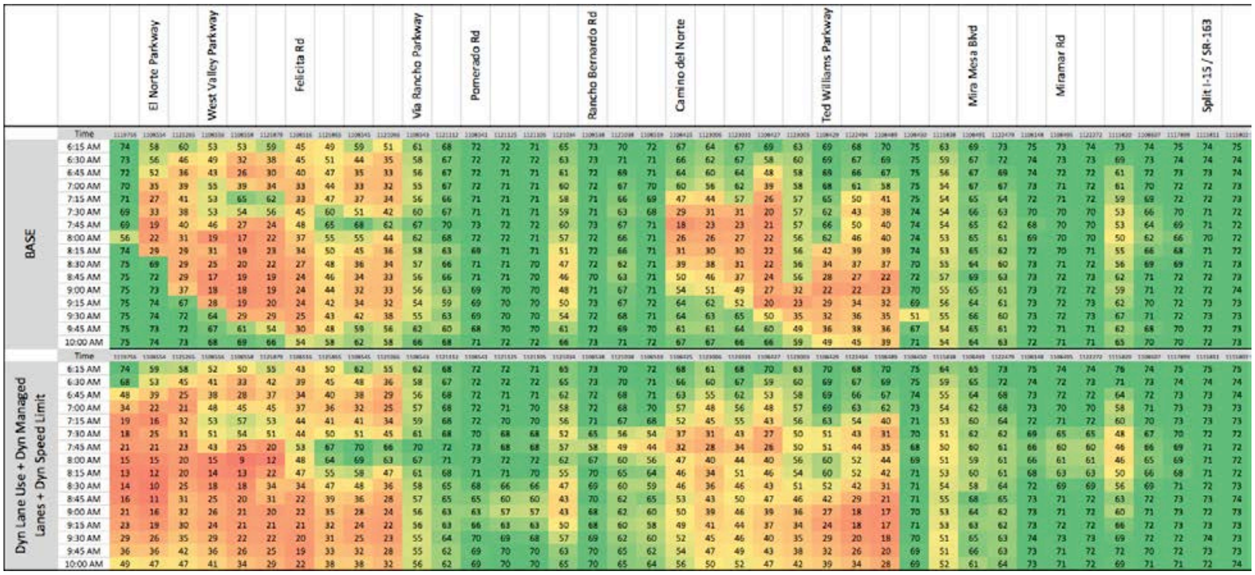


Figure 8-6: Speed contour with Dynamic Lane Use, Dynamic HOV/Managed Lanes and Dynamic Speed Limits compared with the baseline case

If we compare network-wide traffic performance measures with Dynamic Lane Use, Dynamic HOV/Managed Lanes and Dynamic Speed Limits concurrently active with the baseline condition and with the case of only Dynamic Lane Use and Dynamic HOV/Managed Lanes or only Dynamic Speed Limits active (Table 8-3 and Figure 8-7), we can notice that the results are similar to the situation with Dynamic Speed Limits only, with a slightly better throughput and slightly longer travel time.

Table 8-3: Performance measures with Dynamic Lane Use, Dynamic HOV/Managed Lanes and Dynamic Speed Limits compared with the baseline case and with the activation of individual ATDM strategies

Network Statistics	Base	Dyn Lane Use + Dyn Managed Lanes + Dyn Speed Limit	Difference	Dyn Lane Use + Dyn Managed Lanes	Difference	Dynamic Speed Limit	Difference
Vehicle Miles Traveled (mi)	2,320,947	2,297,710	-1.0%	2,325,470	0.2%	2,295,970	-1.1%
Total Travel Time (h)	61,946	64,029	3.4%	60,953	-1.6%	63,713	2.9%
Passenger Hourly Travel Time (h)	78,635	81,614	3.8%	77,591	-1.3%	80,972	3.0%
VMT/VHT (mi/h)	37.47	35.89	-4.2%	38.15	1.8%	36.04	-3.8%

Figure 8-7: Performance measures with Dynamic Lane Use, Dynamic HOV/Managed Lanes and Dynamic Speed Limits compared with the baseline case and with the activation of individual ATDM strategies

In summary, the results show neither a significant conflict nor a significant synergy between these ATDM strategies. The increase of congestion at the entrances and exits of the HOV lanes due to the increase of demand triggered by Dynamic Lane Use, Dynamic HOV/Managed Lanes is sensed by Dynamic Speed Limits, which extends the congestion over a larger space and longer time in order to avoid abrupt speed changes. This increase of safety is obtained at the expense of throughput and travel time. Dynamic Lane Use and Dynamic HOV/Managed Lanes alone would produce better traffic performance, at the expense of safety. Dynamic Speed Limits alone would produce an increase of safety, but with a more pronounced reduction of throughput.

8.2.3 Dynamic Merge Control and Dynamic HOV/Managed Lanes

A set of simulations was run with no toll for SOVs that would use the HOT lanes in the southbound direction (see 7.2.2) and dynamic merge control at the entrance of SR-78 into I-15 southbound (see 7.1.3). A comparison of the speed contour on I-15 in the southbound direction with the baseline conditions shows that the spatial and temporal extension of congestion is essentially unchanged (Figure 8-8).

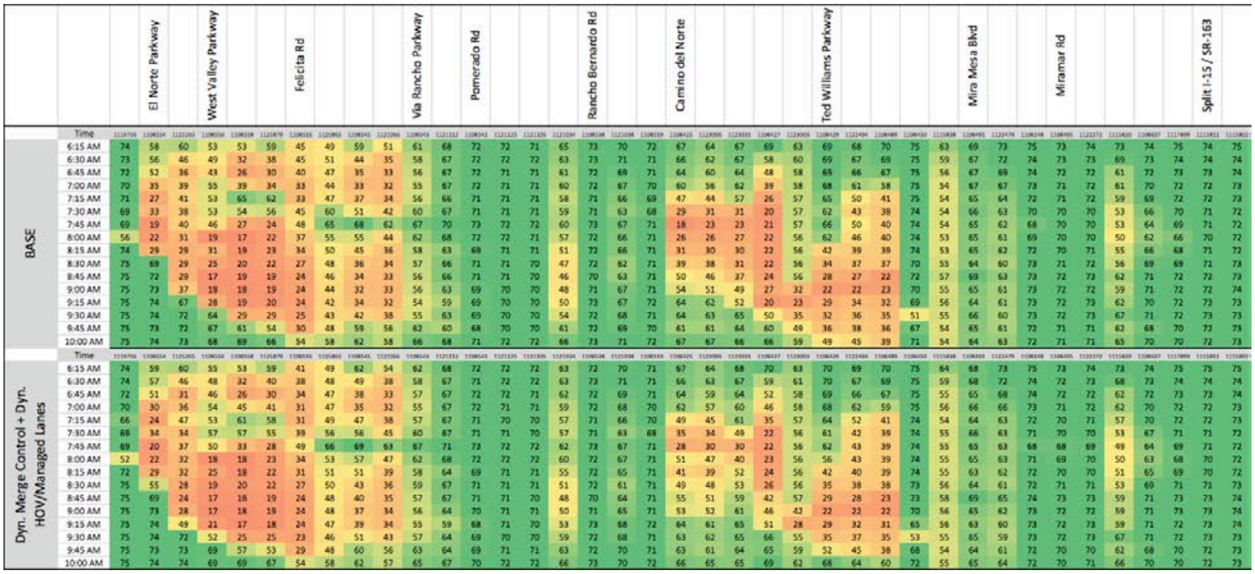


Figure 8-8: Speed contour with Dynamic Merge Control and Dynamic HOV/Managed Lanes compared with the baseline case

If we compare network-wide traffic performance measures with Dynamic Merge Control and Dynamic HOV/Managed Lanes concurrently active with the baseline condition and with the case of only Dynamic Merge Control or only Dynamic HOV/Managed Lanes and Dynamic Lane Use active (Table 8-4 and Figure 8-9), we can notice that the results are similar to the baseline situation.

Table 8-4: Performance measures with Dynamic Merge Control and Dynamic HOV/Managed Lanes compared with the baseline case and with the activation of individual ATDM strategies

Network Statistics	Base	Dyn. Merge Control + Dyn. HOV/Managed Lanes	Difference	Dyn Lane Use + Dyn Managed Lanes	Difference	Dynamic Merge Control	Difference
Vehicle Miles Traveled (mi)	2,320,947	2,321,332	0.0%	2,325,470	0.2%	2,315,264	-0.2%
Total Travel Time (h)	61,946	61,543	-0.7%	60,953	-1.6%	65,191	5.2%
Passenger Hourly Travel Time (h)	78,635	78,300	-0.4%	77,591	-1.3%	83,511	6.2%
VMT/VHT (mi/h)	37.47	37.72	0.7%	38.15	1.8%	35.52	-5.2%

In summary, the results show a synergy between these ATDM strategies. Dynamic HOV/Managed Lanes compensate the slightly negative effect in terms of traffic performance caused by Dynamic Merge Control, which facilitates the entrance from SR-78, at the expense of penalizing traffic coming from the northern boundary of the I-15 corridor in the southbound direction.

Dynamic HOV/Managed Lanes alone hasn't been evaluated (it has been evaluated at minimum in combination with Dynamic Lane Use); it is expected that combining additionally Dynamic Lane Use the synergy of the three ATDM strategies would increase. However, Dynamic HOV/Managed Lanes and Dynamic Lane Use show the best traffic performance. Therefore, the decision to activate Dynamic Merge Control or not should be dictated purely by the need to reduce queueing on the ramp coming from SR-78 rather than by overall traffic performance benefits. If Dynamic Merge Control is activated, Dynamic HOV/Managed Lanes would compensate its slightly negative impact.

Figure 8-9: Performance measures with Dynamic Merge Control and Dynamic HOV/Managed Lanes compared with the baseline case and with the activation of individual ATDM strategies

8.2.4 Dynamic Merge Control, Dynamic HOV/Managed Lanes and Dynamic Routing

A set of simulations was run with dynamic merge control at the entrance of SR-78 into I-15 southbound (see 7.1.3), no toll for SOVs that would use the HOT lanes in the southbound direction (see 7.2.2), and dynamic routing based on current (not predicted) travel times (see 7.2.3.1).

A comparison of the speed contour on I-15 in the southbound direction with the baseline conditions shows that the spatial and temporal extension of congestion is essentially unchanged (Figure 8-10).

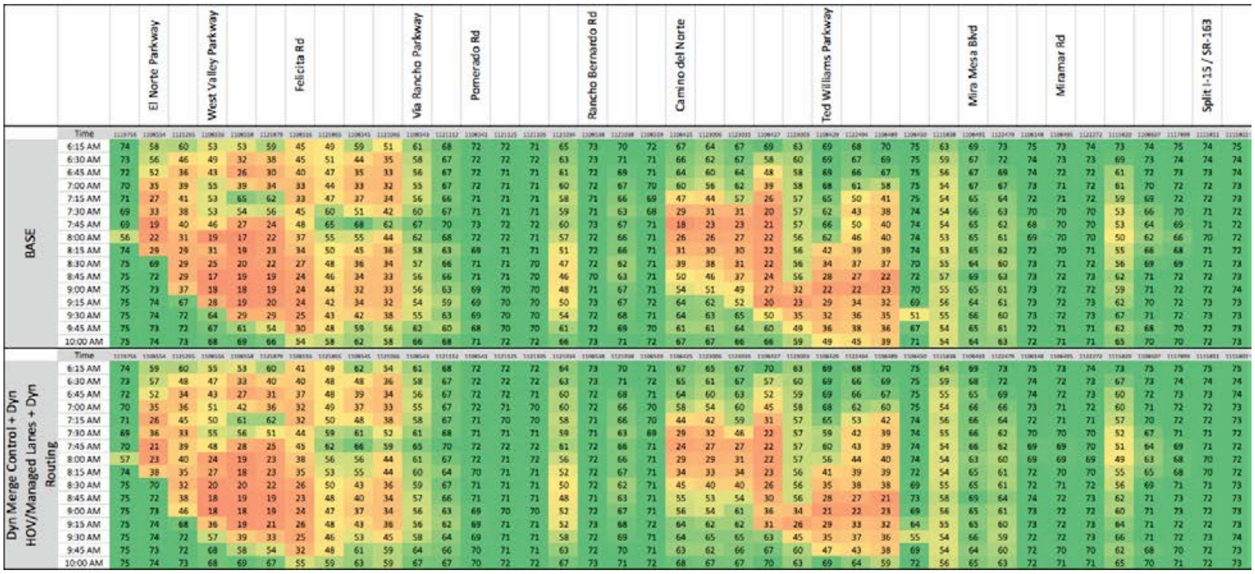


Figure 8-10: Speed contour with Dynamic Merge Control, Dynamic HOV/Managed Lanes and Dynamic Routing compared with the baseline case

If we compare network-wide traffic performance measures with Dynamic Merge Control, Dynamic HOV/Managed Lanes and Dynamic Routing concurrently active with the baseline condition and with the case of only Dynamic Merge Control or only Dynamic HOV/Managed Lanes and Dynamic Lane Use active (Table 8-5 and Figure 8-11), we can notice an almost negligible increase of throughput with a slight decrease of travel time.

Table 8-5: Performance measures with Dynamic Merge Control, Dynamic HOV/Managed Lanes and Dynamic Routing compared with the baseline case and with the activation of individual ATDM strategies

Network Statistics	Base	Dyn Merge Control + Dyn HOV/Managed Lanes + Dyn Routing	Difference	Dyn Lane Use + Dyn Managed Lanes	Difference	Dynamic Merge Control	Difference
Vehicle Miles Traveled (mi)	2,320,947	2,323,165	0.1%	2,325,470	0.2%	2,315,264	-0.2%
Total Travel Time (h)	61946	61,240	-1.1%	60,953	-1.6%	65,191	5.2%
Passenger Hourly Travel Time (h)	78635	77,829	-1.0%	77,591	-1.3%	83,511	6.2%
VMT/VHT (mi/h)	37.47	37.94	1.2%	38.15	1.8%	35.52	-5.2%

Figure 8-11: Performance measures with Dynamic Merge Control, Dynamic HOV/Managed Lanes and Dynamic Routing compared with the baseline case and with the activation of individual ATDM strategies

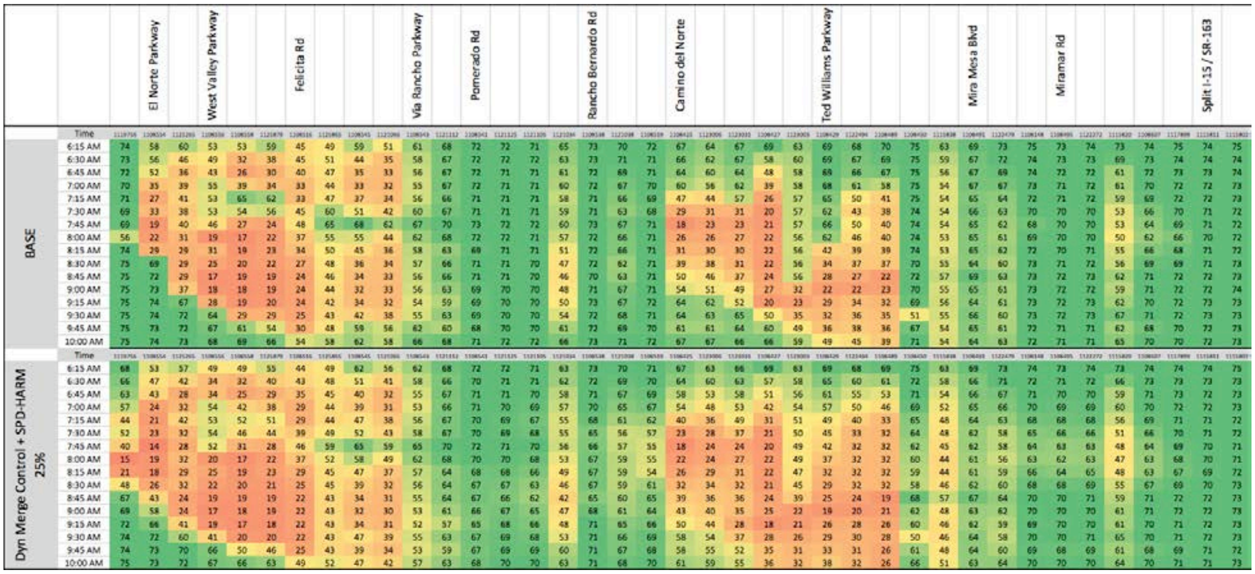
In summary, the results show a synergy between these ATDM strategies. Dynamic HOV/Managed Lanes and Dynamic Routing compensate the slightly negative effect in terms of traffic performance caused by Dynamic Merge Control, which facilitates the entrance from SR-78, at the expense of penalizing traffic coming from the northern boundary of the I-15 corridor in the southbound direction.

Dynamic HOV/Managed Lanes alone hasn't been evaluated (it has been evaluated at minimum in combination with Dynamic Lane Use) nor or Dynamic Routing alone (it has been evaluated with Predictive Traveler Information); it is expected that combining additionally Dynamic Lane Use the synergy of the three ATDM strategies would increase. However, Dynamic HOV/Managed Lanes and Dynamic Lane Use show the best traffic performance. Therefore, the decision to activate Dynamic Merge Control or not should be dictated purely by the need to reduce queueing on the ramp coming from SR-78 rather than by overall traffic performance benefits. If Dynamic Merge Control is activated, Dynamic HOV/Managed Lanes and Dynamic Routing would compensate its slightly negative impact.

8.2.5 SPD-HARM and Dynamic Merge Control

A set of simulations was run with dynamic merge control at the entrance of SR-78 into I-15 southbound (see 7.1.3), and SPD-HARM with different penetration rates of connected vehicles (see 6.1).

A comparison of the speed contour on I-15 in the southbound direction with the baseline conditions shows that SPD-HARM produces a "dilution" of the congestion over space and time that becomes more pronounced as the penetration rate of connected vehicles increase (Figure 8-12, Figure 8-13 and Figure 8-14), which suggests an improvement in safety.



	Time		El Norte Parkway		West Valley Parkway			Felicita Rd				Via Rancho Parkway		Pomerado Rd				Rancho Bernardo Rd			Camino del Norte					Ted Williams Parkway					Mira Mesa Blvd			Miramar Rd					Split I-15 / SR-163	
BASE	6:15 AM	74	58	60	53	53	59	45	49	59	51	61	68	72	72	71	65	73	70	72	67	64	67	69	63	69	68	70	75	63	69	73	75	73	74	73	74	75	74	75
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	7:30 AM	69	33	38	53	54	56	45	60	51	42	60	67	71	71	71	59	71	63	68	29	31	31	20	57	62	43	38	74	54	66	63	70	70	70	53	66	70	71	72
	7:45 AM	69	19	40	46	27	24	48	65	68	62	67	70	73	72	72	60	73	67	71	18	23	23	21	57	66	50	40	74	54	65	62	68	70	70	53	64	69	71	72
	8:00 AM	56	22	31	19	17	22	37	55	55	44	62	68	72	72	71	57	72	66	71	26	26	27	22	56	62	46	40	74	53	65	61	69	70	70	50	62	66	70	72
	8:15 AM	74	29	29	31	19	23	34	50	45	36	58	63	69	71	71	51	72	66	71	31	30	30	22	56	42	39	39	74	53	65	62	72	70	71	55	66	68	71	72
	8:30 AM	75	69	29	25	20	22	27	48	36	34	57	66	71	71	70	47	72	62	71	39	38	31	22	56	34	37	37	70	55	64	60	73	71	72	56	69	69	71	73
	8:45 AM	75	72	29	17	19	19	24	46	34	33	56	66	71	71	70	46	70	63	71	50	46	37	24	56	28	27	22	72	57	69	63	73	72	73	62	71	72	72	73
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	9:45 AM	75	73	72	67	61	54	30	48	59	56	62	60	68	70	70	61	72	69	70	61	61	64	60	49	36	38	36	67	54	65	61	72	71	71	62	68	70	72	73
	10:00 AM	75	74	73	68	69	66	54	58	62	58	66	68	71	72	72	66	73	71	72	67	67	66	66	59	49	45	39	71	54	64	63	72	71	71	65	70	70	72	73
	Time																																							
Dyn Merge Control + SPD-HARM 25%	6:15 AM	68	53	57	49	49	55	44	49	62	56	62	68	72	72	71	63	73	70	71	67	63	66	69	63	69	68	69	75	63	69	73	74	73	74	73	74	74	74	75
	6:30 AM	66	47	42	34	32	40	43	48	51	41	58	66	70	71	71	62	72	69	70	64	60	63	57	58	65	60	61	72	58	66	71	72	71	72	66	73	73	73	73
	6:45 AM	63	43	28	34	25	29	35	45	40	32	55	67	71	71	70	58	71	67	69	58	53	58	51	56	61	55	53	71	54	66	67	71	70	70	59	71	73	72	73
	7:00 AM	57	24	32	54	42	38	29	44	39	31	53	66	71	70	69	57	70	65	67	54	48	53	42	54	57	50	46	69	52	65	66	70	69	69	60	70	72	72	73
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	7:30 AM	52	23	32	54	46	44	39	49	52	43	58	67	70	69	68	55	65	56	57	23	28	37	31	50	45	33	32	64	48	62	58	65	66	66	51	66	70	71	72
	7:45 AM	40	14	28	52	31	28	46	59	65	59	65	70	72	71	70	56	66	57	55	18	24	24	20	49	42	32	32	62	45	62	58	64	63	63	48	64	69	70	71
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	8:45 AM	67	43	24	19	19	19	22	43	34	31	55	64	67	66	62	42	65	60	65	39	36	36	24	39	25	24	19	68	57	67	64	70	70	71	59	71	72	72	73
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	9:15 AM	72	66	41	19	17	18	22	43	34	31	52	57	65	68	66	48	71	65	66	50	44	28	18	21	26	28	26	60	46	62	59	69	70	70	61	70	71	72	73
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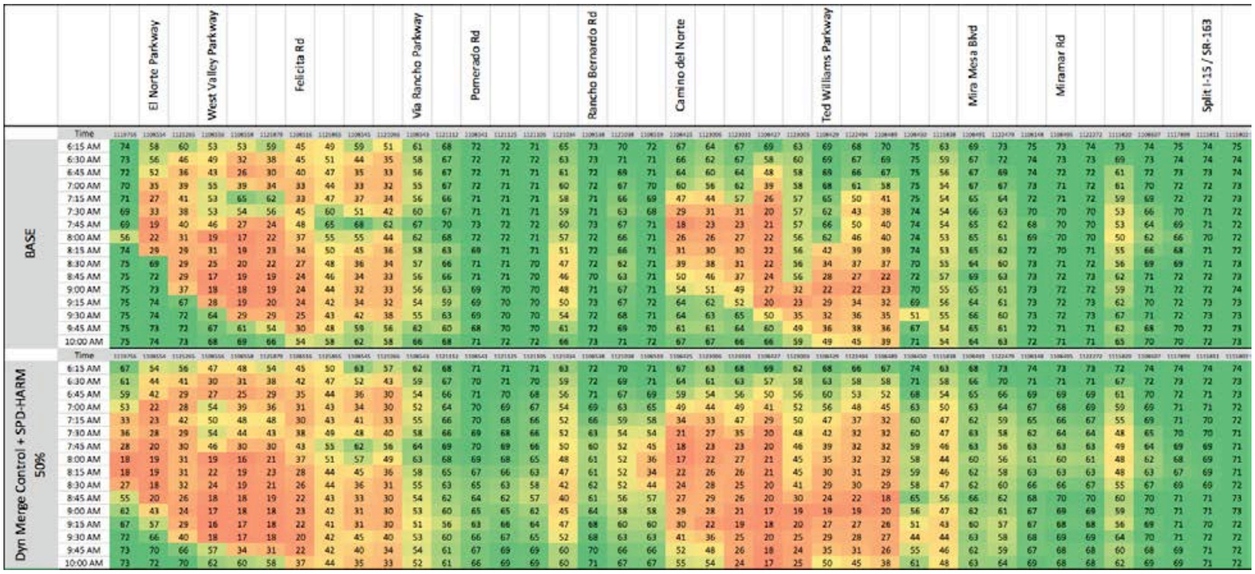
	10:00 AM	75	73	72	67	66	63	49	52	47	42	57	63	68	70	70	63	71	68	70	61	59	55	36	32	38	32	26	66	51	63	64	70	70	70	64	70	71	71	73

Figure 8-12: Speed contour with Dynamic Merge Control and SPD-HARM with 25% penetration rate compared with the baseline case



	Time		El Norte Parkway		West Valley Parkway			Felicita Rd				Via Rancho Parkway		Pomerado Rd				Rancho Bernardo Rd			Camino del Norte					Ted Williams Parkway					Mira Mesa Blvd			Miramar Rd					Split I-15 / SR-163	
BASE	6:15 AM	74	58	60	53	53	59	45	49	59	51	61	68	72	72	71	65	73	70	72	67	64	67	69	63	69	68	70	75	63	69	73	75	73	74	73	74	75	74	75
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	6:45 AM	72	52	36	43	26	30	40	47	35	33	56	67	72	71	71	61	72	69	71	64	60	64	48	58	69	66	67	75	56	67	69	74	72	72	61	72	73	73	74
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	7:30 AM	69	33	38	53	54	56	45	60	51	42	60	67	71	71	71	59	71	63	68	29	31	31	20	57	62	43	38	74	54	66	63	70	70	70	53	66	70	71	72
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	8:00 AM	56	22	31	19	17	22	37	55	55	44	62	68	72	72	71	57	72	66	71	26	26	27	22	56	62	46	40	74	53	65	61	69	70	70	50	62	66	70	72
	8:15 AM	74	29	29	31	19	23	34	50	45	36	58	63	69	71	71	51	72	66	71	31	30	30	22	56	42	39	39	74	53	65	62	72	70	71	55	66	68	71	72
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	9:00 AM	75	73	37	18	18	19	24	44	32	33	56	63	69	70	70	48	71	67	71	54	51	49	27	32	22	22	23	70	55	65	61	73	72	72	59	71	72	72	74
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	10:00 AM	75	74	73	68	69	66	54	58	62	58	66	68	71	72	72	66	73	71	72	67	67	66	66	59	49	45	39	71	54	64	63	72	71	71	65	70	70	72	73
	Time																																							
Dyn Merge Control + SPD-HARM 50%	6:15 AM	67	54	56	47	48	54	45	50	63	57	62	68	71	71	71	63	72	70	71	67	63	68	69	62	68	66	67	74	63	68	73	74	73	73	72	74	74	74	74
	6:30 AM	61	44	41	30	31	38	42	47	52	43	59	67	70	71	70	59	72	69	71	64	61	63	57	58	63	58	58	71	58	66	70	71	71	71	67	72	73	72	73
	6:45 AM	59	42	29	27	25	29	35	44	36	30	54	66	71	70	68	56	71	67	69	59	54	56	50	56	60	53	52	68	54	65	66	69	69	69	61	70	72	71	73
	7:00 AM	53	22	28	54	39	36	31	43	34	30	52	64	70	69	67	54	69	63	65	49	44	49	41	52	56	48	45	63	50	63	64	67	68	69	59	69	71	71	72
	7:15 AM	33	23	42	50	48	48	30	43	41	33	55	66	70	68	66	52	66	59	58	34	33	47	29	50	47	37	32	60	47	62	59	65	66	67	55	69	71	70	72
	7:30 AM	36	28	29	54	44	43	38	49	48	40	58	66	69	68	66	52	63	54	54	21	27	35	30	48	42	32	32	60	47	63	58	62	64	64	48	65	70	70	71
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	8:00 AM	18	19	31	19	16	21	37	51	57	49	63	68	69	68	65	48	61	52	36	17	22	27	21	45	35	32	32	58	44	60	56	61	60	61	48	62	68	69	71
	8:15 AM	18	19	31	22	19	23	28	44	45	36	58	65	67	66	63	47	61	52	34	22	26	26	21	45	30	31	29	59	46	62	58	63	63	63	48	63	67	69	71
	8:30 AM	27	18	32	24	19	21	26	44	36	31	55	63	65	63	58	42	62	52	44	24	28	25	20	41	29	30	29	58	47	62	60	66	66	67	55	67	69	69	72
	8:45 AM	55	20	26	18	18	19	22	43	33	30	54	62	64	62	57	40	61	56	57	27	29	26	20	30	24	22	18	65	56	66	62	68	70	70	60	70	71	71	73
	9:00 AM	62	43	24	17	18	18	23	42	31	30	53	60	65	65	62	45	64	58	58	29	28	21	17	19	19	19	20	56	47	62	61	67	69	69	59	70	71	71	73
	9:15 AM	67	57	29	16	17	18	22	41	31	30	51	56	63	66	64	47	68	60	60	30	22	19	18	20	27	27	26	51	43	60	57	67	68	68	56	69	71	70	72
	9:30 AM	72	66	40	18	17	18	20	42	45	40	53	60	66	67	65	52	68	63	63	41	36	25	20	25	29	28	27	44	44	63	58	68	69	69	64	70	71	72	72
	9:45 AM	73	70	66	57	34	31	22	42	40	34	54	61	67	69	69	60	70	66	66	52	48	26	18	24	35	31	26	55	46	62	59	67	68	68	60	68	69	71	72
	10:00 AM	73	72	70	62	60	58	37	44	35	33	52	61	66	69	69	60	71	67	67	55	54	24	17	25	50	45	38	61	48	63	64	69	68	68	62	69	69	71	72

Figure 8-13: Speed contour with Dynamic Merge Control and SPD-HARM with 50% penetration rate compared with the baseline case

If we compare network-wide traffic performance measures with Dynamic Merge Control and SPD-HARM with different penetration rates concurrently active with the baseline condition and with the case of only Dynamic Merge Control or only SPD-HARM active (Table 8-6 and Figure 8-15), we can notice that the results are similar to the situation with SPD-HARM only.

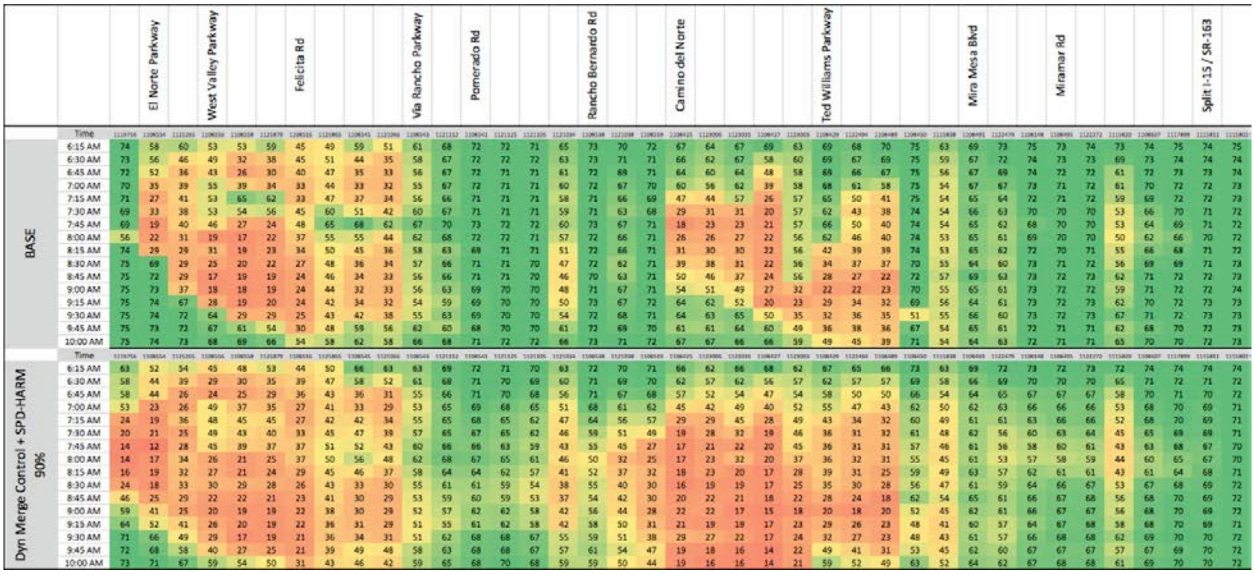


Figure 8-14: Speed contour with Dynamic Merge Control and SPD-HARM with 90% penetration rate compared with the baseline case

Table 8-6: Performance measures with Dynamic Merge Control and SPD-HARM with different penetration rates compared with the baseline case and with the activation of individual ATDM strategies

Network Statistics	Base	Dyn Merge Control + SPD-HARM 25%	Difference	SPD-HARM 25%	Difference	Dynamic Merge Control	Difference
Vehicle Miles Traveled (mi)	2,320,947	2,339,873	0.8%	2,340,587	0.8%	2,315,264	-0.2%
Total Travel Time (h)	61,946	63,965	3.3%	64,185	3.6%	65,191	5.2%
Passenger Hourly Travel Time (h)	78,635	81,211	3.3%	81,499	3.6%	83,511	6.2%
VMT/VHT (mi/h)	37.47	36.58	-2.4%	36.47	-2.7%	35.52	-5.2%
Spatial speed drop (mi/h)	15.0	12.6	-16.0%	12.6	-16.0%		
Temporal speed drop (mi/h)	11.0	9.8	-10.9%	9.8	-10.9%		
Network Statistics	**Base**	**Dyn Merge Control + SPD-HARM 50%**	**Difference**	**SPD-HARM 50%**	**Difference**	**Dynamic Merge Control**	**Difference**
Vehicle Miles Traveled (mi)	2,320,947	2,350,630	1.3%	2,350,332	1.3%	2,315,264	-0.2%
Total Travel Time (h)	61,946	66,520	7.4%	66,744	7.7%	65,191	5.2%
Passenger Hourly Travel Time (h)	78,635	84,370	7.3%	84,659	7.7%	83,511	6.2%
VMT/VHT (mi/h)	37.47	35.34	-5.7%	35.21	-6.0%	35.52	-5.2%
Spatial speed drop (mi/h)	15.0	10.4	-30.7%	10.4	-30.7%		
Temporal speed drop (mi/h)	11.0	7.0	-36.4%	7.0	-36.4%		
Network Statistics	**Base**	**Dyn Merge Control + SPD-HARM 90%**	**Difference**	**SPD-HARM 90%**	**Difference**	**Dynamic Merge Control**	**Difference**
Vehicle Miles Traveled (mi)	2,320,947	2,350,121	1.3%	2,351,385	1.3%	2,315,264	-0.2%
Total Travel Time (h)	61,946	68,946	11.3%	68,997	11.4%	65,191	5.2%
Passenger Hourly Travel Time (h)	78,635	87,135	10.8%	87,306	11.0%	83,511	6.2%
VMT/VHT (mi/h)	37.47	34.09	-9.0%	34.08	-9.0%	35.52	-5.2%
Spatial speed drop (mi/h)	15.0	10.0	-33.3%	10.0	-33.3%		
Temporal speed drop (mi/h)	11.0	6.0	-45.5%	6.2	-43.6%		

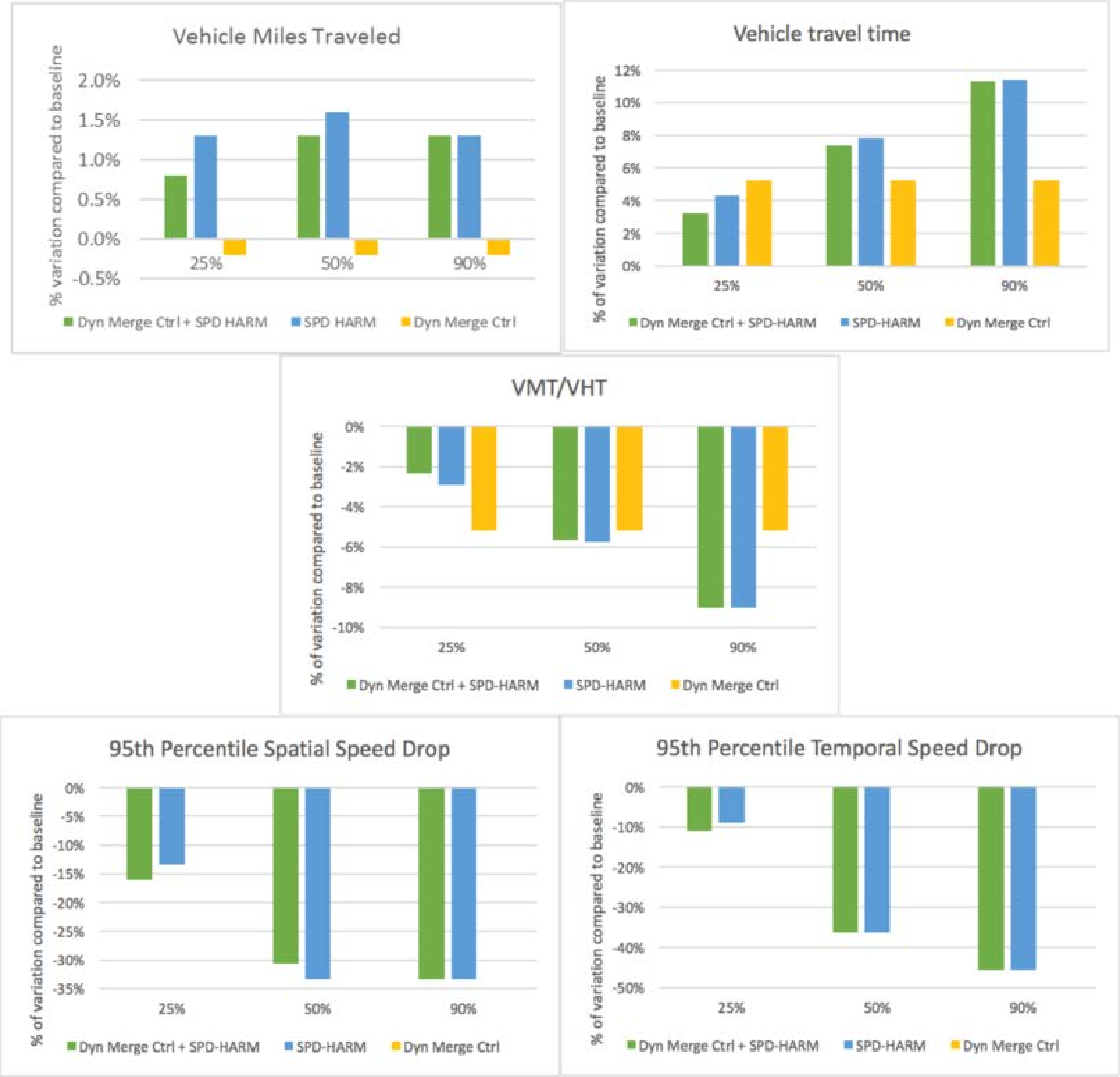


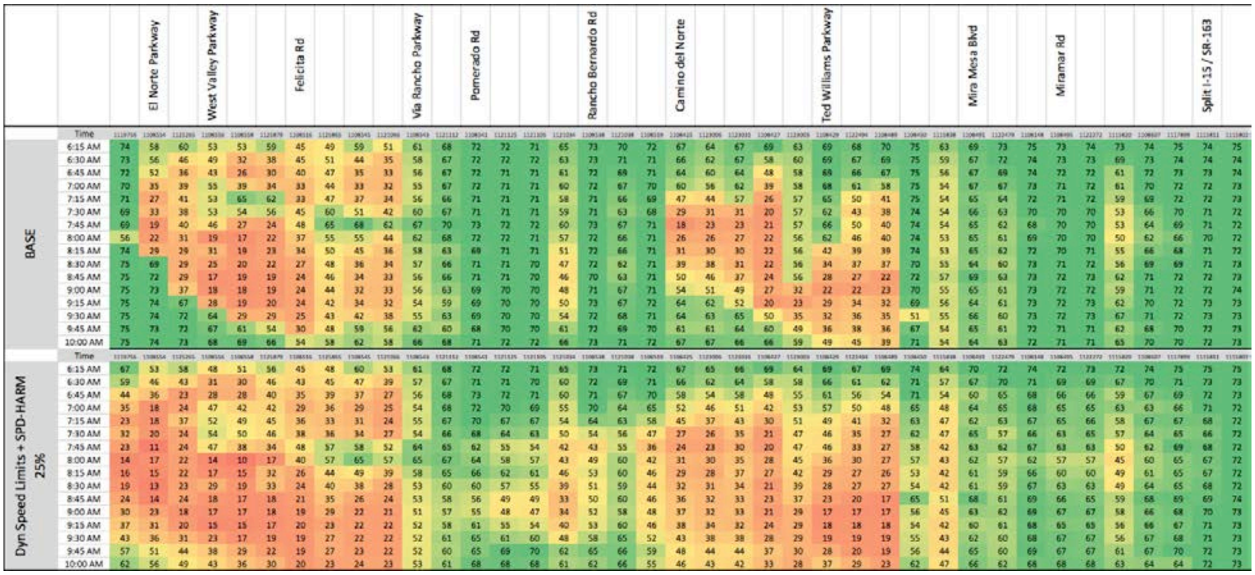
Figure 8-15: Performance measures with Dynamic Merge Control and SPD-HARM with different penetration rates compared with the baseline case and with the activation of individual ATDM strategies

In summary, the results show neither a significant conflict nor a significant synergy between these ATDM strategies. The benefit in terms of SPD-HARM alone in terms of shockwave reduction are not affected by Dynamic Merge Control. The throughput reduction caused by Dynamic Merge Control is compensated by SPD-HARM. Therefore, the decision to activate Dynamic Merge Control or not should be dictated purely by the need to reduce queueing on the ramp coming from SR-78 rather than by overall traffic performance benefits. If Dynamic Merge Control is activated, SPD-HARM would compensate its slightly negative impact on throughput.

8.2.6 SPD-HARM and Dynamic Speed Limits

A set of simulations was run with dynamic speed limits sets according to the ACISA-1 algorithm (see 7.1.2), and SPD-HARM with different penetration rates of connected vehicles (see 6.1). Note that

Dynamic Speed Limits control the speed of non-connected vehicles, while SPD-HARM controls the speed of connected vehicles. A comparison of the speed contour on I-15 in the southbound direction with the baseline conditions shows that SPD-HARM and Dynamic Speed Limits produce a "dilution" of the congestion over space and time (Figure 8-16, Figure 8-17 and Figure 8-18), which suggests an improvement in safety. As the penetration rate increases, the speed contour becomes similar to the one with SPD-HARM only.



	Time		El Norte Parkway		West Valley Parkway			Felicita Rd				Via Rancho Parkway		Pomerado Rd				Rancho Bernardo Rd			Camino del Norte					Ted Williams Parkway					Mira Mesa Blvd			Miramar Rd					Split I-15 / SR-163	
BASE	6:15 AM	74	58	60	53	53	59	45	49	59	51	61	68	72	72	71	65	73	70	72	67	64	67	69	63	69	68	70	75	63	69	73	75	73	74	73	74	75	74	75
	6:30 AM	73	56	46	49	32	38	45	51	44	35	58	67	72	72	72	63	73	71	71	66	62	67	58	60	69	67	69	75	59	67	72	74	73	73	69	73	74	74	74
	6:45 AM	72	52	36	43	26	30	40	47	35	33	56	67	72	71	71	61	72	69	71	64	60	64	48	58	69	66	67	75	56	67	69	74	72	72	61	72	73	73	74
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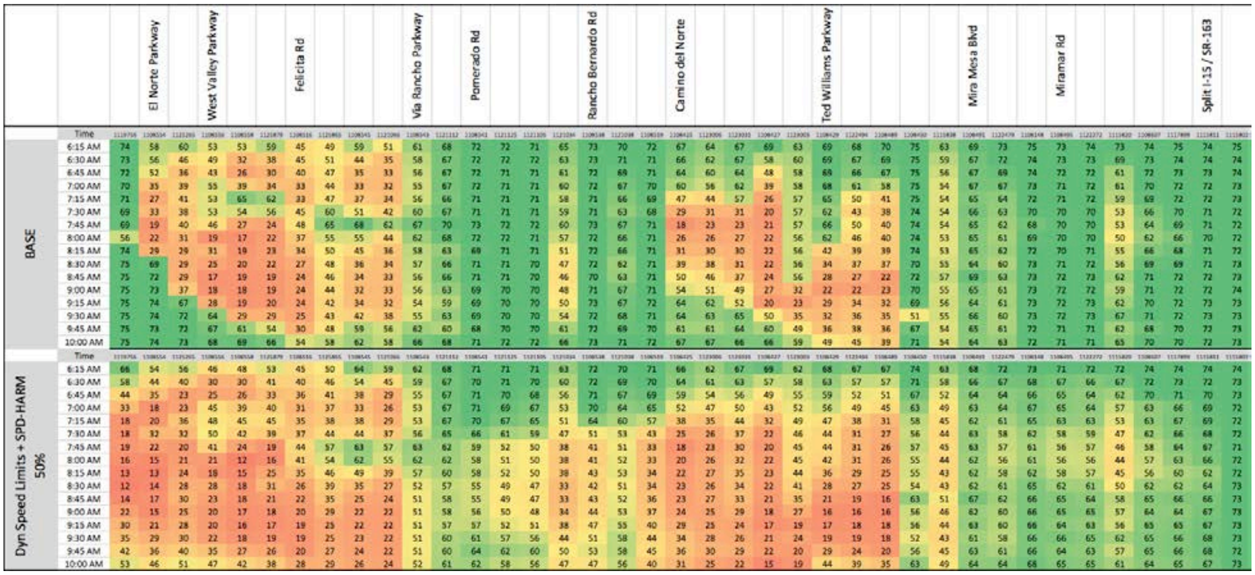
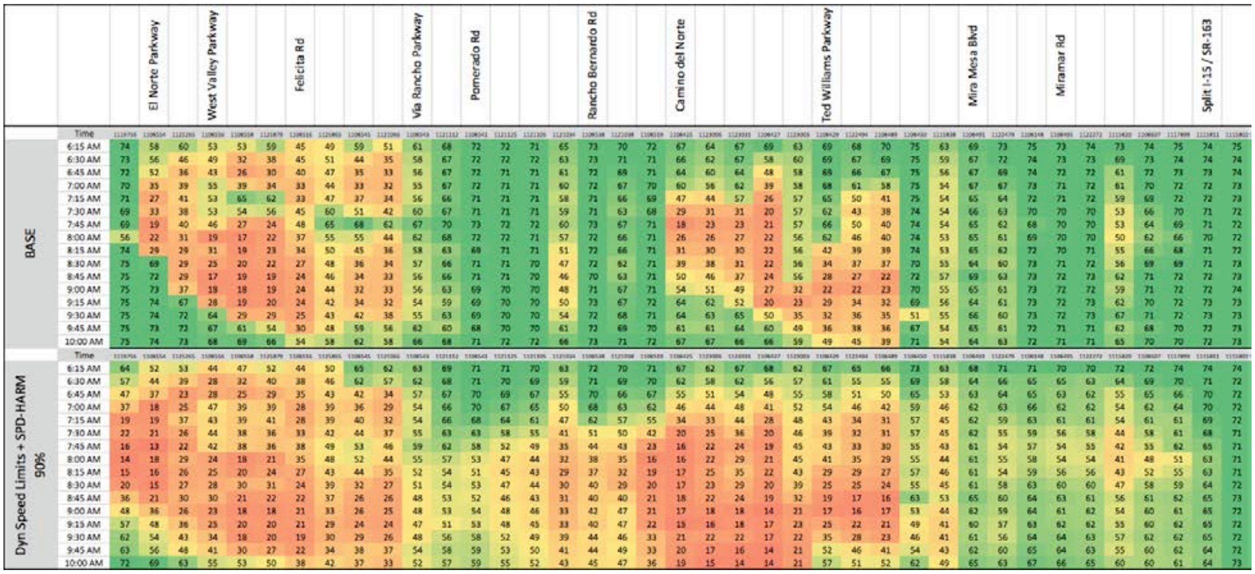
	8:00 AM	56	22	31	19	17	22	37	55	55	44	62	68	72	72	71	57	72	66	71	26	26	27	22	56	62	46	40	74	53	65	61	69	70	70	50	62	66	70	72
	8:15 AM	74	29	29	31	19	23	34	50	45	36	58	63	69	71	71	51	72	66	71	31	30	30	22	56	42	39	39	74	53	65	62	72	70	71	55	66	68	71	72
	8:30 AM	75	69	29	25	20	22	27	48	36	34	57	66	71	71	70	47	72	62	71	39	38	31	22	56	34	37	37	70	55	64	60	73	71	72	56	69	69	71	73
	8:45 AM	75	72	29	17	19	19	24	46	34	33	56	66	71	71	70	46	70	63	71	50	46	37	24	56	28	27	22	72	57	69	63	73	72	73	62	71	72	72	73
	9:00 AM	75	73	37	18	18	19	24	44	32	33	56	63	69	70	70	48	71	67	71	54	51	49	27	32	22	22	23	70	55	65	61	73	72	72	59	71	72	72	74
	9:15 AM	75	74	67	28	19	20	24	42	34	32	54	59	69	70	70	50	73	67	72	64	62	52	20	23	29	34	32	69	56	64	61	73	72	73	62	70	72	73	73
	9:30 AM	75	74	72	64	29	29	25	43	42	38	55	63	69	70	70	54	72	68	71	64	63	65	50	35	32	36	35	51	55	66	60	73	72	73	67	71	72	73	73
	9:45 AM	75	73	72	67	61	54	30	48	59	56	62	60	68	70	70	61	72	69	70	61	61	64	60	49	36	38	36	67	54	65	61	72	71	71	62	68	70	72	73
	10:00 AM	75	74	73	68	69	66	54	58	62	58	66	68	71	72	72	66	73	71	72	67	67	66	66	59	49	45	39	71	54	64	63	72	71	71	65	70	70	72	73
Dyn Speed Limits + SPD-HARM 25%	6:15 AM	67	53	58	48	51	56	45	48	60	53	61	68	72	72	71	65	73	71	72	67	65	66	69	64	69	67	69	74	64	70	72	74	72	73	72	74	75	75	75
	6:30 AM	59	46	43	31	30	46	43	45	47	39	57	67	71	71	70	60	72	69	71	66	62	64	58	58	66	61	62	71	57	67	70	71	69	69	67	70	71	73	73
	6:45 AM	44	36	23	28	28	40	35	39	37	27	56	68	73	72	71	60	71	67	70	58	54	58	48	55	61	56	54	71	54	60	65	68	66	66	59	67	69	72	73
	7:00 AM	35	18	24	47	42	42	29	36	29	25	54	68	72	70	69	55	70	64	65	52	46	51	42	53	57	50	48	65	48	64	65	68	65	65	63	63	66	71	72
	7:15 AM	23	18	37	52	49	45	36	33	31	24	55	67	70	67	67	54	64	63	58	45	37	43	30	51	49	41	32	63	47	62	63	67	65	66	58	67	67	68	72
	7:30 AM	32	20	24	54	50	46	38	36	34	27	54	66	68	64	63	50	54	56	47	27	26	35	21	47	46	35	27	62	47	65	57	66	63	65	57	64	65	66	72
	7:45 AM	23	11	24	47	38	34	48	57	58	52	64	65	62	55	54	42	43	55	36	24	23	30	20	47	46	33	27	58	42	63	62	67	63	63	50	62	69	68	72
	8:00 AM	14	17	22	14	10	17	40	57	65	57	65	67	64	58	57	43	49	60	42	31	30	35	28	45	36	30	27	57	43	62	57	62	57	57	45	60	65	67	72
	8:15 AM	16	15	22	17	15	32	26	44	49	39	58	65	66	62	61	46	53	60	46	29	28	37	27	42	29	27	26	53	42	61	59	66	60	60	49	61	65	67	72
	8:30 AM	19	13	23	29	19	33	24	40	38	28	53	60	60	57	55	39	51	59	44	32	31	34	21	39	28	27	27	54	42	61	59	67	63	63	49	64	65	68	72
	8:45 AM	24	14	24	18	17	18	21	35	26	24	53	58	56	49	49	33	50	60	46	36	32	33	23	37	23	20	17	65	51	68	61	69	66	65	59	68	69	69	74
	9:00 AM	30	23	18	17	17	18	19	29	22	21	51	57	55	48	47	34	52	58	48	37	32	33	21	29	17	17	17	56	45	63	62	69	67	67	58	66	68	70	73
	9:15 AM	37	31	20	15	15	17	20	23	22	22	52	58	61	55	54	40	53	60	46	38	34	32	24	29	18	18	18	54	42	60	61	68	65	65	56	66	67	71	73
	9:30 AM	43	36	31	23	17	19	19	27	22	22	52	61	65	61	60	48	58	65	52	43	38	38	28	29	19	19	19	55	43	62	60	68	67	67	56	67	68	71	73
	9:45 AM	57	51	44	38	29	22	19	27	23	22	52	60	65	69	70	62	65	66	59	48	44	44	37	30	28	20	19	56	44	65	60	69	67	67	61	67	70	72	73
	10:00 AM	62	56	49	43	36	30	20	23	24	23	53	61	68	68	68	61	62	66	55	46	43	42	33	28	37	29	23	62	47	66	62	68	68	68	63	64	64	72	73

Figure 8-16: Speed contour with Dynamic Speed Limits and SPD-HARM with 25% penetration rate compared with the baseline case



	Time		El Norte Parkway		West Valley Parkway			Felicita Rd				Via Rancho Parkway		Pomerado Rd				Rancho Bernardo Rd			Camino del Norte					Ted Williams Parkway					Mira Mesa Blvd			Miramar Rd					Split I-15 / SR-163	
BASE	6:15 AM	74	58	60	53	53	59	45	49	59	51	61	68	72	72	71	65	73	70	72	67	64	67	69	63	69	68	70	75	63	69	73	75	73	74	73	74	75	74	75
	6:30 AM	73	56	46	49	32	38	45	51	44	35	58	67	72	72	72	63	73	71	71	66	62	67	58	60	69	67	69	75	59	67	72	74	73	73	69	73	74	74	74
	6:45 AM	72	52	36	43	26	30	40	47	35	33	56	67	72	71	71	61	72	69	71	64	60	64	48	58	69	66	67	75	56	67	69	74	72	72	61	72	73	73	74
	7:00 AM	70	35	39	55	39	34	33	44	33	32	55	67	72	71	71	60	72	67	70	60	56	62	39	58	68	61	58	75	54	67	67	73	71	72	61	70	72	72	73
	7:15 AM	71	27	41	53	65	62	33	47	37	34	56	66	71	71	71	58	71	66	69	47	44	57	26	57	65	50	41	75	54	65	64	72	71	72	59	69	72	72	73
	7:30 AM	69	33	38	53	54	56	45	60	51	42	60	67	71	71	71	59	71	63	68	29	31	31	20	57	62	43	38	74	54	66	63	70	70	70	53	66	70	71	72
	7:45 AM	69	19	40	46	27	24	48	65	68	62	67	70	73	72	72	60	73	67	71	18	23	23	21	57	66	50	40	74	54	65	62	68	70	70	53	64	69	71	72
	8:00 AM	56	22	31	19	17	22	37	55	55	44	62	68	72	72	71	57	72	66	71	26	26	27	22	56	62	46	40	74	53	65	61	69	70	70	50	62	66	70	72
	8:15 AM	74	29	29	31	19	23	34	50	45	36	58	63	69	71	71	51	72	66	71	31	30	30	22	56	42	39	39	74	53	65	62	72	70	71	55	66	68	71	72
	8:30 AM	75	69	29	25	20	22	27	48	36	34	57	66	71	71	70	47	72	62	71	39	38	31	22	56	34	37	37	70	55	64	60	73	71	72	56	69	69	71	73
	8:45 AM	75	72	29	17	19	19	24	46	34	33	56	66	71	71	70	46	70	63	71	50	46	37	24	56	28	27	22	72	57	69	63	73	72	73	62	71	72	72	73
	9:00 AM	75	73	37	18	18	19	24	44	32	33	56	63	69	70	70	48	71	67	71	54	51	49	27	32	22	22	23	70	55	65	61	73	72	72	59	71	72	72	74
	9:15 AM	75	74	67	28	19	20	24	42	34	32	54	59	69	70	70	50	73	67	72	64	62	52	20	23	29	34	32	69	56	64	61	73	72	73	62	70	72	73	73
	9:30 AM	75	74	72	64	29	29	25	43	42	38	55	63	69	70	70	54	72	68	71	64	63	65	50	35	32	36	35	51	55	66	60	73	72	73	67	71	72	73	73
	9:45 AM	75	73	72	67	61	54	30	48	59	56	62	60	68	70	70	61	72	69	70	61	61	64	60	49	36	38	36	67	54	65	61	72	71	71	62	68	70	72	73
	10:00 AM	75	74	73	68	69	66	54	58	62	58	66	68	71	72	72	66	73	71	72	67	67	66	66	59	49	45	39	71	54	64	63	72	71	71	65	70	70	72	73
Dyn Speed Limits + SPD-HARM 50%	6:15 AM	66	54	56	46	48	53	45	50	64	59	62	68	71	71	71	63	72	70	71	66	62	67	69	62	68	67	67	74	63	68	72	73	71	72	72	74	74	74	74
	6:30 AM	58	44	40	30	30	41	40	46	54	45	59	67	70	71	70	60	72	69	70	64	61	63	57	58	63	57	57	71	58	66	67	68	67	66	67	72	73	72	73
	6:45 AM	44	35	23	25	26	33	36	41	38	29	55	67	71	70	68	56	71	67	69	59	54	56	49	55	59	52	51	67	52	64	64	66	65	64	62	70	71	70	73
	7:00 AM	33	18	23	45	39	40	31	37	33	26	53	67	71	69	67	53	70	64	65	52	47	50	43	52	56	49	45	63	49	63	64	67	65	64	57	63	66	69	72
	7:15 AM	18	20	36	48	45	45	35	38	38	29	53	67	70	67	65	51	64	60	57	38	35	44	32	49	47	38	31	58	45	62	61	65	63	63	53	63	67	69	72
	7:30 AM	18	32	32	50	42	39	37	44	44	37	56	65	66	61	59	47	51	53	43	25	26	37	22	46	44	31	27	56	44	63	58	62	58	59	47	62	66	68	72
	7:45 AM	19	22	20	41	24	19	44	57	63	57	63	62	59	52	50	38	41	51	33	18	23	30	20	45	44	31	26	57	45	63	57	61	56	57	46	58	64	67	71
	8:00 AM	16	15	21	21	12	16	41	54	62	55	62	62	58	51	50	38	41	52	33	20	26	32	22	45	42	31	26	55	44	62	56	61	56	56	44	57	63	66	72
	8:15 AM	13	13	24	18	15	25	35	46	49	39	57	60	58	52	50	38	43	53	34	22	27	35	23	44	36	29	25	55	43	62	58	62	58	57	45	56	60	62	72
	8:30 AM	12	14	28	28	18	31	26	39	35	27	52	57	55	49	47	33	42	51	34	23	26	34	22	41	28	27	25	54	43	62	61	65	62	61	50	62	62	64	73
	8:45 AM	14	17	30	23	18	21	22	35	25	24	51	58	55	49	47	33	43	52	36	23	27	33	21	35	21	19	16	63	51	67	62	66	65	64	58	65	66	66	73
	9:00 AM	22	15	25	20	17	18	20	29	22	22	51	58	56	50	48	34	44	53	37	24	25	29	18	27	16	16	16	56	46	62	60	66	65	65	57	64	64	67	73
	9:15 AM	30	21	28	20	16	17	19	25	22	22	51	57	57	52	51	38	47	55	40	29	25	24	17	19	17	18	18	56	44	63	60	66	64	63	56	65	65	67	73
	9:30 AM	35	29	30	22	18	19	19	25	23	22	51	60	61	57	56	44	51	58	44	34	28	26	21	24	19	19	18	52	43	61	58	66	66	65	62	65	66	68	73
	9:45 AM	42	36	40	35	27	26	20	27	24	22	51	60	64	62	60	50	53	58	45	36	30	29	22	20	29	24	20	56	45	63	61	66	64	63	57	65	66	68	72
	10:00 AM	53	46	51	47	42	38	28	29	26	24	52	61	62	58	56	47	47	56	40	31	25	22	15	19	44	39	35	63	49	64	64	68	65	65	61	64	65	67	73

Figure 8-17: Speed contour with Dynamic Speed Limits and SPD-HARM with 50% penetration rate compared with the baseline case



			El Norte Parkway		West Valley Parkway			Felicita Rd				Via Rancho Parkway		Pomerado Rd				Rancho Bernardo Rd			Camino del Norte					Ted Williams Parkway					Mira Mesa Blvd			Miramar Rd					Split I-15 / SR-163	
	Time	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
BASE	6:15 AM	74	58	60	53	53	59	45	49	59	51	61	68	72	72	71	65	73	70	72	67	64	67	69	63	69	68	70	75	63	69	73	75	73	74	73	74	75	74	75
	6:30 AM	73	56	46	49	32	38	45	51	44	35	58	67	72	72	72	63	73	71	71	66	62	67	58	60	69	67	69	75	59	67	72	74	73	73	69	73	74	74	74
	6:45 AM	72	52	36	43	26	30	40	47	35	33	56	67	72	71	71	61	72	69	71	64	60	64	48	58	69	66	67	75	56	67	69	74	72	72	61	72	73	73	74
	7:00 AM	70	35	39	55	39	34	33	44	33	32	55	67	72	71	71	60	72	67	70	60	56	62	39	58	68	61	58	75	54	67	67	73	71	72	61	70	72	72	73
	7:15 AM	71	27	41	53	65	62	33	47	37	34	56	66	71	71	71	58	71	66	69	47	44	57	26	57	65	50	41	75	54	65	64	72	71	72	59	69	72	72	73
	7:30 AM	69	33	38	53	54	56	45	60	51	42	60	67	71	71	71	59	71	63	68	29	31	31	20	57	62	43	38	74	54	66	63	70	70	70	53	66	70	71	72
	7:45 AM	69	19	40	46	27	24	48	65	68	62	67	70	73	72	72	60	73	67	71	18	23	23	21	57	66	50	40	74	54	65	62	68	70	70	53	64	69	71	72
	8:00 AM	56	22	31	19	17	22	37	55	55	44	62	68	72	72	71	57	72	66	71	26	26	27	22	56	62	46	40	74	53	65	61	69	70	70	50	62	66	70	72
	8:15 AM	74	29	29	31	19	23	34	50	45	36	58	63	69	71	71	51	72	66	71	31	30	30	22	56	42	39	39	74	53	65	62	72	70	71	55	66	68	71	72
	8:30 AM	75	69	29	25	20	22	27	48	36	34	57	66	71	71	70	47	72	62	71	39	38	31	22	56	34	37	37	70	53	64	60	73	71	72	56	69	69	71	73
	8:45 AM	75	72	29	17	19	19	24	46	34	33	56	66	71	71	70	46	70	63	71	50	46	37	24	56	28	27	22	72	57	69	63	73	72	73	62	71	72	72	73
	9:00 AM	75	73	37	18	18	19	24	44	32	33	56	63	69	70	70	48	71	67	71	54	51	49	27	32	22	22	23	70	55	65	61	73	72	72	59	71	72	72	74
	9:15 AM	75	74	67	28	19	20	24	42	34	32	54	59	69	70	70	50	73	67	72	64	62	52	20	23	29	34	32	69	56	64	61	73	72	73	62	70	72	73	73
	9:30 AM	75	74	72	64	29	29	25	43	42	38	55	63	69	70	70	54	72	68	71	64	63	65	50	35	32	36	35	51	55	66	60	73	72	73	67	71	72	73	73
	9:45 AM	75	73	72	67	61	54	30	48	59	56	62	60	68	70	70	61	72	69	70	61	61	64	60	49	36	38	36	67	54	65	61	72	71	71	62	68	70	72	73
	10:00 AM	75	74	73	68	69	66	54	58	62	58	66	68	71	72	72	66	73	71	72	67	67	66	66	59	49	45	39	71	54	64	63	72	71	71	65	70	70	72	73
	Time	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Dyn Speed Limits + SPD-HARM 90%	6:15 AM	64	52	53	44	47	52	44	50	65	62	63	69	71	71	70	63	72	70	71	67	62	67	68	62	67	65	66	73	63	68	71	71	70	70	72	72	74	74	74
	6:30 AM	57	44	39	28	32	40	38	46	62	57	62	68	71	70	69	59	71	69	70	62	58	62	56	57	61	55	55	69	58	64	66	65	65	63	64	69	70	71	72
	6:45 AM	47	37	23	28	25	29	35	43	42	34	57	67	70	69	67	55	70	66	67	55	51	54	48	55	58	51	50	65	53	63	64	65	63	62	55	65	66	70	72
	7:00 AM	37	18	25	47	39	39	28	39	36	29	54	66	70	67	65	50	68	63	62	46	44	48	41	52	54	46	42	59	46	62	63	66	62	62	54	62	64	70	72
	7:15 AM	19	19	37	43	39	41	28	39	40	32	54	66	68	64	61	47	62	57	55	34	33	44	28	48	43	34	31	57	45	62	59	63	61	61	54	61	61	69	72
	7:30 AM	22	21	26	44	38	36	33	42	44	37	55	63	63	58	55	41	51	50	42	20	25	36	20	46	39	32	31	57	45	62	55	59	56	58	44	58	61	68	71
	7:45 AM	16	13	22	42	38	36	38	49	53	46	59	62	58	52	49	35	44	43	23	16	22	24	19	45	43	33	30	55	43	61	54	57	54	55	42	55	62	65	71
	8:00 AM	14	18	29	24	18	21	35	48	52	44	55	57	53	47	44	32	38	35	16	16	22	29	21	45	41	35	29	55	44	61	55	58	54	54	41	48	51	63	71
	8:15 AM	15	16	26	25	20	24	27	43	44	35	52	54	51	45	43	29	37	32	19	17	25	35	22	43	29	29	27	57	46	61	54	59	56	56	43	52	55	63	71
	8:30 AM	20	15	27	28	30	31	24	39	32	27	51	54	53	47	44	30	40	29	20	17	23	29	20	39	25	25	24	55	45	61	58	63	60	60	47	58	59	64	72
	8:45 AM	36	21	30	30	21	22	22	37	26	26	48	53	52	46	43	31	40	40	21	18	22	24	19	32	19	17	16	63	53	65	60	64	63	61	56	61	62	65	73
	9:00 AM	48	36	26	23	18	18	21	33	26	25	48	53	54	48	46	33	42	47	21	17	18	18	14	21	17	16	17	53	44	62	59	64	61	62	54	60	61	65	72
	9:15 AM	57	48	36	25	20	20	21	29	24	24	47	51	53	48	45	33	40	47	22	15	16	18	17	23	25	22	21	49	41	60	57	63	62	62	55	60	62	65	72
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	10:00 AM	72	69	63	55	53	50	38	42	37	33	52	57	59	55	52	43	45	47	36	19	15	14	14	21	57	51	52	62	49	65	63	67	66	65	60	60	61	64	73

Figure 8-18: Speed contour with Dynamic Speed Limits and SPD-HARM with 90% penetration rate compared with the baseline case

If we compare network-wide traffic performance measures with Dynamic Speed Limits and SPD-HARM with different penetration rates concurrently active with the baseline condition and with the case of only Dynamic Speed Limits or only SPD-HARM active (Table 8-7 and Figure 8-19), we can notice that the results become similar to the situation with SPD-HARM only as the penetration rate increases; this is intuitive because as the number of connected vehicles increase, the number of vehicles that respond to SDP-HARM increases and the number of vehicles that respond to Dynamic Speed Limits decreases.

In summary, the results show a synergy between these ATDM strategy and DMA application. With low penetration rates of connected vehicles, the number of vehicles affected by SPD-HARM is reduced, and the activation of an ATDM strategy that targets non-connected vehicles allows producing a higher shockwave reduction. As the penetration rate of connected vehicles approaches 90%, the contribution of Dynamic Speed Limits gets less significant, though still positive.

Table 8-7: Performance measures with Dynamic Speed Limits and SPD-HARM with different penetration rates compared with the baseline case and with the activation of individual ATDM strategies and DMA applications

Network Statistics	Base	Dyn Speed Limits + SPD-HARM 25%	Difference	SPD-HARM 25%	Difference	Dynamic Speed Limit	Difference
Vehicle Miles Traveled (mi)	2,320,947	2,323,846	0.1%	2,340,587	0.8%	2,295,970	-1.1%
Total Travel Time (h)	61,946	65,807	6.2%	64,185	3.6%	63,713	2.9%
Passenger Hourly Travel Time (h)	78,635	83,711	6.5%	81,499	3.6%	80,972	3.0%
VMT/VHT (mi/h)	37.47	35.31	-5.7%	36.47	-2.7%	36.04	-3.8%
Spatial speed drop (mi/h)	15.0	12.2	-18.7%	12.6	-16.0%		
Temporal speed drop (mi/h)	11.0	9.0	-18.2%	9.8	-10.9%		

Network Statistics	Base	Dyn Speed Limits + SPD-HARM 50%	Difference	SPD-HARM 50%	Difference	Dynamic Speed Limit	Difference
Vehicle Miles Traveled (mi)	2,320,947	2,331,078	0.4%	2,350,332	1.3%	2,295,970	-1.1%
Total Travel Time (h)	61,946	67,963	9.7%	66,744	7.7%	63,713	2.9%
Passenger Hourly Travel Time (h)	78,635	86,352	9.8%	84,659	7.7%	80,972	3.0%
VMT/VHT (mi/h)	37.47	34.30	-8.5%	35.21	-6.0%	36.04	-3.8%
Spatial speed drop (mi/h)	15.0	10.0	-33.3%	10.4	-30.7%		
Temporal speed drop (mi/h)	11.0	7.0	-36.4%	7.0	-36.4%		

Network Statistics	Base	Dyn Speed Limits + SPD-HARM 90%	Difference	SPD-HARM 90%	Difference	Dynamic Speed Limit	Difference
Vehicle Miles Traveled (mi)	2,320,947	2,347,075	1.1%	2,351,385	1.3%	2,295,970	-1.1%
Total Travel Time (h)	61,946	69,237	11.8%	68,997	11.4%	63,713	2.9%
Passenger Hourly Travel Time (h)	78,635	87,550	11.3%	87,306	11.0%	80,972	3.0%
VMT/VHT (mi/h)	37.47	33.90	-9.5%	34.08	-9.0%	36.04	-3.8%
Spatial speed drop (mi/h)	15.0	9.8	-34.7%	10.0	-33.3%		
Temporal speed drop (mi/h)	11.0	6.0	-45.5%	6.2	-43.6%		

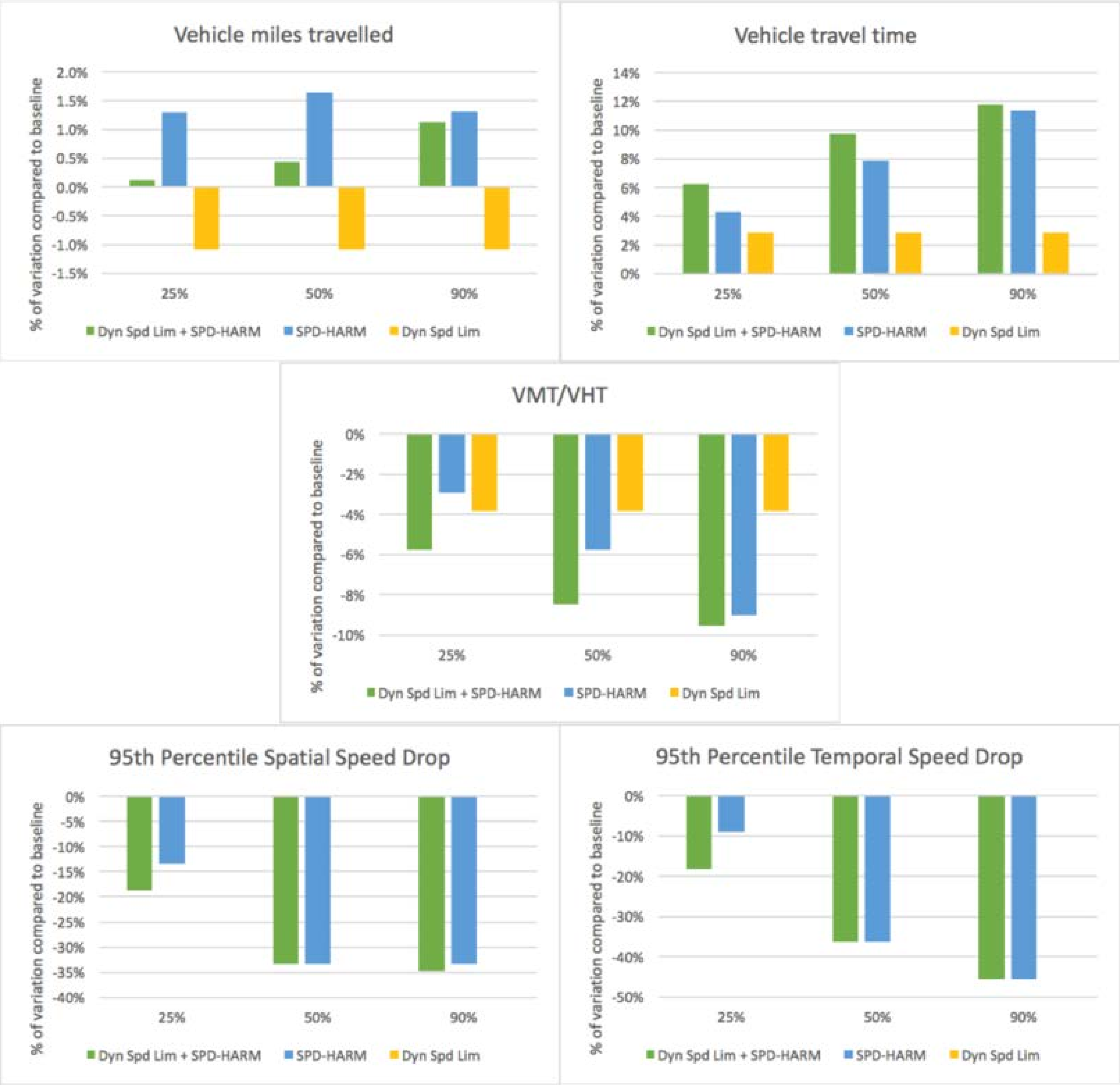

Figure 8-19: Performance measures with Dynamic Speed Limits and SPD-HARM with different penetration rates compared with the baseline case and with the activation of individual ATDM strategies and DMA applications

8.2.7 SPD-HARM and Predictive Traveler Information

A set of simulations was run with SPD-HARM with different penetration rates of connected vehicles (see 6.1) and dynamic routing based on predictive traveler information (see 7.2.1).A comparison of the speed contour on I-15 in the southbound direction with the baseline conditions shows that SPD-HARM produce a “dilution” of the congestion over space and time that becomes more pronounced as the penetration rate of connected vehicles increase (Figure 8-20, Figure 8-21 and Figure 8-22), which suggests an improvement in safety.

If we compare network-wide traffic performance measures with Predictive Traveler Information and SPD-HARM with different penetration rates concurrently active with the baseline condition and with the case of only Predictive Traveler Information or only SPD-HARM active (Table 8-8 and Figure 8-19), we can notice that the results become similar to the situation with SPD-HARM only as the penetration rate increases. However, even at the highest penetration rate the shockwave improvement doesn't reach the same levels as SPD-HARM alone, while the traffic performance degrades even more than with SPD-HARM alone.

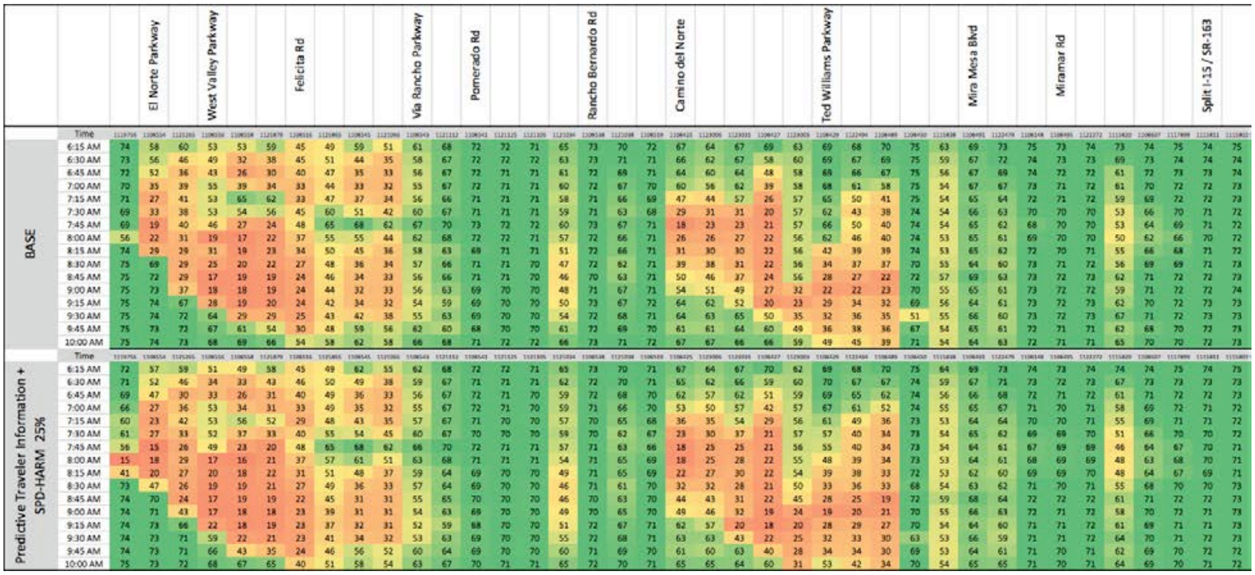

Figure 8-20: Speed contour with Predictive Traveler Information and SPD-HARM with 25% penetration rate compared with the baseline case

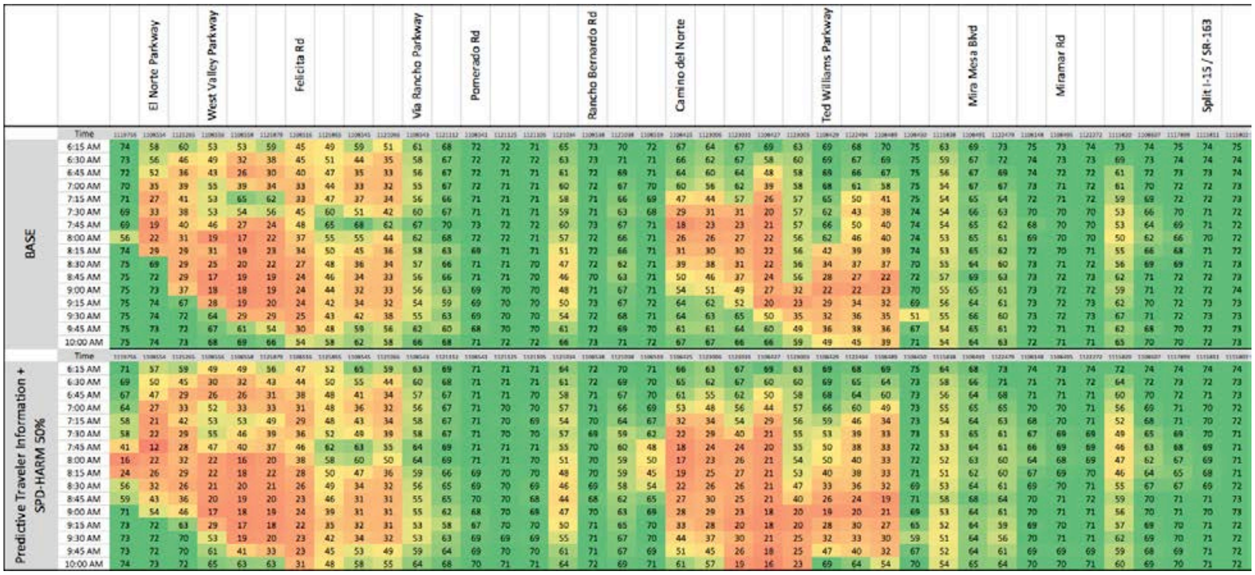

Figure 8-21: Speed contour with Predictive Traveler Information and SPD-HARM with 50% penetration rate compared with the baseline case

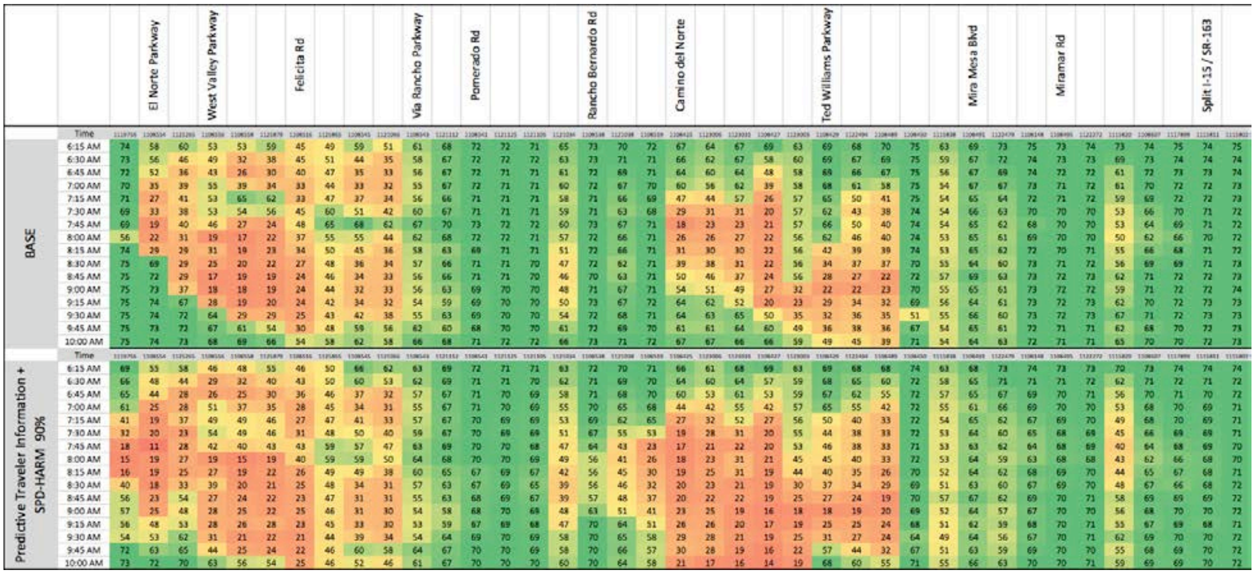

Figure 8-22: Speed contour with Predictive Traveler Information and SPD-HARM with 90% penetration rate compared with the baseline case

Table 8-8: Performance measures with Predictive Traveler Information and SPD-HARM with different penetration rates compared with the baseline case and with the activation of individual ATDM strategies and DMA applications

Network Statistics	Base	Predictive Traveler Information + SPD-HARM 25%	Difference	SPD-HARM 25%	Difference	Predictive Traveler Information	Difference
Vehicle Miles Traveled (mi)	2,320,947	2,332,893	0.5%	2,340,587	0.8%	2,322,078	0.0%
Total Travel Time (h)	61,946	62,502	0.9%	64,185	3.6%	61,920	0.0%
Passenger Hourly Travel Time (h)	78,635	79,365	0.9%	81,499	3.6%	78,727	0.1%
VMT/VHT (mi/h)	37.47	37.33	-0.4%	36.47	-2.7%	37.50	0.1%
Spatial speed drop (mi/h)	15.0	14.0	-6.7%	12.6	-16.0%		
Temporal speed drop (mi/h)	11.0	10.6	-3.6%	9.8	-10.9%		
Network Statistics	**Base**	**Predictive Traveler Information + SPD-HARM 50%**	**Difference**	**SPD-HARM 50%**	**Difference**	**Predictive Traveler Information**	**Difference**
Vehicle Miles Traveled (mi)	2,320,947	2,333,617	0.5%	2,350,332	1.3%	2,322,078	0.0%
Total Travel Time (h)	61,946	63,454	2.4%	66,744	7.7%	61,920	0.0%
Passenger Hourly Travel Time (h)	78,635	80,335	2.2%	84,659	7.7%	78,727	0.1%
VMT/VHT (mi/h)	37.47	36.78	-1.8%	35.21	-6.0%	37.50	0.1%
Spatial speed drop (mi/h)	15.0	12.6	-16.0%	10.4	-30.7%		
Temporal speed drop (mi/h)	11.0	8.0	-27.3%	7.0	-36.4%		
Network Statistics	**Base**	**Predictive Traveler Information + SPD-HARM 90%**	**Difference**	**SPD-HARM 90%**	**Difference**	**Predictive Traveler Information**	**Difference**
Vehicle Miles Traveled (mi)	2,320,947	2,354,493	1.4%	2,350,961	1.3%	2,322,078	0.0%
Total Travel Time (h)	61,946	67,865	9.6%	64,617	4.3%	61,920	0.0%
Passenger Hourly Travel Time (h)	78,635	85,859	9.2%	81,982	4.3%	78,727	0.1%
VMT/VHT (mi/h)	37.47	34.69	-7.4%	36.38	-2.9%	37.50	0.1%
Spatial speed drop (mi/h)	15.0	12.2	-18.7%	10.0	-33.3%		
Temporal speed drop (mi/h)	11.0	6.8	-38.2%	6.2	-43.6%		

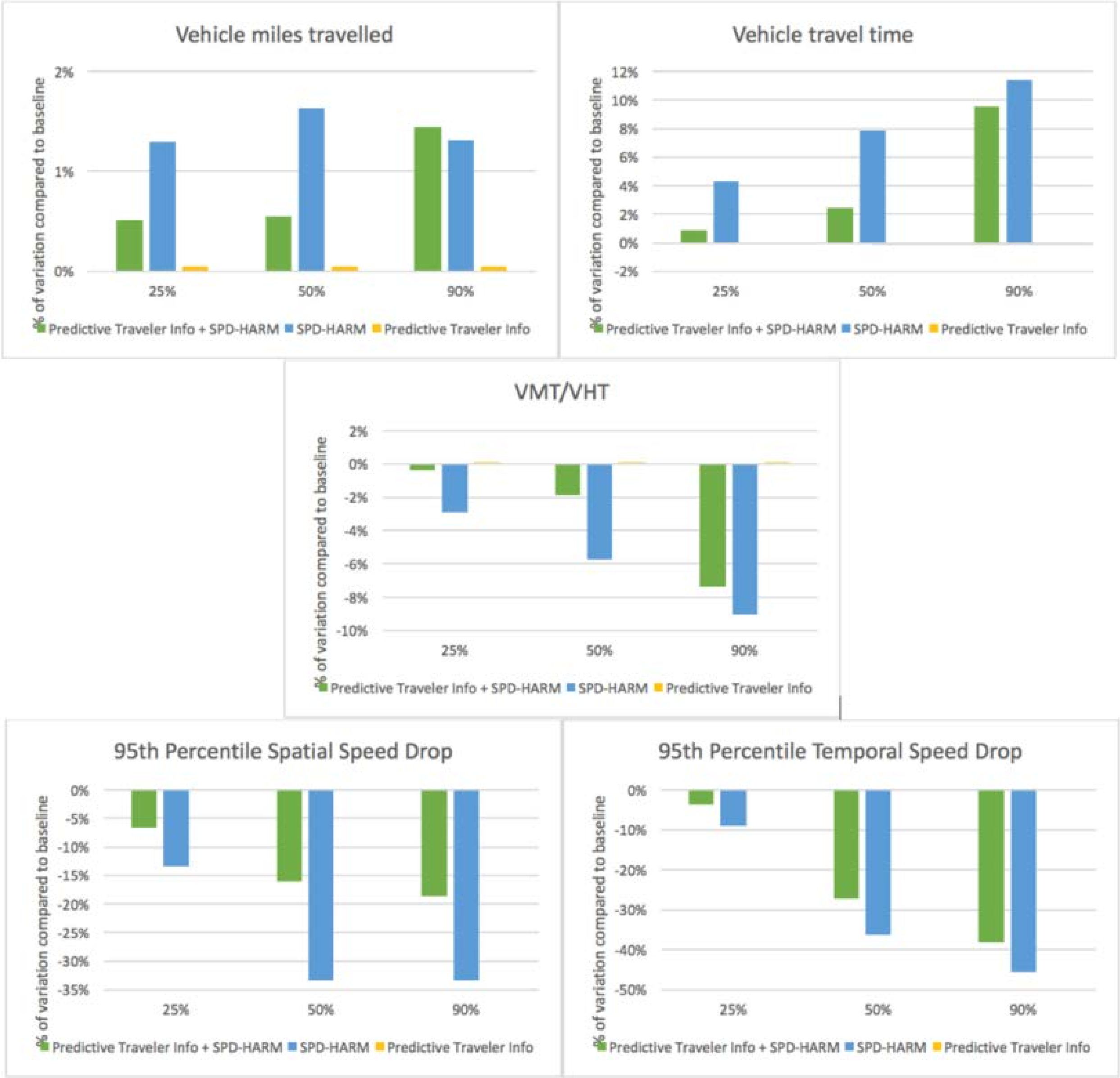

Figure 8-23: Performance measures with Predictive Traveler Information and SPD-HARM with different penetration rates compared with the baseline case and with the activation of individual ATDM strategies and DMA applications

In summary, the results don't show good synergy between these ATDM strategy and DMA application. With low penetration rates of connected vehicles, the shockwave reduction is limited, and the increase of throughput reduced compared to SPD-HARM alone. As the penetration rate of connected vehicles approaches 90%, the gain in terms of shockwave reduction doesn't increase as quickly as with SPD-HARM alone, but the travel time increases significantly more.

The reason may be that predictions are made without taking into account what speeds SPD-HARM will suggest, and SPD-HARM operates without knowing what rerouting has been triggered by predictive travel time information[15]. It is therefore expected that a tighter integration between these two ATDM strategy and DMA application, with some interchange of information, would solve the conflict identified in this analysis.

8.3 Summary of Results

A set of simulation scenarios was run to assess the impact of DMA applications and ATDM strategies deployed in combination, and identify synergies and conflicts between them. The results confirm the hypotheses: some DMA applications and/or ATDM strategies show synergy and produce higher benefits when deployed together, while other show conflicts and produce reduced benefits when deployed together.

Synergy between SPD-HARM and CACC appeared to be minimal: at all penetration rates the effect of SPD-HARM seems to prevail over CACC, even though the vehicles engaged by CACC are not affected by SPD-HARM messages, and in fact it seems to neutralize the benefit in terms of traffic performance that CACC produces when deployed alone.

At low penetration rates the results show some synergy in terms of shockwave reduction; however, at high penetration rates the shockwave reduction is similar to that produced by SPD-HARM alone, and at 50% penetration rate the two DMA applications seem to produce a clear conflict, with lower traffic performance than each application alone, and less shockwave reduction than SPD-HARM alone. The explanation is that at 50% penetration rate CACC platoons are long enough to constitute an impediment for lane-changing of non-connected vehicles, and the addition of SPD-HARM introduces a heterogeneity in the desired speed of non-connected vehicles, which are not affected by SPD-HARM, compared to connected vehicles, which are affected; this increases the desire for non-connected vehicles to overtake connected vehicles, and thus exacerbates the lane-changing issue.

Dynamic Lane Use, Dynamic HOV/Managed Lanes and Dynamic Speed Limits show neither a significant conflict nor a significant synergy. The increase of congestion at the entrances and exits of the HOV lanes due to the increase of demand triggered by Dynamic Lane Use, Dynamic HOV/Managed Lanes is sensed by Dynamic Speed Limits, which extends the congestion over a larger space and longer time in order to avoid abrupt speed changes. This increase of safety is obtained at the expense of throughput and travel time. Dynamic Lane Use and Dynamic HOV/Managed Lanes alone would produce better traffic performance, at the expense of safety. Dynamic Speed Limits alone would produce an increase of safety, but with a more pronounced reduction of throughput. The combined effect of having an increase of safety with less reduction of throughput can be interpreted as a good compromise, which can be considered a synergy.

Dynamic Merge Control and Dynamic HOV/Managed Lanes show a synergy: Dynamic HOV/Managed Lanes compensate the slightly negative effect in terms of traffic performance caused by Dynamic Merge Control, which facilitates the entrance from SR-78, at the expense of penalizing traffic coming from the northern boundary of the I-15 corridor in the southbound direction. In other words, the decision to activate Dynamic Merge Control or not should be dictated purely by the need to reduce queueing on the ramp coming from SR-78 rather than by overall traffic performance benefits, and if Dynamic Merge Control is activated, Dynamic HOV/Managed Lanes would compensate its slightly negative impact on throughput.

Dynamic Merge Control, Dynamic HOV/Managed Lanes and Dynamic Routing show also a synergy: Dynamic HOV/Managed Lanes and Dynamic Routing compensate the slightly negative effect in terms of traffic performance caused by Dynamic Merge Control, which facilitates the entrance from SR-78, at the

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[15] The Windows application emulating INFLO cannot be started programmatically (it requires user interaction) and therefore cannot be interface with the Predictive Traveler Information framework. This doesn't allow the evaluation of a tighter integration between these ATDM strategy and DMA application.

expense of penalizing traffic coming from the northern boundary of the I-15 corridor in the southbound direction. Again, the decision to activate Dynamic Merge Control or not should be dictated purely by the need to reduce queueing on the ramp coming from SR-78 rather than by overall traffic performance benefits, and if Dynamic Merge Control is activated, Dynamic HOV/Managed Lanes and Dynamic Routing would compensate its slightly negative impact on throughput.

SPD-HARM and Dynamic Merge Control show also a synergy: the benefit in terms of SPD-HARM alone in terms of shockwave reduction are not affected by Dynamic Merge Control, and the throughput reduction caused by Dynamic Merge Control is compensated by SPD-HARM. Again, the decision to activate Dynamic Merge Control or not should be dictated purely by the need to reduce queueing on the ramp coming from SR-78 rather than by overall traffic performance benefits, and if Dynamic Merge Control is activated, SPD-HARM would compensate its slightly negative impact on throughput.

SPD-HARM and Dynamic Speed Limits show a synergy in terms of safety improvement: with low penetration rates of connected vehicles, the number of vehicles affected by SPD-HARM is reduced, and the activation of an ATDM strategy that targets non-connected vehicles allows producing a higher shockwave reduction. As the penetration rate of connected vehicles approaches 90%, the contribution of Dynamic Speed Limits gets less significant, though still positive.

SPD-HARM and Predictive Traveler Information don’t show good synergy: with low penetration rates of connected vehicles, the shockwave reduction is limited, and the increase of throughput reduced compared to SPD-HARM alone; as the penetration rate of connected vehicles approaches 90%, the gain in terms of shockwave reduction doesn’t increase as quickly as with SPD-HARM alone, but the travel time increases significantly more. The explanation is that predictions are made without taking into account what speeds SPD-HARM will suggest, and SPD-HARM operates without knowing what rerouting has been triggered by predictive travel time information. It is therefore expected that a tighter integration between these two ATDM strategy and DMA application, with some interchange of information, would solve the conflict identified in this analysis.

Chapter 9. Operational Conditions with Most Benefit

This chapter analyses the effectiveness of DMA applications and ATDM strategies under different operational conditions. The evaluation was performed under four different operational conditions.

9.1 Research Questions

The following research questions are answered using this analysis:

1. Under what operational conditions are specific DMA applications the most beneficial?
2. Which ATDM strategy will be the most beneficial under what operational conditions?

The given research questions try to answer a plethora of topics related to operational conditions, and facility types. The tactical applications/bundles, such as INFLO, and MMITSS, are specific to a facility type. In order to answer these questions, the following hypotheses were made:

1. A DMA application will yield the highest benefits only under certain operational conditions. For example, on non-incident days, SPD-HARM will have a limited impact.
2. Certain ATDM strategies will yield the highest benefits under certain operational conditions.

9.2 Analysis Approach

Each DMA application and ATDM strategy was evaluated in isolation under four different operational condition (see 3.2). The first two operational conditions (AM1 and AM2) represent a morning peak situation (i.e. higher traffic in the southbound direction) with medium demand and a medium (AM1) or high accident (AM2) affecting the southbound direction. The other two operational conditions (PM3 and PM4) represent an evening peak situation (i.e. higher traffic in the northbound direction) with medium demand and a medium (PM4) or high accident (PM3) affecting the northbound direction.

The DMA applications that have been tested are:

- SPD-HARM (part of the INFLO bundle)
- CACC (part of the INFLO bundle)

The ATDM strategies that have been tested are:

- Dynamic Lane Use and Dynamic HOV/Managed Lanes
- Dynamic Speed Limits
- Dynamic Merge Control
- Predictive Traveler Information with Dynamic Routing

Simulations were conducted activating on top of the baseline model a DMA application or ATDM strategy, modeled as described in Chapters 6 and 7. The performance measures obtained in these simulations have been compared with the baseline case.

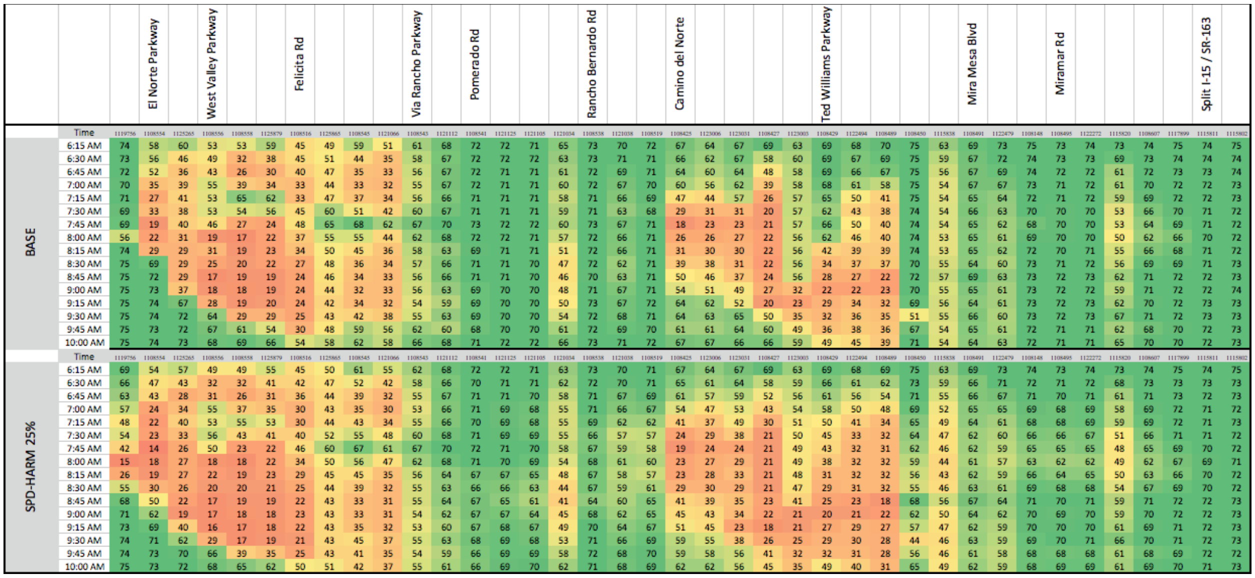
In all the evaluations of DMA applications presented in this chapter, which are based on connected vehicles (SPD-HARM and CACC), perfect communication was assumed. The impact of communication issues on the effectiveness of these applications in isolation has been evaluated with a separate set of simulations, whose results are presented in Chapter 10. .

9.2.1 SPD-HARM

SPD-HARM is a part of the INFLO bundle. Simulations were run with different penetration rates of connected vehicles (25%, 50% and 90%). Q-WARN was modelled as 100% compliance of the connected vehicles to SPD-HARM speed advisories (see Section 6.1).

9.2.1.1 Operational condition 1 (AM1)

A comparison of the speed contour on I-15 in the southbound direction with the baseline conditions shows that SPD-HARM produces a “dilution” of the congestion over space and time (Figure 9-1, Figure 9-2 and Figure 9-3), which suggests an improvement in safety. This effect increases as the penetration rate increases.



			El Norte Parkway		West Valley Parkway			Felicita Rd				Via Rancho Parkway		Pomerado Rd				Rancho Bernardo Rd			Camino del Norte					Ted Williams Parkway					Mira Mesa Blvd			Miramar Rd					Split I-15 / SR-163	
	Time	1119756	1108554	1125265	1108556	1108558	1125879	1108516	1125865	1108545	1121066	1108543	1121112	1108541	1121125	1121105	1121034	1108538	1121038	1108519	1108425	1123006	1123031	1108427	1123003	1108429	1122494	1108489	1108450	1115838	1108491	1122479	1108148	1108495	1122272	1115820	1108607	1117899	1115811	1115802
BASE	6:15 AM	74	58	60	53	53	59	45	49	59	51	61	68	72	72	71	65	73	70	72	67	64	67	69	63	69	68	70	75	63	69	73	75	73	74	73	74	75	74	75
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	7:00 AM	70	35	39	55	39	34	33	44	33	32	55	67	72	71	71	60	72	67	70	60	56	62	39	58	68	61	58	75	54	67	67	73	71	72	61	70	72	72	73
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	10:00 AM	75	74	73	68	69	66	54	58	62	58	66	68	71	72	72	66	73	71	72	67	67	66	66	59	49	45	39	71	54	64	63	72	71	71	65	70	70	72	73
	Time	1119756	1108554	1125265	1108556	1108558	1125879	1108516	1125865	1108545	1121066	1108543	1121112	1108541	1121125	1121105	1121034	1108538	1121038	1108519	1108425	1123006	1123031	1108427	1123003	1108429	1122494	1108489	1108450	1115838	1108491	1122479	1108148	1108495	1122272	1115820	1108607	1117899	1115811	1115802
SPD-HARM 25%	6:15 AM	69	54	57	49	49	55	45	50	61	55	62	68	72	72	71	63	73	70	71	67	64	67	69	63	69	68	69	75	63	69	73	74	73	74	73	74	75	74	75
	6:30 AM	66	47	43	32	32	41	42	47	52	42	58	66	70	71	71	62	72	70	71	65	61	64	58	59	66	61	62	73	59	66	71	72	71	72	68	73	73	73	73
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	7:30 AM	54	23	33	56	43	41	40	52	55	48	60	68	71	69	69	55	66	57	57	24	29	38	21	50	45	33	32	64	47	62	60	66	66	67	51	66	71	71	72
	7:45 AM	42	14	26	50	23	22	46	60	67	61	67	70	72	71	70	58	67	59	58	19	24	24	21	49	43	32	31	62	46	62	59	65	65	65	48	65	69	70	72
	8:00 AM	15	18	27	18	18	22	34	50	56	47	62	68	71	70	69	54	68	61	60	23	27	29	21	49	38	32	32	59	44	61	57	63	62	62	49	62	67	69	71
	8:15 AM	26	19	27	22	19	23	29	45	45	35	56	64	67	67	65	48	67	58	57	23	28	33	21	48	31	32	32	56	43	62	59	66	64	65	50	63	66	70	72
	8:30 AM	55	30	26	20	20	21	25	44	39	32	55	63	66	66	63	44	67	59	61	29	30	29	21	47	29	31	32	55	46	63	61	69	68	68	54	67	69	70	72
	8:45 AM	68	50	22	17	19	19	22	43	33	31	55	64	67	65	61	41	64	60	65	41	39	35	23	41	25	23	18	68	56	67	64	71	70	71	59	71	72	72	73
	9:00 AM	71	62	19	17	18	18	23	43	33	31	54	62	67	67	64	45	68	62	65	45	43	34	22	21	20	21	22	62	50	64	62	70	69	70	59	70	72	72	73
	9:15 AM	73	69	40	16	17	18	22	43	35	32	53	60	67	68	67	49	70	64	67	51	45	23	18	21	27	29	27	57	47	62	59	70	70	70	61	69	71	72	73
	9:30 AM	74	71	62	29	17	19	21	43	45	37	55	63	68	69	68	53	71	66	69	59	55	38	26	25	29	30	28	44	46	63	59	69	70	71	66	70	71	72	73
	9:45 AM	74	73	70	66	39	35	25	43	41	35	54	59	66	69	69	58	72	68	70	59	58	56	41	32	32	31	28	56	46	61	58	68	68	68	61	68	69	72	72
	10:00 AM	75	73	72	68	65	62	50	51	42	37	55	61	66	69	70	62	71	68	69	62	62	56	45	35	49	40	31	65	49	62	59	68	69	69	61	69	70	71	73

Figure 9-1: Speed contour with SPD-HARM with 25% penetration rate compared with the baseline case under Operational Condition 1

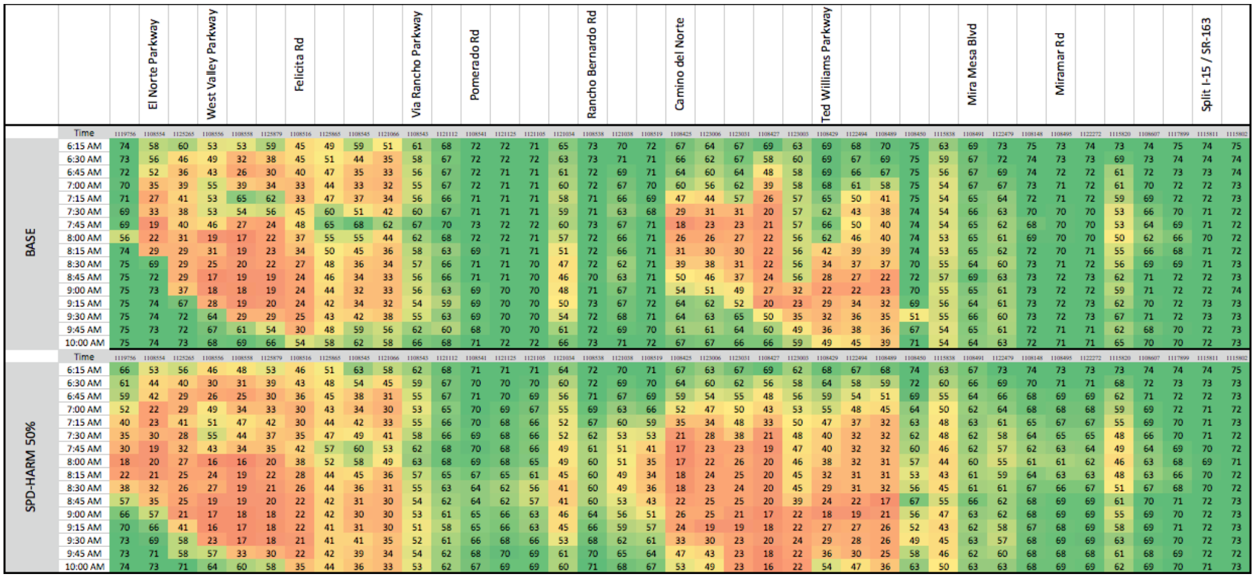


Figure 9-2: Speed contour with SPD-HARM with 50% penetration rate compared with the baseline case under Operational Condition 1

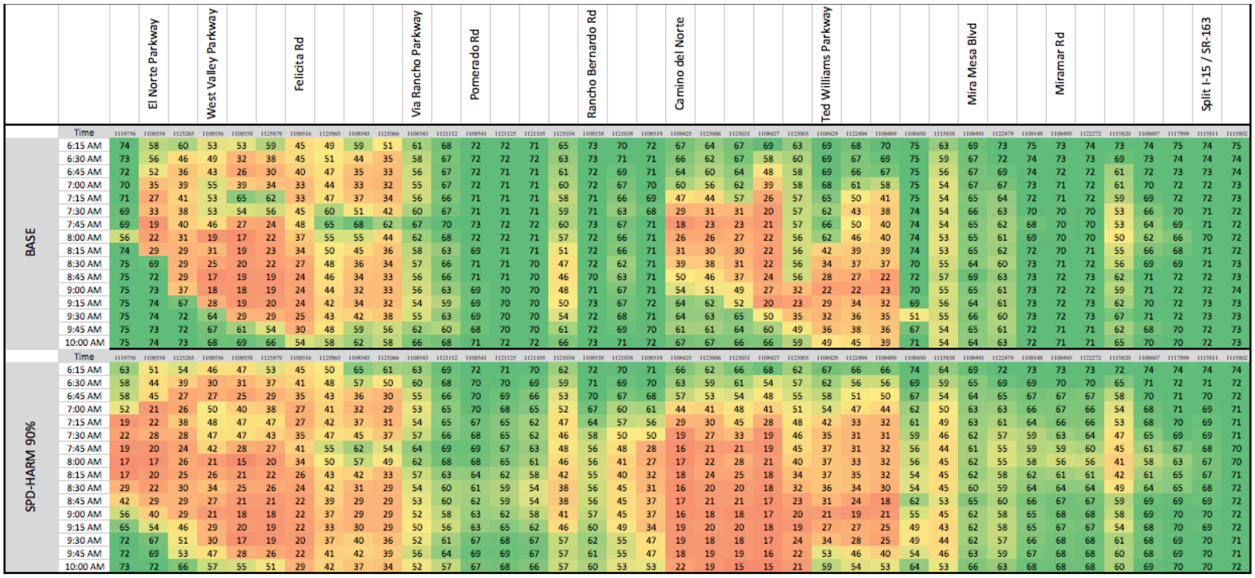


Figure 9-3: Speed contour with SPD-HARM with 90% penetration rate compared with the baseline case under Operational Condition 1

If we compare network-wide traffic performance measures with SPD-HARM with different penetration rates with the baseline condition (Table 9-1, Table 9-2 and Table 9-3), we can notice that this application produces a slight increase of throughput accompanied by a reduction of the overall speed, which increases with the penetration rate.

However, the benefit in terms of increase of safety is indicated by the decrease of shockwaves, measured with 95th percentile spatial and temporal speed drop; this benefit increases as the penetration rate increases, but with 50% penetration it is already close to what can be obtained with 90% penetration. This is intuitive because under congested conditions even if the speed message targets just a portion of the vehicles, other vehicles get influenced via car-following.

Table 9-1: Performance measures with SPD-HARM with 25% penetration rate compared with the baseline case under Operational Condition 1

Network Statistics	Base	SPD-HARM	Difference
Vehicles Miles Travelled (mi)	2,320,947	2,340,587	0.8%
Total Travel Time (h)	61,946	64,185	3.6%
Passenger Hourly Travel Time (h)	78,635	81,499	3.6%
VMT/VHT (mi/h)	37.47	36.47	-2.7%
95th Percentile Spatial Speed Drop (mi/h)	15.0	12.6	-16.0%
95th Percentile Temporal Speed Drop (mi/h)	11.0	9.8	-10.9%

Table 9-2: Performance measures with SPD-HARM with 50% penetration rate compared with the baseline case under Operational Condition 1

Network Statistics	Base	SPD-HARM	Difference
Vehicles Miles Travelled (mi)	2,320,947	2,350,332	1.3%
Total Travel Time (h)	61,946	66,744	7.7%
Passenger Hourly Travel Time (h)	78,635	84,659	7.7%
VMT/VHT (mi/h)	37.47	35.21	-6.0%
95th Percentile Spatial Speed Drop (mi/h)	15.0	10.4	-30.7%
95th Percentile Temporal Speed Drop (mi/h)	11.0	7.0	-36.4%

Table 9-3: Performance measures with SPD-HARM with 90% penetration rate compared with the baseline case under Operational Condition 1

Network Statistics	Base	SPD-HARM	Difference
Vehicles Miles Travelled (mi)	2,320,947	2,351,385	1.3%
Total Travel Time (h)	61,946	68,997	11.4%
Passenger Hourly Travel Time (h)	78,635	87,306	11.0%
VMT/VHT (mi/h)	37.47	34.08	-9.0%
95th Percentile Spatial Speed Drop (mi/h)	15.0	10.0	-33.3%
95th Percentile Temporal Speed Drop (mi/h)	11.0	6.2	-43.6%

9.2.1.2 Operational condition 2 (AM2)

A comparison of the speed contour on I-15 in the southbound direction with the baseline conditions shows that SPD-HARM produces a “dilution” of the congestion over space and time (Figure 9-4, Figure 9-5 and Figure 9-6), which suggests an improvement in safety. This effect increases as the penetration rate increases.

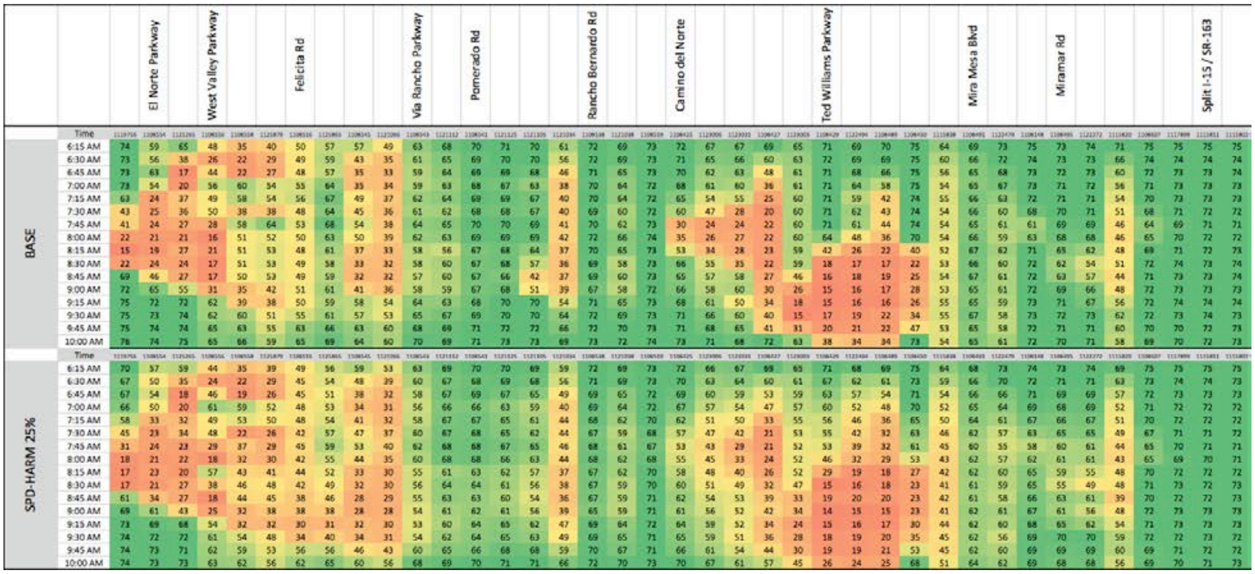


Figure 9-4: Speed contour with SPD-HARM with 25% penetration rate compared with the baseline case under Operational Condition 2

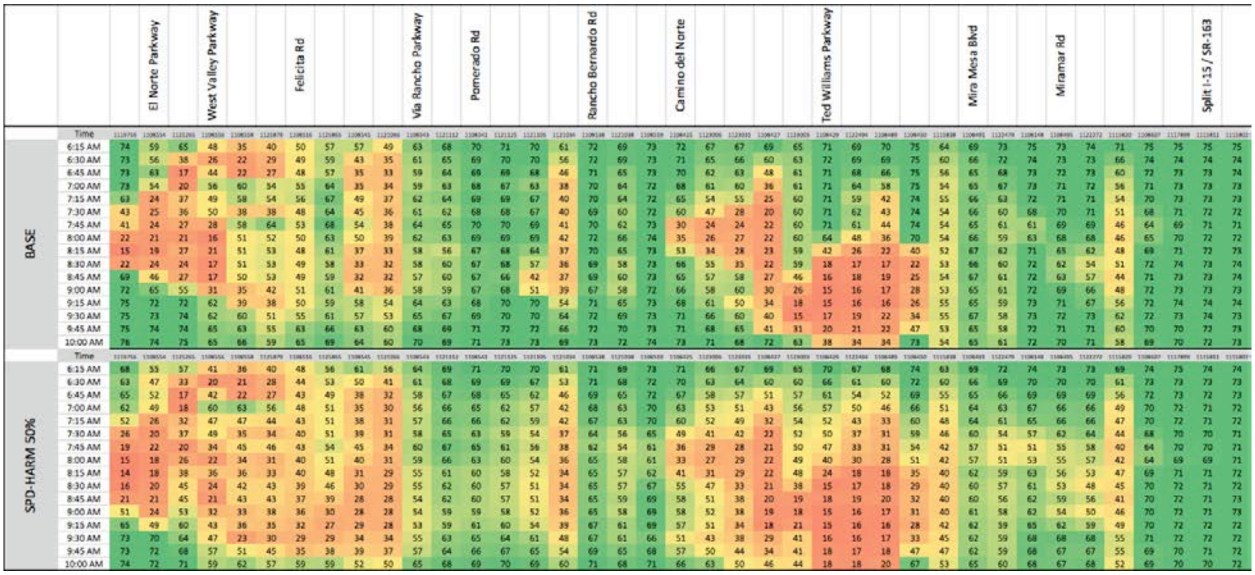


Figure 9-5: Speed contour with SPD-HARM with 50% penetration rate compared with the baseline case under Operational Condition 2

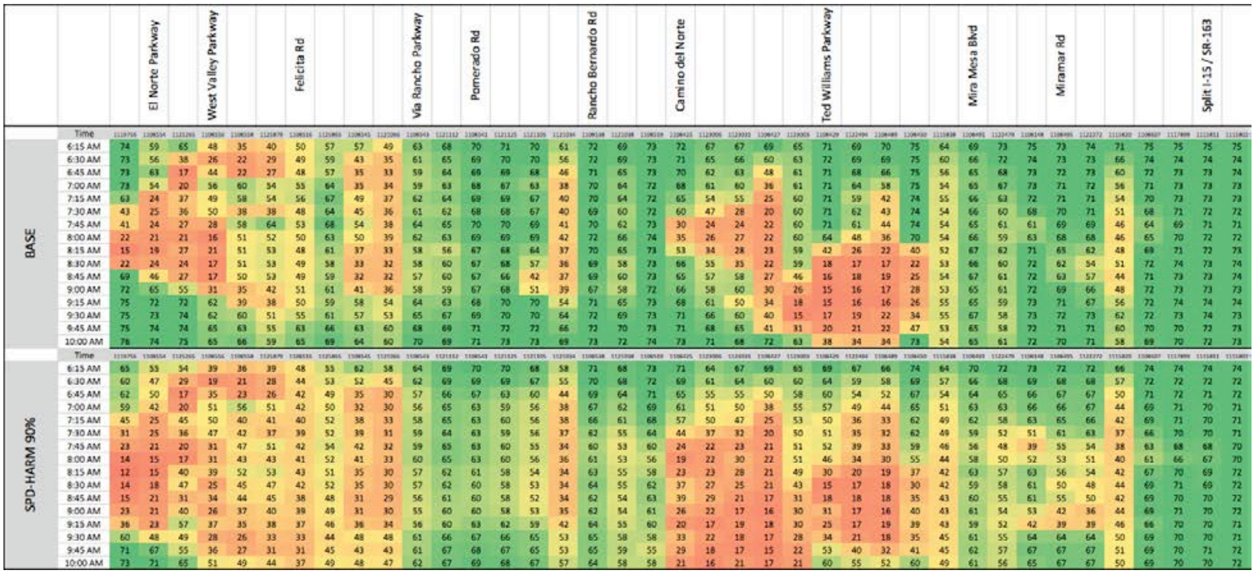


Figure 9-6: Speed contour with SPD-HARM with 90% penetration rate compared with the baseline case under Operational Condition 2

If we compare network-wide traffic performance measures with SPD-HARM with different penetration rates with the baseline condition (Table 9-4, Table 9-5 and Table 9-6), we can notice that this application produces a slight increase of throughput accompanied by a reduction of the overall speed, which increases with the penetration rate.

However, the benefit in terms of increase of safety is clearly indicated by the decrease of shockwaves, measured with 95th percentile spatial and temporal speed drop.

Table 9-4: Performance measures with SPD-HARM with 25% penetration rate compared with the baseline case under Operational Condition 2

Network Statistics	Base	SPD-HARM	Difference
Vehicles Miles Travelled (mi)	2,304,353	2,330,196	1.1%
Total Travel Time (h)	61,509	62,540	1.7%
Passenger Hourly Travel Time (h)	78,853	80,172	1.7%
VMT/VHT (mi/h)	37.46	37.26	-0.5%
95th Percentile Spatial Speed Drop (mi/h)	16.0	14.0	-12.5%
95th Percentile Temporal Speed Drop (mi/h)	12.0	11.0	-8.3%

Table 9-5: Performance measures with SPD-HARM with 50% penetration rate compared with the baseline case under Operational Condition 2

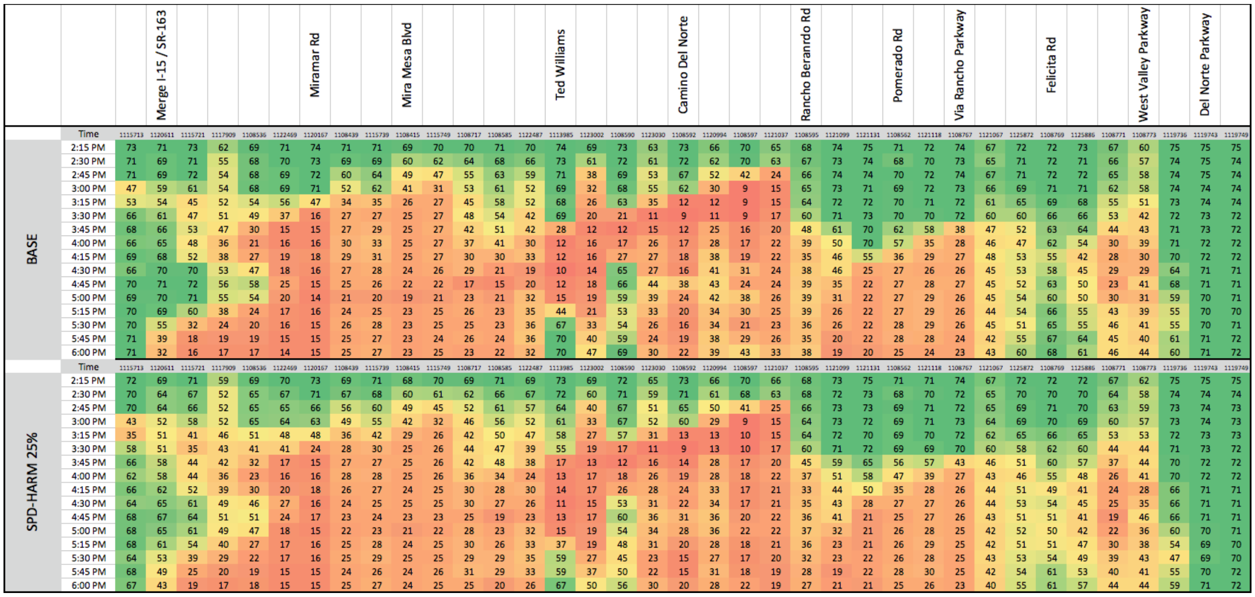
Network Statistics	Base	SPD-HARM	Difference
Vehicles Miles Travelled (mi)	2,304,353	2,345,282	1.8%
Total Travel Time (h)	61,509	65,529	6.5%
Passenger Hourly Travel Time (h)	78,853	84,065	6.6%
VMT/VHT (mi/h)	37.46	35.79	-4.5%
95th Percentile Spatial Speed Drop (mi/h)	16.0	11.8	-26.3%
95th Percentile Temporal Speed Drop (mi/h)	12.0	8.0	-33.3%

Table 9-6: Performance measures with SPD-HARM with 90% penetration rate compared with the baseline case under Operational Condition 2

Network Statistics	Base	SPD-HARM	Difference
Vehicles Miles Travelled (mi)	2,304,353	2,328,735	1.1%
Total Travel Time (h)	61,509	67,478	9.7%
Passenger Hourly Travel Time (h)	78,853	86,513	9.7%
VMT/VHT (mi/h)	37.46	34.51	-7.9%
95th Percentile Spatial Speed Drop (mi/h)	16.0	11.0	-31.3%
95th Percentile Temporal Speed Drop (mi/h)	12.0	6.8	-43.3%

9.2.1.3 Operational condition 3 (PM3)

A comparison of the speed contour on I-15 in the northbound direction with the baseline conditions shows that SPD-HARM produces a “dilution” of the congestion over space and time (Figure 9-7, Figure 9-8 and Figure 9-9), which suggests an improvement in safety. This effect increases as the penetration rate increases.



			Merge I-15 / SR-163					Miramar Rd			Mira Mesa Blvd					Ted Williams				Camino Del Norte				Rancho Berandro Rd			Pomerado Rd		Via Rancho Parkway			Felicita Rd			West Valley Parkway		Del Norte Parkway	
	Time	1115713	1120611	1115721	1117909	1108536	1122469	1120167	1108439	1115739	1108415	1115749	1108717	1108585	1122487	1113985	1123002	1108590	1123030	1108592	1120994	1108597	1121037	1108595	1121099	1121131	1108562	1121118	1108767	1121067	1125872	1108769	1125886	1108771	1108773	1119736	1119743	1119749
BASE	2:15 PM	73	71	73	62	69	71	74	71	71	69	70	70	71	70	74	69	73	63	73	66	70	65	68	74	75	71	72	74	67	72	72	73	67	60	75	75	75
	2:30 PM	71	69	71	55	68	70	73	69	69	60	62	64	68	66	73	61	72	61	72	62	70	63	67	73	74	68	70	73	65	71	72	71	66	57	74	75	74
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	3:30 PM	66	61	47	51	49	37	16	27	27	25	27	48	54	42	69	20	21	11	9	11	9	17	60	71	73	70	70	72	60	60	66	66	53	42	72	73	72
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SPD-HARM 25%	2:15 PM	72	69	71	59	69	70	73	69	71	68	70	69	71	69	73	69	72	65	73	66	70	66	68	73	75	71	71	74	67	72	72	72	67	62	75	75	75
	2:30 PM	70	64	67	52	65	67	71	67	68	60	61	62	66	67	72	60	71	59	71	61	68	63	68	72	73	68	70	72	65	70	70	70	64	58	74	74	74
	2:45 PM	70	64	66	52	65	65	66	56	60	49	45	52	61	57	64	40	67	51	65	50	41	25	66	73	73	69	71	72	65	69	71	70	63	59	73	74	73
	3:00 PM	43	52	58	52	65	64	63	49	55	42	32	46	56	52	61	33	67	52	60	29	9	15	64	73	72	69	71	73	64	69	70	69	60	57	73	74	73
	3:15 PM	35	51	41	46	51	48	48	36	42	29	26	42	50	47	58	27	57	31	13	13	10	15	64	72	70	69	70	72	62	65	66	65	53	53	72	73	73
	3:30 PM	58	51	35	43	41	41	24	28	30	25	26	44	47	39	55	19	17	11	9	13	10	17	60	71	72	69	69	70	60	58	62	60	44	44	71	73	72
	3:45 PM	66	58	44	42	32	17	15	27	27	25	26	42	48	38	17	13	12	16	14	28	17	20	45	59	65	56	57	43	46	51	60	57	37	44	70	72	72
	4:00 PM	62	58	44	36	23	16	16	28	28	25	26	36	34	24	13	17	18	26	19	28	18	22	37	51	58	47	39	27	43	46	55	48	26	41	70	72	72
	4:15 PM	66	62	52	39	30	20	18	26	27	24	25	30	28	30	14	17	26	28	24	33	17	21	33	44	50	35	28	26	44	51	49	41	24	28	66	71	71
	4:30 PM	64	65	61	49	46	27	16	24	25	25	25	30	27	26	11	15	53	31	22	34	17	21	35	43	28	27	27	26	44	53	54	45	25	35	66	71	71
	4:45 PM	68	67	64	51	51	24	17	23	24	23	23	25	19	23	13	17	60	36	31	36	20	22	36	41	21	25	27	26	43	51	51	41	19	46	66	71	71
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	6:00 PM	67	43	19	17	18	15	15	25	27	24	25	25	20	26	67	50	56	30	20	28	22	19	27	21	21	25	26	23	40	55	61	57	44	44	59	71	72

Figure 9-7: Speed contour with SPD-HARM with 25% penetration rate compared with the baseline case under Operational Condition 3

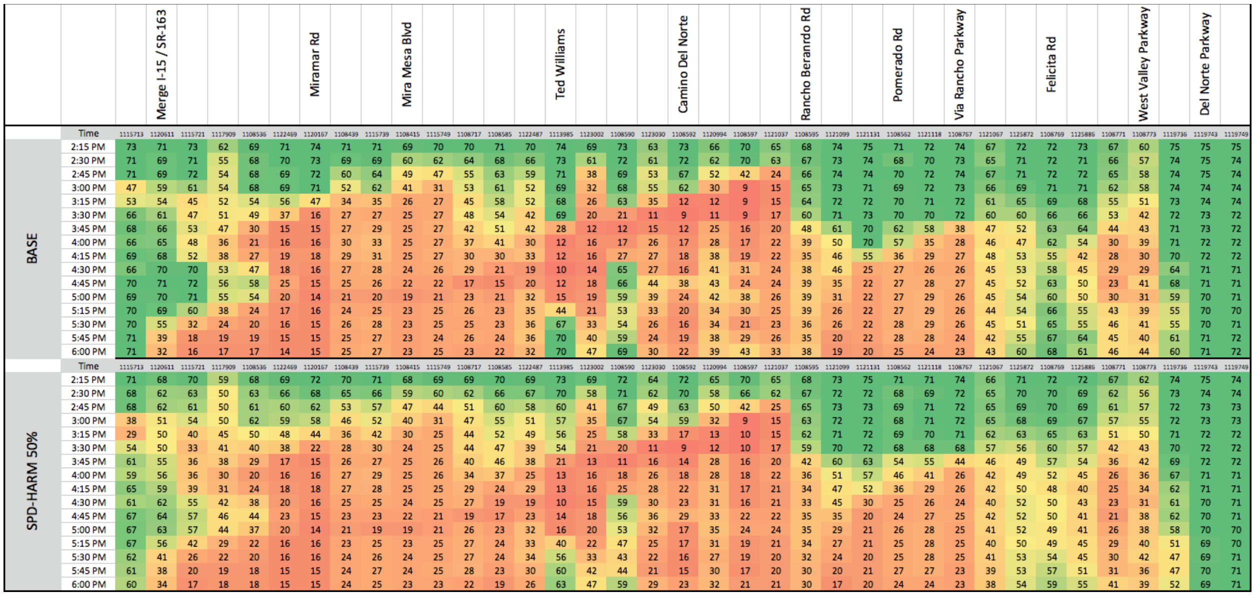


Figure 9-8: Speed contour with SPD-HARM with 50% penetration rate compared with the baseline case under Operational Condition 3

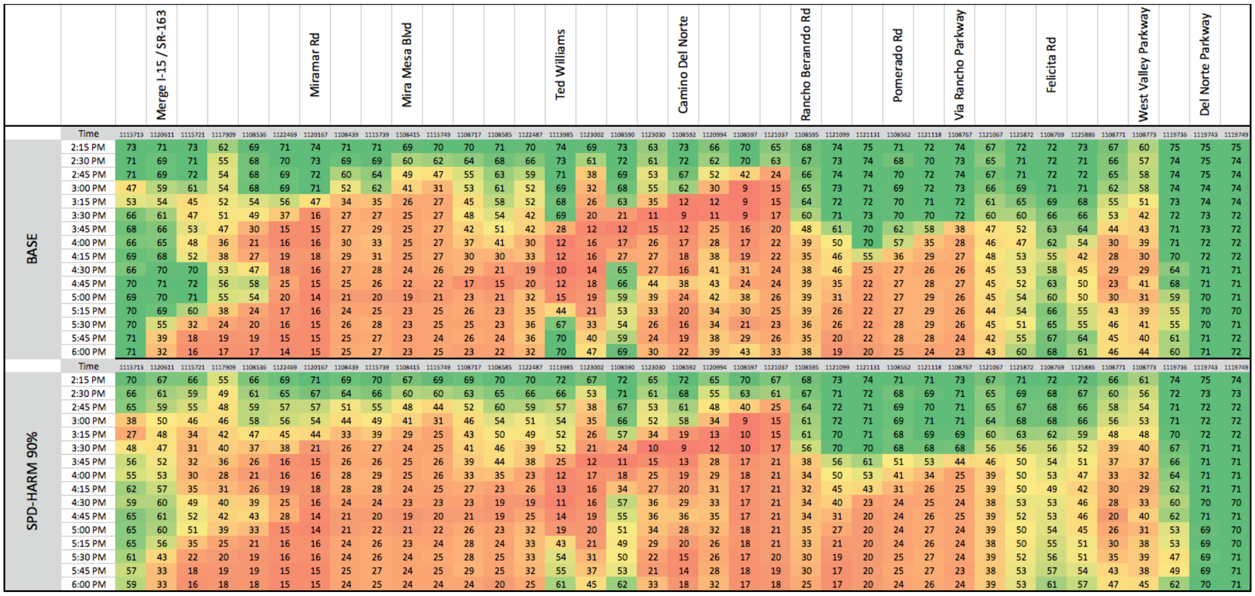


Figure 9-9: Speed contour with SPD-HARM with 90% penetration rate compared with the baseline case under Operational Condition 3

If we compare network-wide traffic performance measures with SPD-HARM with different penetration rates with the baseline condition (Table 9-7, Table 9-8 and Table 9-9), we can notice that this application doesn’t change significantly the throughput, but it produces a significant decrease of shockwaves, which becomes more pronounced as the penetration rate increases, at the price of a slight reduction of speed. When viewing the speed contour figures, the improvement in shockwave performance may not be evident because the congestion is all over the corridor which led to a dilution effect. Hence the change is only visually marginal. However, when the median speed in the speed contours are compared, we have 47 mi/h in the base case when compared to 44 mi/h, 42 mi/h and 40 mi/h for market penetrations of 25%, 50% and 90% respectively. The benefit in terms of increase of safety is indicated by the decrease of shockwaves, measured with 95th percentile spatial and temporal speed drop.

Table 9-7: Performance measures with SPD-HARM with 25% penetration rate compared with the baseline case under Operational Condition 3

Network Statistics	Base	SPD-HARM	Difference
Vehicles Miles Travelled (mi)	2,518,604	2,513,704	-0.2%
Total Travel Time (h)	76,531	79,314	3.6%
Passenger Hourly Travel Time (h)	99,052	102,547	3.5%
VMT/VHT (mi/h)	32.91	31.69	-3.7%
95th Percentile Spatial Speed Drop (mi/h)	28.0	22.8	-18.6%
95th Percentile Temporal Speed Drop (mi/h)	22.0	18.4	-16.4%

Table 9-8: Performance measures with SPD-HARM with 50% penetration rate compared with the baseline case under Operational Condition 3

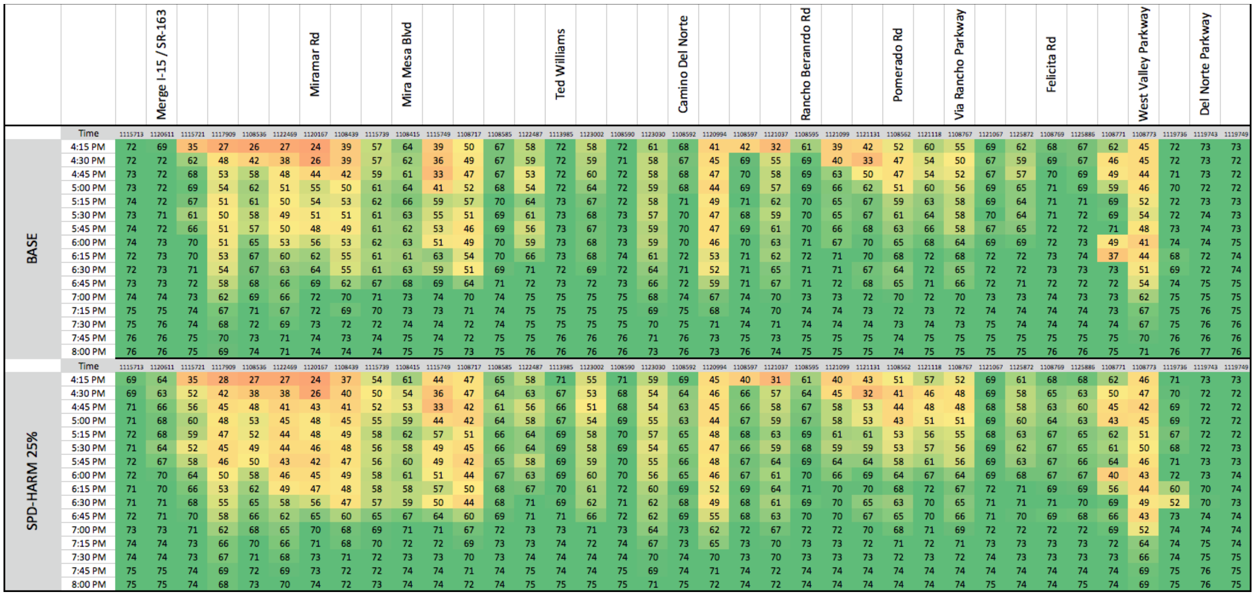
Network Statistics	Base	SPD-HARM	Difference
Vehicles Miles Travelled (mi)	2,518,604	2,520,009	0.1%
Total Travel Time (h)	76,531	80,278	4.9%
Passenger Hourly Travel Time (h)	99,052	103,677	4.7%
VMT/VHT (mi/h)	32.91	31.39	-4.6%
95th Percentile Spatial Speed Drop (mi/h)	28.0	13.0	-53.6%
95th Percentile Temporal Speed Drop (mi/h)	22.0	12.2	-44.5%

Table 9-9: Performance measures with SPD-HARM with 90% penetration rate compared with the baseline case under Operational Condition 3

Network Statistics	Base	SPD-HARM	Difference
Vehicles Miles Travelled (mi)	2,518,604	2,515,631	-0.1%
Total Travel Time (h)	76,531	80,244	4.9%
Passenger Hourly Travel Time (h)	99,052	103,631	4.6%
VMT/VHT (mi/h)	32.91	31.35	-4.7%
95th Percentile Spatial Speed Drop (mi/h)	28.0	9.0	-67.9%
95th Percentile Temporal Speed Drop (mi/h)	22.0	8.8	-60.0%

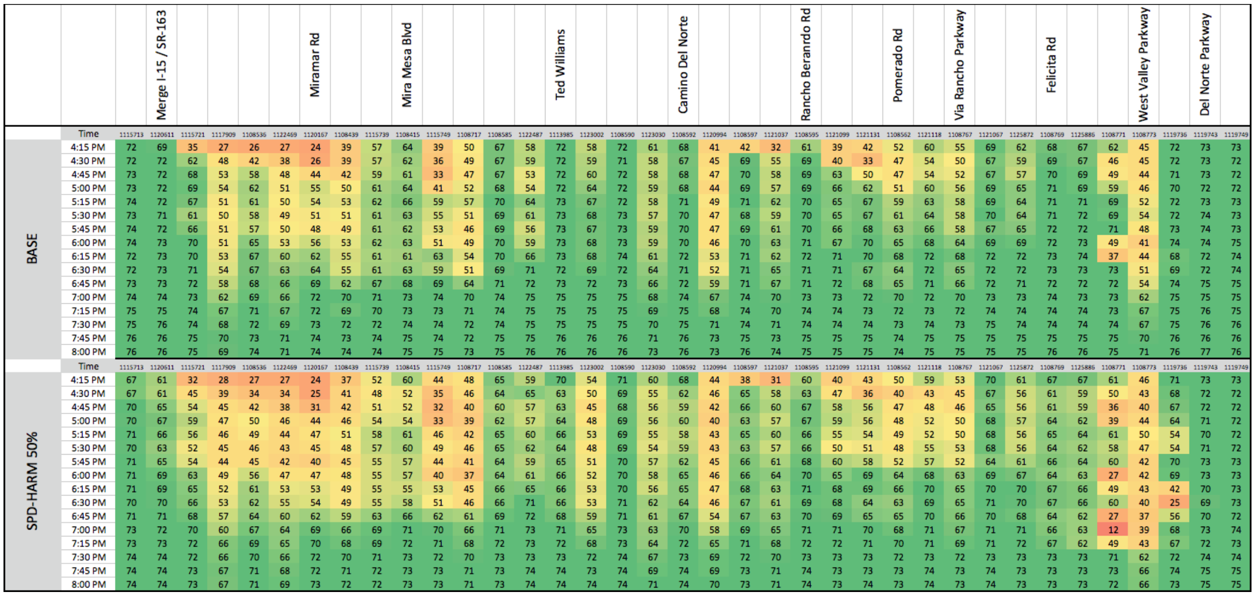
9.2.1.4 Operational condition 4 (PM4)

A comparison of the speed contour on I-15 in the northbound direction with the baseline conditions shows that SPD-HARM produces a “dilution” of the congestion over space and time (Figure 9-10, Figure 9-11 and Figure 9-12), which suggests an increase of safety. However, in a situation with no significant congestion the change is not as strong as in the other operational conditions.



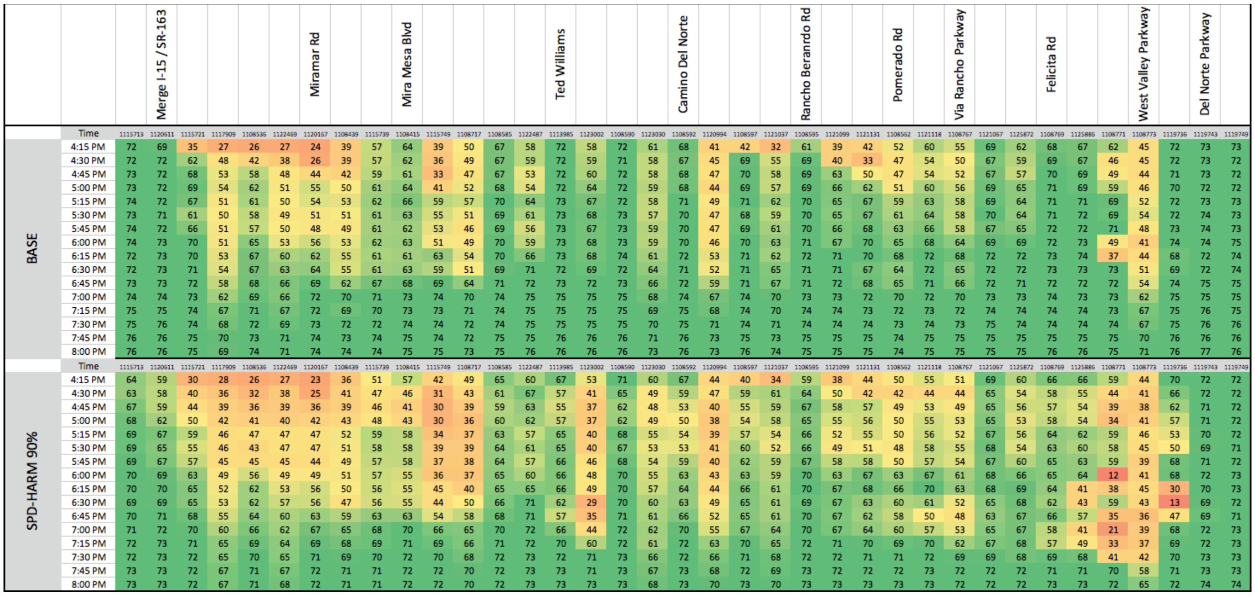
			Merge I-15 / SR-163					Miramar Rd			Mira Mesa Blvd					Ted Williams				Camino Del Norte				Rancho Beranrdo Rd			Pomerado Rd		Via Rancho Parkway			Felicita Rd			West Valley Parkway		Del Norte Parkway	
	Time	1115713	1120611	1115721	1117909	1108536	1122469	1120167	1108439	1115739	1108415	1115749	1108717	1108585	1122487	1113985	1123002	1108590	1123030	1108592	1120994	1108597	1121037	1108595	1121099	1121131	1108562	1121118	1108767	1121067	1125872	1108769	1125886	1108771	1108773	1119736	1119743	1119749
BASE	4:15 PM	72	69	35	27	26	27	24	39	57	64	39	50	67	58	72	58	72	61	68	41	42	32	61	39	42	52	60	55	69	62	68	67	62	45	72	73	73
	4:30 PM	72	72	62	48	42	38	26	39	57	62	36	49	67	59	72	59	71	58	67	45	69	55	69	40	33	47	54	50	67	59	69	67	46	45	72	73	72
	4:45 PM	73	72	68	53	58	48	44	42	59	61	33	47	67	53	72	60	72	58	68	47	70	58	69	63	50	47	54	52	67	57	70	69	49	44	71	73	72
	5:00 PM	73	72	69	54	62	51	55	50	61	64	41	52	68	54	72	64	72	59	68	44	69	57	69	66	62	51	60	56	69	65	71	69	59	46	70	72	72
	5:15 PM	74	72	67	51	61	50	54	53	62	66	59	57	70	64	73	67	72	58	71	49	71	62	70	65	67	59	63	58	69	64	71	71	69	52	72	73	73
	5:30 PM	73	71	61	50	58	49	51	51	61	63	55	51	69	61	73	68	73	57	70	47	68	59	70	65	67	61	64	58	70	64	71	72	69	54	72	74	73
	5:45 PM	74	72	66	51	57	50	48	49	61	62	53	46	69	56	73	67	73	59	70	47	69	61	70	66	68	63	66	58	67	65	72	72	71	48	73	74	73
	6:00 PM	74	73	70	51	65	53	56	53	62	63	51	49	70	59	73	68	73	59	70	46	70	63	71	67	70	65	68	64	69	69	72	73	49	41	74	74	75
	6:15 PM	72	73	70	53	67	60	62	55	61	61	63	54	70	66	73	68	74	61	72	53	71	62	72	71	70	68	72	68	72	72	73	74	37	44	68	72	74
	6:30 PM	72	73	71	54	67	63	64	55	61	63	59	51	69	71	72	69	72	64	71	52	71	65	71	71	67	64	72	65	72	72	73	73	73	51	69	72	74
	6:45 PM	73	73	72	58	68	66	69	62	67	68	69	64	71	72	73	72	73	66	72	59	71	67	71	72	68	65	71	66	72	71	72	72	72	54	74	75	75
	7:00 PM	74	74	73	62	69	66	72	70	71	73	74	70	74	75	75	75	75	68	74	67	74	70	73	73	72	70	72	70	73	73	74	73	73	62	75	75	75
	7:15 PM	75	75	74	67	71	67	72	69	70	73	73	71	74	75	75	75	75	69	75	68	74	70	74	74	73	72	73	72	74	74	74	74	73	67	75	76	75
	7:30 PM	75	76	74	68	72	69	73	72	72	74	74	72	74	75	75	75	75	70	75	71	74	71	74	74	74	73	74	73	75	74	74	74	74	67	75	76	76
	7:45 PM	76	76	75	70	73	71	74	73	74	75	74	72	75	75	76	76	76	71	76	73	75	73	75	75	75	74	75	75	75	75	75	75	75	70	76	76	76
	8:00 PM	76	76	75	69	74	71	74	74	74	75	75	73	75	76	76	76	76	73	76	73	76	74	75	75	75	74	75	75	75	75	76	76	75	71	76	77	76
	Time	1115713	1120611	1115721	1117909	1108536	1122469	1120167	1108439	1115739	1108415	1115749	1108717	1108585	1122487	1113985	1123002	1108590	1123030	1108592	1120994	1108597	1121037	1108595	1121099	1121131	1108562	1121118	1108767	1121067	1125872	1108769	1125886	1108771	1108773	1119736	1119743	1119749
SPD-HARM 25%	4:15 PM	69	64	35	28	27	27	24	37	54	61	44	47	65	58	71	55	71	59	69	45	40	31	61	40	43	51	57	52	69	61	68	68	62	46	71	73	73
	4:30 PM	69	63	52	42	38	38	26	40	50	54	36	47	64	63	67	53	68	54	64	46	66	57	64	45	32	41	46	48	69	58	65	63	50	47	70	72	72
	4:45 PM	71	66	56	45	48	41	43	41	52	53	33	42	61	56	66	51	68	54	63	45	66	58	67	58	53	44	48	48	68	58	63	60	45	42	69	72	72
	5:00 PM	71	68	60	48	53	45	48	45	55	59	44	42	64	58	67	54	69	55	63	44	67	59	67	58	53	43	51	51	69	60	64	63	43	45	69	72	72
	5:15 PM	72	68	59	47	52	44	48	49	58	62	57	51	66	64	69	58	70	57	65	48	68	63	69	61	61	53	56	55	68	63	67	65	62	51	67	72	72
	5:30 PM	71	64	52	45	49	44	46	48	56	58	49	45	66	64	69	58	69	54	65	47	66	59	68	59	59	53	57	56	69	62	67	65	61	50	68	72	73
	5:45 PM	72	67	58	46	50	43	42	47	56	60	49	42	65	58	69	59	70	55	66	48	67	64	69	64	64	58	61	56	69	63	67	66	64	46	71	73	73
	6:00 PM	72	70	64	50	58	46	45	49	58	61	51	44	67	63	69	60	70	56	65	46	67	61	70	66	69	64	67	64	69	68	67	67	40	43	72	73	74
	6:15 PM	71	70	66	53	62	49	47	48	58	58	57	50	68	67	70	61	72	60	69	52	69	64	71	70	70	68	72	67	72	71	69	69	56	44	60	70	74
	6:30 PM	71	71	68	55	65	58	56	47	57	59	50	44	68	71	69	62	71	62	68	49	68	61	69	70	65	63	70	65	71	71	71	70	69	49	52	70	73
	6:45 PM	72	71	70	58	66	62	65	60	65	67	64	60	69	71	71	66	72	62	69	55	68	63	70	70	67	65	70	66	71	70	69	68	66	43	73	74	74
	7:00 PM	73	73	71	62	68	65	70	68	69	71	71	67	72	73	73	71	73	64	73	62	72	67	72	72	70	68	71	69	72	72	72	72	69	52	74	74	74
	7:15 PM	74	74	73	66	70	66	71	68	70	72	72	69	73	73	74	72	74	67	73	65	73	70	73	73	72	71	72	71	73	73	73	73	72	64	74	75	74
	7:30 PM	74	74	73	67	71	68	73	71	72	73	73	70	73	74	74	74	74	70	74	70	73	70	73	73	73	72	73	72	74	73	73	73	73	66	74	75	75
	7:45 PM	75	75	74	69	72	69	73	72	72	74	74	71	74	75	74	74	75	69	74	71	74	72	74	74	74	74	74	74	74	74	74	74	74	69	75	76	75
	8:00 PM	75	75	74	68	73	70	74	72	73	74	74	72	74	75	75	75	75	71	75	72	74	72	74	74	74	74	74	74	75	74	74	75	74	69	75	76	75

Figure 9-10: Speed contour with SPD-HARM with 25% penetration rate compared with the baseline case under Operational Condition 4



			Merge I-15 / SR-163					Miramar Rd			Mira Mesa Blvd					Ted Williams				Camino Del Norte				Rancho Beranrdo Rd			Pomerado Rd		Via Rancho Parkway			Felicita Rd			West Valley Parkway		Del Norte Parkway	
	Time	1115713	1120611	1115721	1117909	1108536	1122469	1120167	1108439	1115739	1108415	1115749	1108717	1108585	1122487	1113985	1123002	1108590	1123030	1108592	1120994	1108597	1121037	1108595	1121099	1121131	1108562	1121118	1108767	1121067	1125872	1108769	1125886	1108771	1108773	1119736	1119743	1119749
BASE	4:15 PM	72	69	35	27	26	27	24	39	57	64	39	50	67	58	72	58	72	61	68	41	42	32	61	39	42	52	60	55	69	62	68	67	62	45	72	73	73
	4:30 PM	72	72	62	48	42	38	26	39	57	62	36	49	67	59	72	59	71	58	67	45	69	55	69	40	33	47	54	50	67	59	69	67	46	45	72	73	72
	4:45 PM	73	72	68	53	58	48	44	42	59	61	33	47	67	53	72	60	72	58	68	47	70	58	69	63	50	47	54	52	67	57	70	69	49	44	71	73	72
	5:00 PM	73	72	69	54	62	51	55	50	61	64	41	52	68	54	72	64	72	59	68	44	69	57	69	66	62	51	60	56	69	65	71	69	59	46	70	72	72
	5:15 PM	74	72	67	51	61	50	54	53	62	66	59	57	70	64	73	67	72	58	71	49	71	62	70	65	67	59	63	58	69	64	71	71	69	52	72	73	73
	5:30 PM	73	71	61	50	58	49	51	51	61	63	55	51	69	61	73	68	73	57	70	47	68	59	70	65	67	61	64	58	70	64	71	72	69	54	72	74	73
	5:45 PM	74	72	66	51	57	50	48	49	61	62	53	46	69	56	73	67	73	59	70	47	69	61	70	66	68	63	66	58	67	65	72	72	71	48	73	74	73
	6:00 PM	74	73	70	51	65	53	56	53	62	63	51	49	70	59	73	68	73	59	70	46	70	63	71	67	70	65	68	64	69	69	72	73	49	41	74	74	75
	6:15 PM	72	73	70	53	67	60	62	55	61	61	63	54	70	66	73	68	74	61	72	53	71	62	72	71	70	68	72	68	72	72	73	74	37	44	68	72	74
	6:30 PM	72	73	71	54	67	63	64	55	61	63	59	51	69	71	72	69	72	64	71	52	71	65	71	71	67	64	72	65	72	72	73	73	73	51	69	72	74
	6:45 PM	73	73	72	58	68	66	69	62	67	68	69	64	71	72	73	72	73	66	72	59	71	67	71	72	68	65	71	66	72	71	72	72	72	54	74	75	75
	7:00 PM	74	74	73	62	69	66	72	70	71	73	74	70	74	75	75	75	75	68	74	67	74	70	73	73	72	70	72	70	73	73	74	73	73	62	75	75	75
	7:15 PM	75	75	74	67	71	67	72	69	70	73	73	71	74	75	75	75	75	69	75	68	74	70	74	74	73	72	73	72	74	74	74	74	73	67	75	76	75
	7:30 PM	75	76	74	68	72	69	73	72	72	74	74	72	74	75	75	75	75	70	75	71	74	71	74	74	74	73	74	73	75	74	74	74	74	67	75	76	76
	7:45 PM	76	76	75	70	73	71	74	73	74	75	74	72	75	75	76	76	76	71	76	73	75	73	75	75	75	74	75	75	75	75	75	75	75	70	76	76	76
	8:00 PM	76	76	75	69	74	71	74	74	74	75	75	73	75	76	76	76	76	73	76	73	76	74	75	75	75	74	75	75	75	75	76	76	75	71	76	77	76
	Time	1115713	1120611	1115721	1117909	1108536	1122469	1120167	1108439	1115739	1108415	1115749	1108717	1108585	1122487	1113985	1123002	1108590	1123030	1108592	1120994	1108597	1121037	1108595	1121099	1121131	1108562	1121118	1108767	1121067	1125872	1108769	1125886	1108771	1108773	1119736	1119743	1119749
SPD-HARM 50%	4:15 PM	67	61	32	28	27	27	24	37	52	60	44	48	65	59	70	54	71	60	68	44	38	31	60	40	43	50	59	53	70	61	67	67	61	46	71	73	73
	4:30 PM	67	61	45	39	34	34	25	41	48	52	35	46	64	65	63	50	69	55	62	46	65	58	63	47	36	40	43	45	67	56	61	59	50	43	68	72	72
	4:45 PM	70	65	54	45	42	38	31	42	51	52	32	40	60	57	63	45	68	56	59	42	66	60	67	58	56	47	48	46	65	56	61	59	36	40	67	72	72
	5:00 PM	70	67	59	47	50	46	44	46	54	54	33	39	62	57	64	48	69	56	60	40	63	57	67	59	56	48	52	50	68	57	64	62	39	44	64	71	72
	5:15 PM	71	66	56	46	49	44	47	51	58	61	46	42	65	60	66	53	69	55	58	43	65	60	66	55	54	49	52	50	68	56	65	64	61	50	54	70	72
	5:30 PM	70	63	52	45	46	43	45	48	57	60	49	46	65	62	64	48	69	54	59	43	63	57	66	50	51	48	55	53	68	56	64	62	58	47	54	71	72
	5:45 PM	71	65	54	44	45	42	40	45	55	57	44	41	64	59	65	51	70	57	62	45	66	61	68	60	58	52	57	52	64	61	66	64	60	42	70	73	73
	6:00 PM	71	69	63	49	56	47	47	48	55	57	40	37	64	61	66	52	70	58	65	46	66	64	70	65	69	64	68	63	69	67	64	63	27	42	69	73	73
	6:15 PM	71	69	65	52	61	53	53	49	55	55	53	45	66	65	66	53	70	56	65	47	68	63	71	68	69	66	70	65	70	70	67	66	49	43	42	70	73
	6:30 PM	70	70	66	53	62	55	54	49	55	58	51	46	66	71	66	53	71	62	64	46	67	61	69	68	64	63	69	65	71	70	67	66	60	40	25	69	73
	6:45 PM	71	71	68	57	64	60	62	59	63	66	62	61	69	72	68	59	71	61	67	54	67	63	70	69	65	65	70	66	70	68	64	62	27	37	56	70	72
	7:00 PM	73	72	70	60	67	64	69	66	69	71	70	66	71	73	71	65	73	63	70	58	69	65	71	71	70	68	71	67	71	71	66	63	12	39	68	73	74
	7:15 PM	73	73	72	66	69	65	70	68	69	72	71	68	72	73	72	68	73	64	72	65	71	68	72	72	71	70	71	69	71	72	67	62	49	43	67	72	73
	7:30 PM	74	74	72	66	70	66	72	70	71	73	72	70	73	73	73	72	74	67	73	69	72	70	73	73	73	72	73	72	73	73	73	73	71	62	72	74	74
	7:45 PM	74	74	73	67	71	68	72	71	72	73	73	71	73	74	74	73	74	69	74	69	73	71	74	73	73	73	74	73	74	73	73	73	73	66	74	75	75
	8:00 PM	74	74	73	67	71	69	73	72	72	73	73	71	73	74	74	74	74	71	74	70	73	71	74	73	74	73	74	73	74	73	73	73	72	66	73	75	75

Figure 9-11: Speed contour with SPD-HARM with 50% penetration rate compared with the baseline case under Operational Condition 4



			Merge I-15 / SR-163					Miramar Rd			Mira Mesa Blvd					Ted Williams				Camino Del Norte				Rancho Beranrdo Rd			Pomerado Rd		Via Rancho Parkway			Felicita Rd			West Valley Parkway		Del Norte Parkway	
	Time	1115713	1120611	1115721	1117909	1108536	1122469	1120167	1108439	1115739	1108415	1115749	1108717	1108585	1122487	1113985	1123002	1108590	1123030	1108592	1120994	1108597	1121037	1108595	1121099	1121131	1108562	1121118	1108767	1121067	1125872	1108769	1125886	1108771	1108773	1119736	1119743	1119749
BASE	4:15 PM	72	69	35	27	26	27	24	39	57	64	39	50	67	58	72	58	72	61	68	41	42	32	61	39	42	52	60	55	69	62	68	67	62	45	72	73	73
	4:30 PM	72	72	62	48	42	38	26	39	57	62	36	49	67	59	72	59	71	58	67	45	69	55	69	40	33	47	54	50	67	59	69	67	46	45	72	73	72
	4:45 PM	73	72	68	53	58	48	44	42	59	61	33	47	67	53	72	60	72	58	68	47	70	58	69	63	50	47	54	52	67	57	70	69	49	44	71	73	72
	5:00 PM	73	72	69	54	62	51	55	50	61	64	41	52	68	54	72	64	72	59	68	44	69	57	69	66	62	51	60	56	69	65	71	69	59	46	70	72	72
	5:15 PM	74	72	67	51	61	50	54	53	62	66	59	57	70	64	73	67	72	58	71	49	71	62	70	65	67	59	63	58	69	64	71	71	69	52	72	73	73
	5:30 PM	73	71	61	50	58	49	51	51	61	63	55	51	69	61	73	68	73	57	70	47	68	59	70	65	67	61	64	58	70	64	71	72	69	54	72	74	73
	5:45 PM	74	72	66	51	57	50	48	49	61	62	53	46	69	56	73	67	73	59	70	47	69	61	70	66	68	63	66	58	67	65	72	72	71	48	73	74	73
	6:00 PM	74	73	70	51	65	53	56	53	62	63	51	49	70	59	73	68	73	59	70	46	70	63	71	67	70	65	68	64	69	69	72	73	49	41	74	74	75
	6:15 PM	72	73	70	53	67	60	62	55	61	61	63	54	70	66	73	68	74	61	72	53	71	62	72	71	70	68	72	68	72	72	73	74	37	44	68	72	74
	6:30 PM	72	73	71	54	67	63	64	55	61	63	59	51	69	71	72	69	72	64	71	52	71	65	71	71	67	64	72	65	72	72	73	73	73	51	69	72	74
	6:45 PM	73	73	72	58	68	66	69	62	67	68	69	64	71	72	73	72	73	66	72	59	71	67	71	72	68	65	71	66	72	71	72	72	72	54	74	75	75
	7:00 PM	74	74	73	62	69	66	72	70	71	73	74	70	74	75	75	75	75	68	74	67	74	70	73	73	72	70	72	70	73	73	74	73	73	62	75	75	75
	7:15 PM	75	75	74	67	71	67	72	69	70	73	73	71	74	75	75	75	75	69	75	68	74	70	74	74	73	72	73	72	74	74	74	74	73	67	75	76	75
	7:30 PM	75	76	74	68	72	69	73	72	72	74	74	72	74	75	75	75	75	70	75	71	74	71	74	74	74	73	74	73	75	74	74	74	74	67	75	76	76
	7:45 PM	76	76	75	70	73	71	74	73	74	75	74	72	75	75	76	76	76	71	76	73	75	73	75	75	75	74	75	75	75	75	75	75	75	70	76	76	76
	8:00 PM	76	76	75	69	74	71	74	74	74	75	75	73	75	76	76	76	76	73	76	73	76	74	75	75	75	74	75	75	75	75	76	76	75	71	76	77	76
	Time	1115713	1120611	1115721	1117909	1108536	1122469	1120167	1108439	1115739	1108415	1115749	1108717	1108585	1122487	1113985	1123002	1108590	1123030	1108592	1120994	1108597	1121037	1108595	1121099	1121131	1108562	1121118	1108767	1121067	1125872	1108769	1125886	1108771	1108773	1119736	1119743	1119749
SPD-HARM 90%	4:15 PM	64	59	30	28	26	27	23	36	51	57	42	49	65	60	67	53	71	60	67	44	40	34	59	38	44	50	55	51	69	60	66	66	59	44	70	72	72
	4:30 PM	63	58	40	36	32	38	25	41	47	46	31	43	61	67	57	41	65	49	59	47	59	61	64	50	42	42	44	44	65	54	58	55	44	41	66	72	72
	4:45 PM	67	59	44	39	36	39	36	39	46	41	30	39	59	63	55	37	62	48	53	40	55	59	67	58	57	49	53	49	65	56	57	54	39	38	62	71	72
	5:00 PM	68	62	50	42	41	40	42	43	48	43	30	36	60	62	57	37	62	49	50	38	54	58	65	55	56	50	55	53	65	53	58	54	34	41	57	71	72
	5:15 PM	69	67	59	46	47	47	47	52	59	58	34	37	63	57	65	40	68	55	54	39	57	54	66	52	55	50	56	52	67	56	64	62	59	46	53	70	72
	5:30 PM	69	65	55	46	43	47	47	51	58	58	39	39	64	61	65	40	67	53	53	41	60	52	66	49	51	48	58	55	68	54	63	60	58	45	50	69	71
	5:45 PM	69	67	57	45	45	45	44	49	57	58	37	38	64	57	66	46	68	54	59	40	62	59	67	58	58	50	57	54	67	60	65	63	59	39	68	71	72
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Figure 9-12: Speed contour with SPD-HARM with 90% penetration rate compared with the baseline case under Operational Condition 4

If we compare network-wide traffic performance measures with SPD-HARM with different penetration rates with the baseline condition (Table 9-10, Table 9-11 and Table 9-12), we can notice that this application produces a slight increase of throughput accompanied by a reduction of the overall speed, which increases with the penetration rate. Additionally, the benefit in terms of increase of safety, measured with 95th percentile spatial and temporal speed drop, becomes significant only at the highest penetration rate.

Table 9-10: Performance measures with SPD-HARM with 25% penetration rate compared with the baseline case under Operational Condition 4

Network Statistics	Base	SPD-HARM	Difference
Vehicles Miles Travelled (mi)	2,302,897	2,332,873	1.3%
Total Travel Time (h)	57,547	58,215	1.2%
Passenger Hourly Travel Time (h)	75,856	76,725	1.1%
VMT/VHT (mi/h)	40.02	40.07	0.1%
95th Percentile Spatial Speed Drop (mi/h)	11.0	10.5	-4.5%
95th Percentile Temporal Speed Drop (mi/h)	11.0	10.3	-6.8%

Table 9-11: Performance measures with SPD-HARM with 50% penetration rate compared with the baseline case under Operational Condition 4

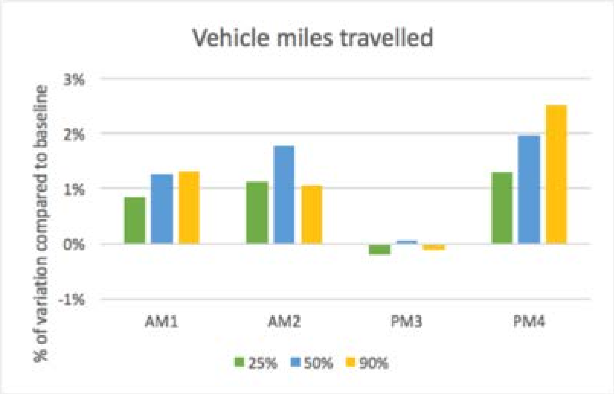
Network Statistics	Base	SPD-HARM	Difference
Vehicles Miles Travelled (mi)	2,302,897	2,348,157	2.0%
Total Travel Time (h)	57,547	58,502	1.7%
Passenger Hourly Travel Time (h)	75,856	76,967	1.5%
VMT/VHT (mi/h)	40.02	40.14	0.3%
95th Percentile Spatial Speed Drop (mi/h)	11.0	10.8	-2.3%
95th Percentile Temporal Speed Drop (mi/h)	11.0	11.0	0.0%

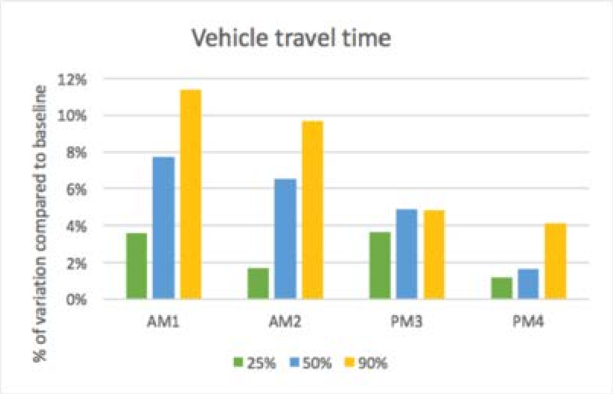
Table 9-12: Performance measures with SPD-HARM with 90% penetration rate compared with the baseline case under Operational Condition 4

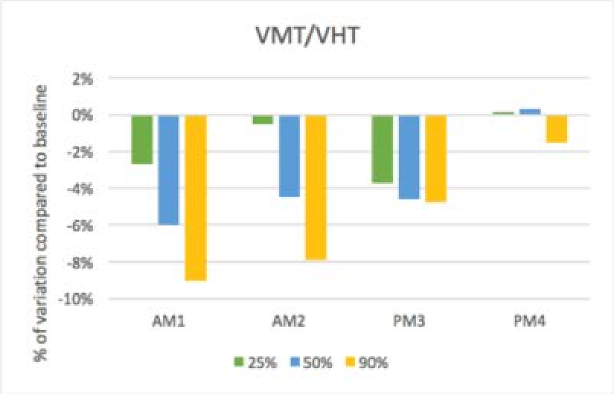
Network Statistics	Base	SPD-HARM	Difference
Vehicles Miles Travelled (mi)	2,302,897	2,361,133	2.5%
Total Travel Time (h)	57,547	59,902	4.1%
Passenger Hourly Travel Time (h)	75,856	78,445	3.4%
VMT/VHT (mi/h)	40.02	39.42	-1.5%
95th Percentile Spatial Speed Drop (mi/h)	11.0	9.0	-18.2%
95th Percentile Temporal Speed Drop (mi/h)	11.0	10.0	-9.1%

9.2.1.5 Comparison between operational conditions

A comparison of the performance measures under different operational conditions and different penetration rates shows that SPD-HARM doesn't produce significant benefits in terms of traffic performance, but a benefit in terms of safety. Its effectiveness is more evident in congested situations (Figure 9-13): PM3, which has congestion distributed throughout the corridor, shows the highest reduction of shockwaves, especially at lower penetration rates, while PM4, which has minimal amounts of congestion, shows a significant shockwave reduction only at the highest penetration rate. The benefit in terms of safety comes at the cost of a slight increase of travel time under all operational conditions.







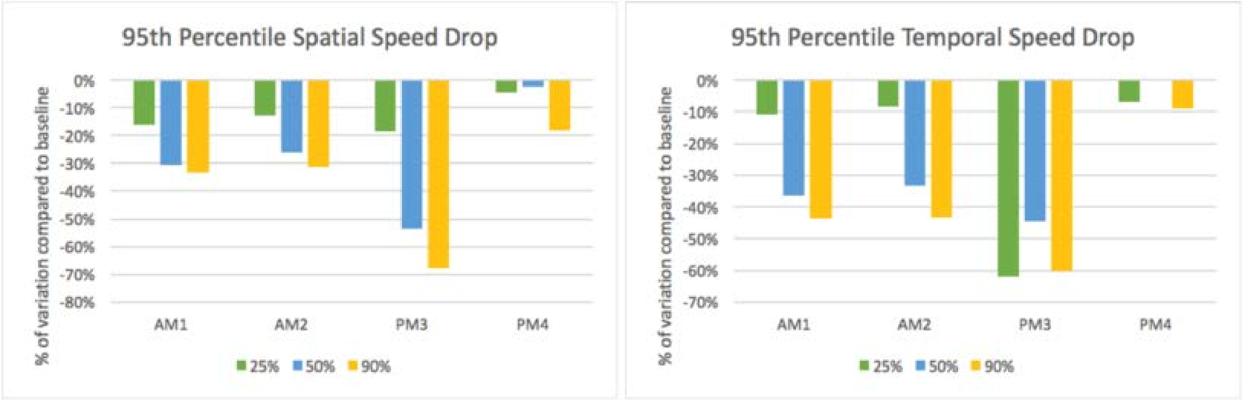


Figure 9-13: Change of the performance measures with SPD-HARM with different penetration rates compared with the baseline case under the different operational conditions

9.2.2 CACC

CACC is part of the INFLO bundle. Simulations were run with different penetration rates of connected vehicles (25%, 50% and 90%) and with different lane configurations (on I-15, connected vehicles have to use the three leftmost general-purpose lanes with 25% and 50% penetration, and can use any of the lanes with 90% penetration); when a connected vehicle driving on I-15 is following another connected vehicle, it enables CACC car-following (see Section 6.2 for more explanation).

9.2.2.1 Operational condition 1 (AM1)

A comparison of the speed contour on I-15 in the southbound direction with the baseline conditions shows that CACC adoption increases the average speed along the corridor, and at the higher penetration rates this application reduces significantly the congestion at the bottlenecks (Figure 9-14, Figure 9-15 and Figure 9-16).

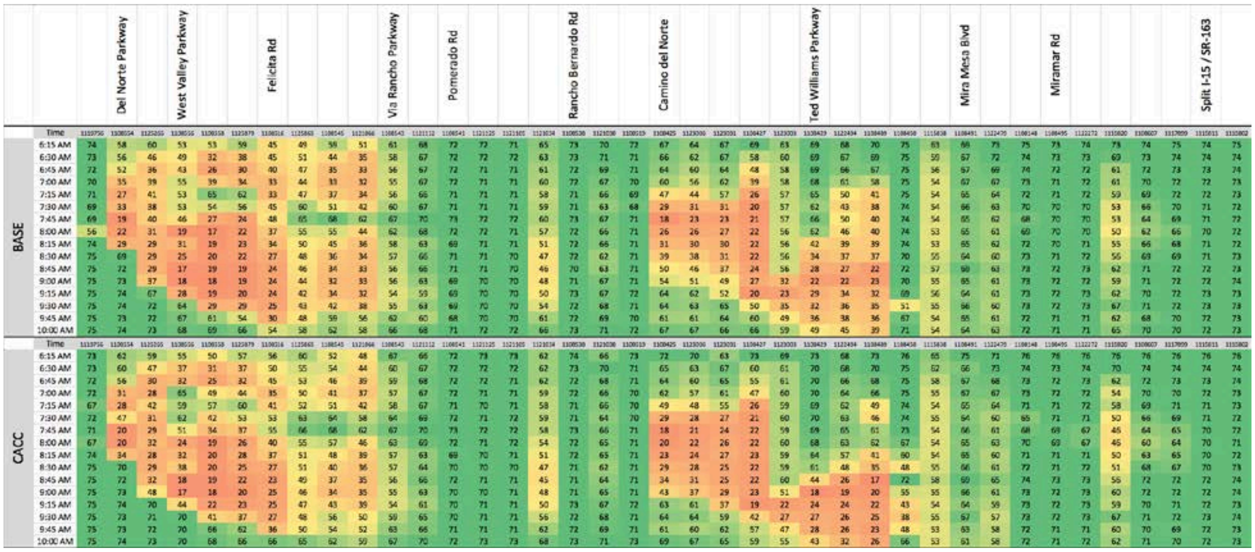


Figure 9-14: Speed contour with CACC with 25% penetration rate compared with the baseline case under Operational Condition 1

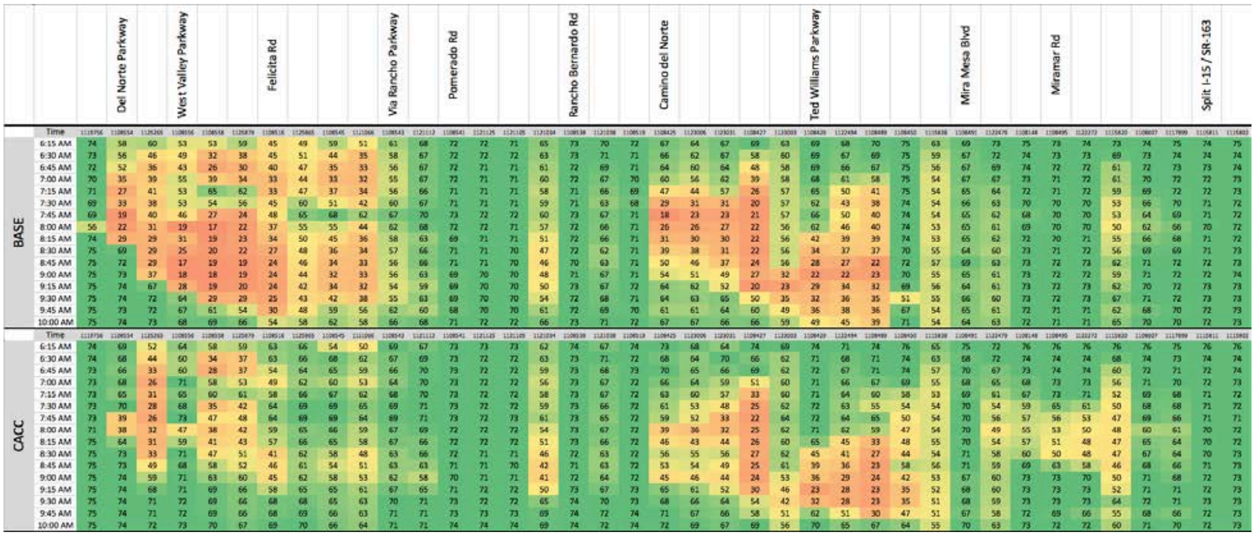


Figure 9-15: Speed contour with CACC with 50% penetration rate compared with the baseline case under Operational Condition 1

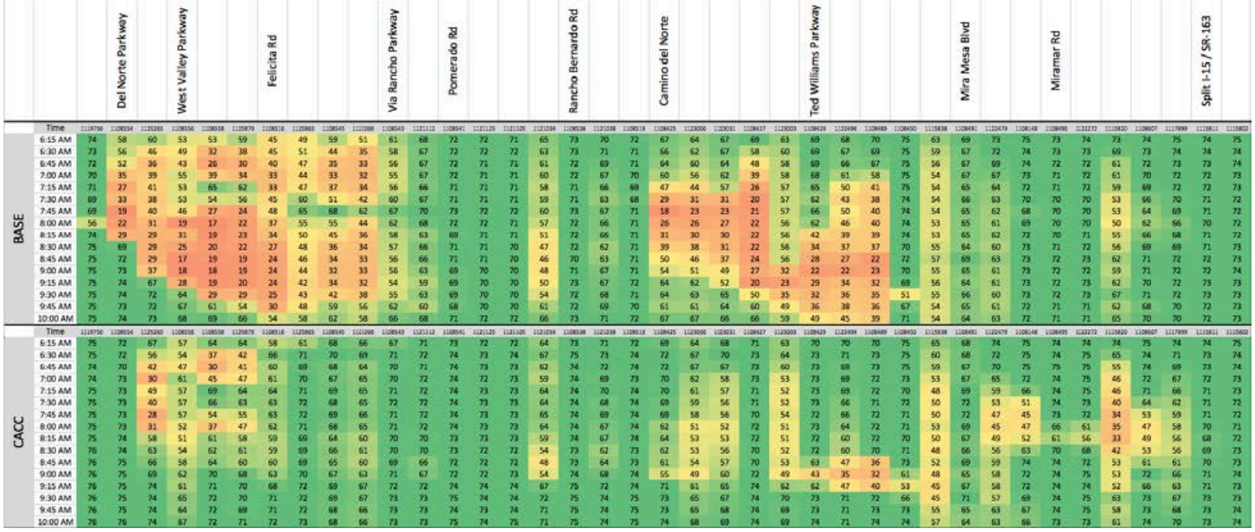


Figure 9-16: Speed contour with CACC with 90% penetration rate compared with the baseline case under Operational Condition 1

If we compare network-wide traffic performance measures with CACC with different penetration rates with the baseline condition (Table 9-13, Table 9-14 and Table 9-15), we can notice that CACC shows a positive impact in terms of increase of throughput and reduction of travel time under this operational condition. This benefit increases with the increase of the penetration rate.

Table 9-13: Performance measures with CACC with 25% penetration rate compared with the baseline case under Operational Condition 1

Network Statistics	CACC	Base	Difference
Vehicles Miles Travelled (miles)	2,336,549	2,320,947	0.7%
Total Travel Time (h)	61,602	61,946	-0.6%
Passenger Hourly Travel Time (h)	78,375	78,635	-0.3%
VMT/VHT (miles/h)	37.93	37.47	1.2%

Table 9-14: Performance measures with CACC with 50% penetration rate compared with the baseline case under Operational Condition 1

Network Statistics	CACC	Base	Difference
Vehicles Miles Travelled (miles)	2,379,451	2,320,947	2.5%
Total Travel Time (h)	60,803	61,946	-1.8%
Passenger Hourly Travel Time (h)	77,461	78,635	-1.5%
VMT/VHT (miles/h)	39.13	37.47	4.4%

Table 9-15: Performance measures with CACC with 90% penetration rate compared with the baseline case under Operational Condition 1

Network Statistics	CACC	Base	Difference
Vehicles Miles Travelled (miles)	2,402,310	2,320,947	3.5%
Total Travel Time (h)	58,358	61,946	-5.8%
Passenger Hourly Travel Time (h)	74,407	78,635	-5.4%
VMT/VHT (miles/h)	41.16	37.47	9.9%

9.2.2.2 Operational condition 2 (AM2)

A comparison of the speed contour on I-15 in the southbound direction with the baseline conditions shows that CACC adoption increases the average speed along the corridor, and at the higher penetration rates this application reduces the congestion at the bottlenecks (Figure 9-17, Figure 9-18 and Figure 9-19). Additionally, the fact that the speed of a vehicle is related to that of up to 5 leaders downstream, when the penetration rate is high enough (>= 50%) we can observe more clearly than in AM1 a “dilution” over space of the speed reduction at bottlenecks, which suggests a benefit also in terms of safety.

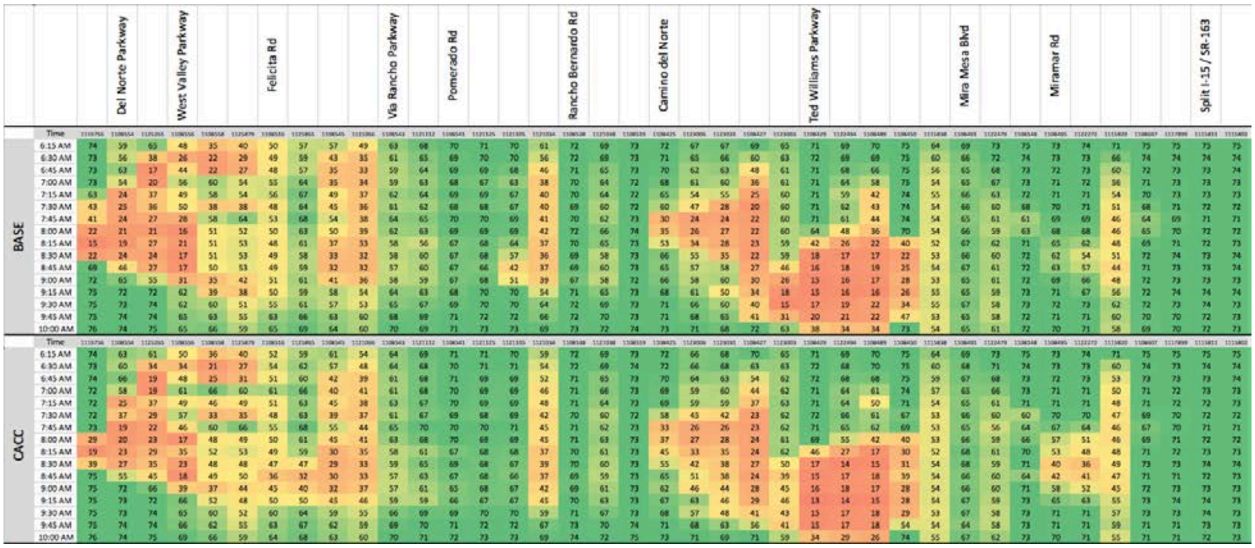


Figure 9-17: Speed contour with CACC with 25% penetration rate compared with the baseline case under Operational Condition 2

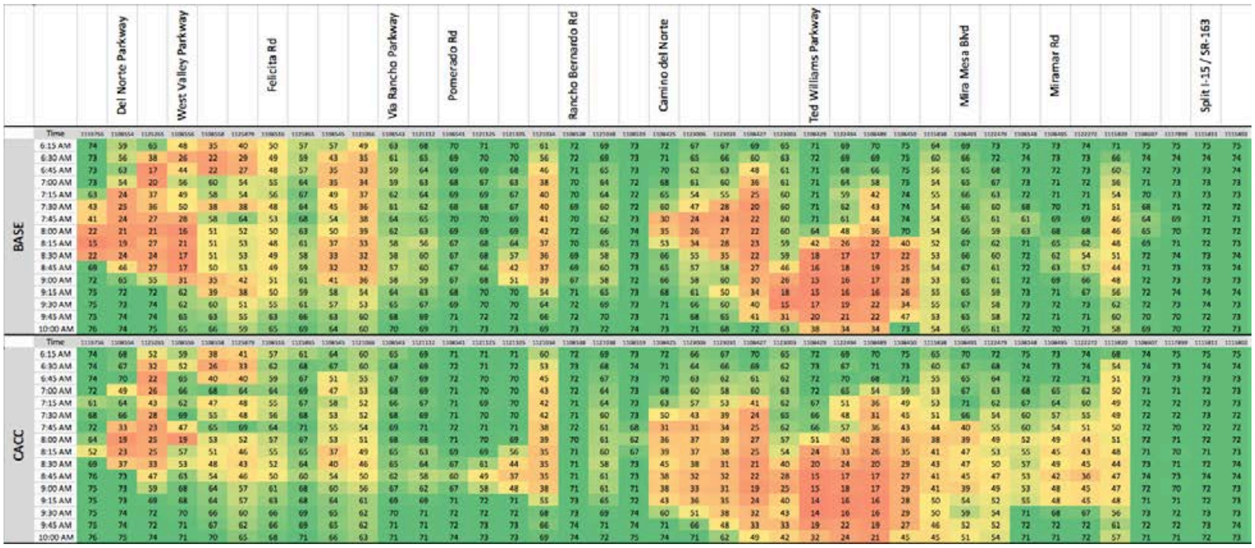


Figure 9-18: Speed contour with CACC with 50% penetration rate compared with the baseline case under Operational Condition 2

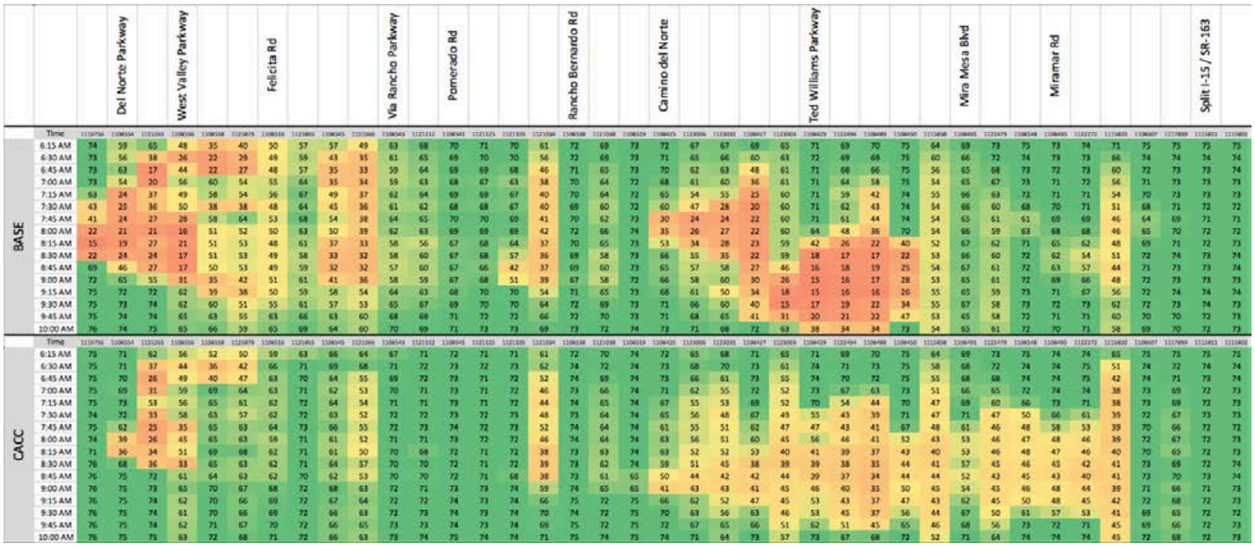


Figure 9-19: Speed contour with CACC with 90% penetration rate compared with the baseline case under Operational Condition 2

If we compare network-wide traffic performance measures with CACC with different penetration rates with the baseline condition (Table 9-16, Table 9-17 and Table 9-18), we can notice that CACC shows generally a positive impact in terms of increase of throughput and reduction of travel time under this operational condition, which has localized bottlenecks but more severe congestion compared to AM1. Among the different penetration rates, 50% seems to be the most delicate situation, as it shows an increase of throughput (thanks to shorter headways between CACC vehicles), but also a slight increase of travel time (caused by the fact that CACC platoons may cause an obstacle for non-connected vehicles that want to change lane, and that speed reductions are propagated more quickly through CACC platoons).

Table 9-16: Performance measures with CACC with 25% penetration rate compared with the baseline case under Operational Condition 2

Network Statistics	CACC	Base	Difference
Vehicles Miles Travelled (miles)	2,329,398	2,304,353	1.1%
Total Travel Time (h)	60,722	61,509	-1.3%
Passenger Hourly Travel Time (h)	78,151	78,853	-0.9%
VMT/VHT (miles/h)	38.36	37.46	2.4%

Table 9-17: Performance measures with CACC with 50% penetration rate compared with the baseline case under Operational Condition 2

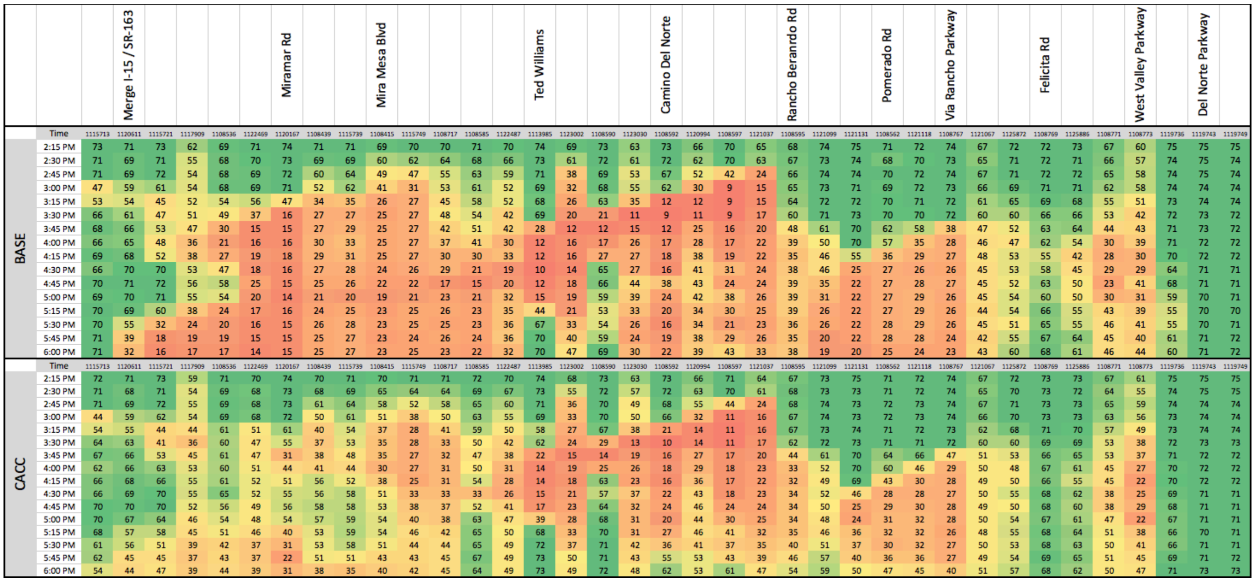
Network Statistics	CACC	Base	Difference
Vehicles Miles Travelled (miles)	2,329,302	2,304,353	1.1%
Total Travel Time (h)	62,206	61,509	1.1%
Passenger Hourly Travel Time (h)	79,424	78,853	0.7%
VMT/VHT (miles/h)	37.44	37.46	0.0%

Table 9-18: Performance measures with CACC with 90% penetration rate compared with the baseline case under Operational Condition 2

Network Statistics	CACC	Base	Difference
Vehicles Miles Travelled (miles)	2,382,112	2,304,353	3.4%
Total Travel Time (h)	59,719	61,509	-2.9%
Passenger Hourly Travel Time (h)	76,560	78,853	-2.9%
VMT/VHT (miles/h)	39.89	37.46	6.5%

9.2.2.3 Operational condition 3 (PM3)

A comparison of the speed contour on I-15 in the northbound direction with the baseline conditions shows that CACC adoption increases the average speed along the corridor, and at the higher penetration rates this application reduces the congestion at the bottlenecks (Figure 9-20, Figure 9-21 and Figure 9-22).



			Merge I-15 / SR-163					Miramar Rd			Mira Mesa Blvd					Ted Williams				Camino Del Norte				Rancho Berarndo Rd			Pomerado Rd		Via Rancho Parkway			Felicita Rd			West Valley Parkway		Del Norte Parkway	
	Time	1115713	1120611	1115721	1117909	1108536	1122469	1120167	1108439	1115739	1108415	1115749	1108717	1108585	1122487	1113985	1123002	1108590	1123030	1108592	1120994	1108597	1121037	1108595	1121099	1121131	1108562	1121118	1108767	1121067	1125872	1108769	1125886	1108771	1108773	1119736	1119743	1119749
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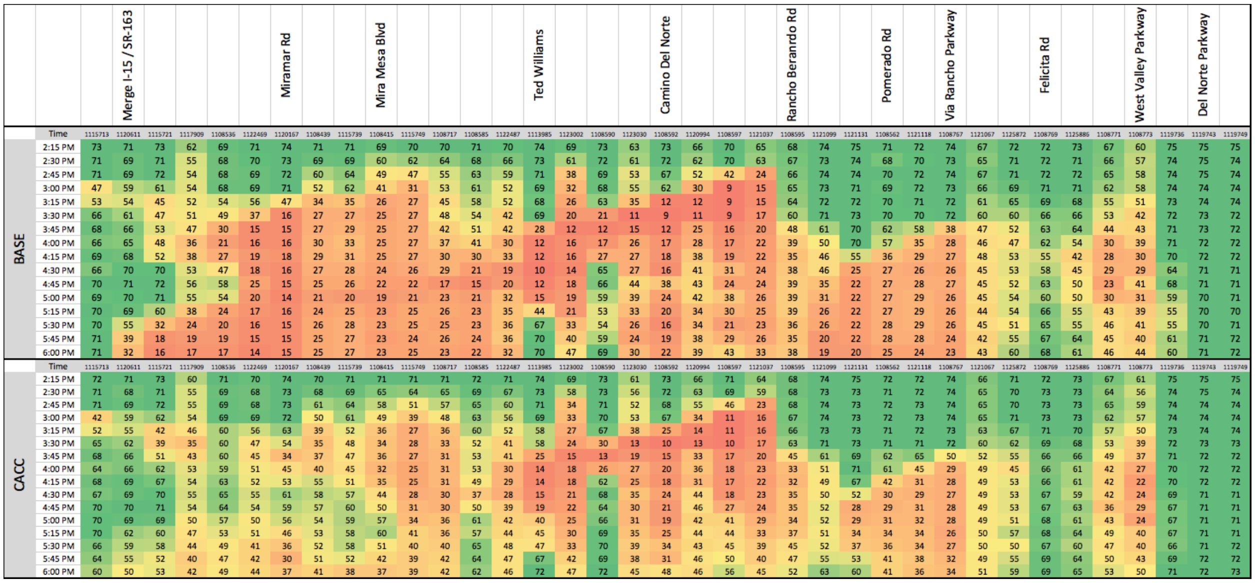
Figure 9-20: Speed contour with CACC with 25% penetration rate compared with the baseline case under Operational Condition 3



			Merge I-15 / SR-163					Miramar Rd			Mira Mesa Blvd					Ted Williams				Camino Del Norte				Rancho Berarndo Rd			Pomerado Rd		Via Rancho Parkway			Felicita Rd			West Valley Parkway		Del Norte Parkway	
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	2:45 PM	71	69	72	54	68	69	72	60	64	49	47	55	63	59	71	38	69	53	67	52	42	24	66	74	74	70	72	74	67	71	72	72	65	58	74	75	74
	3:00 PM	47	59	61	54	68	69	71	52	62	41	31	53	61	52	69	32	68	55	62	30	9	15	65	73	71	69	72	73	66	69	71	71	62	58	74	74	74
	3:15 PM	53	54	45	52	54	56	47	34	35	26	27	45	58	52	68	26	63	35	12	12	9	15	64	72	72	70	71	72	61	65	69	68	55	51	73	74	74
	3:30 PM	66	61	47	51	49	37	16	27	27	25	27	48	54	42	69	20	21	11	9	11	9	17	60	71	73	70	70	72	60	60	66	66	53	42	72	73	72
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	4:15 PM	69	68	52	38	27	19	18	29	31	25	27	30	30	33	12	16	27	27	18	38	19	22	35	46	55	36	29	27	48	53	55	42	28	30	70	72	72
	4:30 PM	66	70	70	53	47	18	16	27	28	24	26	29	21	19	10	14	65	27	16	41	31	24	38	46	25	27	26	26	45	53	58	45	29	29	64	71	71
	4:45 PM	70	71	72	56	58	25	15	25	26	22	22	17	15	20	12	18	66	44	38	43	24	24	39	35	22	27	28	27	45	52	63	50	23	41	68	71	71
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	5:30 PM	70	55	32	24	20	16	15	26	28	23	25	25	23	36	67	33	54	26	16	34	21	23	36	26	22	28	29	26	45	51	65	55	46	41	55	70	71
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	Time	1115713	1120611	1115721	1117909	1108536	1122469	1120167	1108439	1115739	1108415	1115749	1108717	1108585	1122487	1113985	1123002	1108590	1123030	1108592	1120994	1108597	1121037	1108595	1121099	1121131	1108562	1121118	1108767	1121067	1125872	1108769	1125886	1108771	1108773	1119736	1119743	1119749
CACC	2:15 PM	72	71	73	60	71	70	74	70	71	71	71	71	72	71	74	69	73	61	73	66	71	64	68	74	75	72	72	74	66	71	72	73	67	61	75	75	75
	2:30 PM	71	68	71	55	69	68	73	68	69	65	64	65	69	67	73	58	73	56	72	63	69	59	68	73	73	71	72	74	65	70	73	73	64	56	74	75	74
	2:45 PM	71	69	72	55	69	68	73	61	64	58	51	57	65	60	71	34	71	52	68	55	46	23	68	74	73	72	73	74	65	70	73	73	65	59	74	74	74
	3:00 PM	42	59	62	54	69	69	72	50	61	49	39	48	63	56	69	33	70	53	67	34	11	16	67	74	73	72	73	74	65	71	73	73	62	57	74	74	74
	3:15 PM	52	55	42	46	60	56	63	39	52	36	27	36	60	52	58	27	67	38	25	14	11	16	66	73	73	71	72	73	63	67	71	70	57	50	73	74	74
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	3:45 PM	68	66	51	43	60	45	34	37	47	36	27	31	53	41	25	15	13	19	15	33	17	20	45	61	69	62	65	50	52	55	66	66	49	37	71	72	72
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	5:00 PM	70	69	69	50	57	50	56	54	59	57	34	36	61	42	40	25	66	31	19	42	41	29	34	52	29	31	32	28	49	51	68	61	43	24	67	71	71
	5:15 PM	70	62	60	47	53	51	46	53	58	60	41	36	57	44	45	30	69	35	25	44	44	33	37	51	34	34	34	26	50	57	68	64	49	40	67	71	71
	5:30 PM	66	59	58	44	49	41	36	52	58	51	40	40	65	48	47	33	70	39	34	43	45	39	45	52	37	36	34	27	50	50	67	60	47	40	66	71	72
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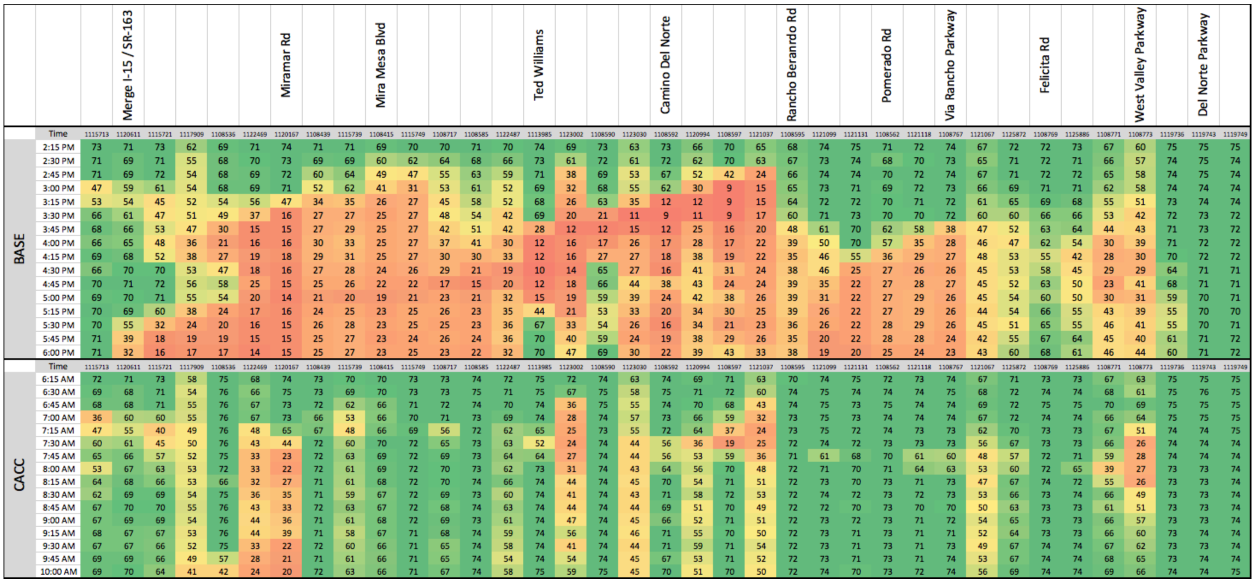
	6:00 PM	60	50	53	42	49	44	37	41	38	37	39	42	62	46	72	47	72	45	48	46	56	45	52	63	60	41	36	34	51	59	69	65	53	50	71	72	73

Figure 9-21: Speed contour with CACC with 50% penetration rate compared with the baseline case under Operational Condition 3



			Merge I-15 / SR-163					Miramar Rd			Mira Mesa Blvd					Ted Williams				Camino Del Norte				Rancho Berarndo Rd			Pomerado Rd		Via Rancho Parkway			Felicita Rd			West Valley Parkway		Del Norte Parkway	
	Time	1115713	1120611	1115721	1117909	1108536	1122469	1120167	1108439	1115739	1108415	1115749	1108717	1108585	1122487	1113985	1123002	1108590	1123030	1108592	1120994	1108597	1121037	1108595	1121099	1121131	1108562	1121118	1108767	1121067	1125872	1108769	1125886	1108771	1108773	1119736	1119743	1119749
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	2:45 PM	71	69	72	54	68	69	72	60	64	49	47	55	63	59	71	38	69	53	67	52	42	24	66	74	74	70	72	74	67	71	72	72	65	58	74	75	74
	3:00 PM	47	59	61	54	68	69	71	52	62	41	31	53	61	52	69	32	68	55	62	30	9	15	65	73	71	69	72	73	66	69	71	71	62	58	74	74	74
	3:15 PM	53	54	45	52	54	56	47	34	35	26	27	45	58	52	68	26	63	35	12	12	9	15	64	72	72	70	71	72	61	65	69	68	55	51	73	74	74
	3:30 PM	66	61	47	51	49	37	16	27	27	25	27	48	54	42	69	20	21	11	9	11	9	17	60	71	73	70	70	72	60	60	66	66	53	42	72	73	72
	3:45 PM	68	66	53	47	30	15	15	27	29	25	27	42	51	42	28	12	12	15	12	25	16	20	48	61	70	62	58	38	47	52	63	64	44	43	71	73	72
	4:00 PM	66	65	48	36	21	16	16	30	33	25	27	37	41	30	12	16	17	26	17	28	17	22	39	50	70	57	35	28	46	47	62	54	30	39	71	72	72
	4:15 PM	69	68	52	38	27	19	18	29	31	25	27	30	30	33	12	16	27	27	18	38	19	22	35	46	55	36	29	27	48	53	55	42	28	30	70	72	72
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	4:45 PM	70	71	72	56	58	25	15	25	26	22	22	17	15	20	12	18	66	44	38	43	24	24	39	35	22	27	28	27	45	52	63	50	23	41	68	71	71
	5:00 PM	69	70	71	55	54	20	14	21	20	19	21	23	21	32	15	19	59	39	24	42	38	26	39	31	22	27	29	26	45	54	60	50	30	31	59	70	71
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	5:45 PM	71	39	18	19	19	15	15	25	27	23	24	26	24	36	70	40	59	24	19	38	29	26	35	20	22	28	28	24	42	55	67	64	45	40	61	71	72
	6:00 PM	71	32	16	17	17	14	15	25	27	23	25	23	22	32	70	47	69	30	22	39	43	33	38	19	20	25	24	23	43	60	68	61	46	44	60	71	72
	Time	1115713	1120611	1115721	1117909	1108536	1122469	1120167	1108439	1115739	1108415	1115749	1108717	1108585	1122487	1113985	1123002	1108590	1123030	1108592	1120994	1108597	1121037	1108595	1121099	1121131	1108562	1121118	1108767	1121067	1125872	1108769	1125886	1108771	1108773	1119736	1119743	1119749
CACC	6:15 AM	72	71	73	58	75	68	74	73	70	70	73	73	74	72	75	72	74	63	74	69	71	63	70	74	75	72	73	74	67	71	73	73	67	63	75	75	75
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	6:45 AM	68	68	71	55	76	67	73	72	62	66	71	72	74	70	74	36	75	55	74	70	68	43	74	75	73	75	74	74	69	72	75	75	70	69	75	75	75
	7:00 AM	36	60	60	55	76	67	73	66	53	66	70	71	73	69	74	28	74	57	73	66	59	32	73	75	73	74	74	74	67	72	74	74	66	64	75	75	75
	7:15 AM	47	55	40	49	76	48	65	67	48	66	69	56	72	62	65	25	73	55	72	64	37	24	73	75	72	74	73	73	62	70	73	73	67	51	74	74	75
	7:30 AM	60	61	45	50	76	43	44	72	60	70	72	65	73	63	52	24	74	44	56	36	19	25	72	74	72	73	73	73	56	67	73	73	66	26	74	74	74
	7:45 AM	65	66	57	52	75	33	23	72	63	69	72	69	73	64	64	27	74	44	56	53	59	36	71	61	68	70	61	60	48	57	72	71	59	28	74	74	74
	8:00 AM	53	67	63	53	72	33	22	72	61	69	72	70	73	62	73	31	74	43	64	56	70	48	72	71	70	71	64	63	53	60	72	65	39	27	73	73	74
	8:15 AM	64	68	66	53	66	32	27	71	61	68	72	70	74	66	74	44	74	45	70	54	71	51	72	73	70	73	71	73	47	67	74	72	55	26	73	73	74
	8:30 AM	62	69	69	54	75	36	35	71	59	67	72	69	73	60	74	41	74	43	71	58	72	53	72	74	72	73	72	73	53	66	73	74	66	49	73	73	74
	8:45 AM	67	70	70	55	76	43	33	72	63	67	72	68	74	63	74	44	74	44	69	51	70	49	72	72	70	73	70	70	50	63	73	73	61	51	73	73	74
	9:00 AM	67	69	69	54	76	44	36	71	61	68	72	69	73	61	74	47	74	45	66	52	71	51	72	73	72	73	71	72	54	65	73	73	66	57	73	73	74
	9:15 AM	68	67	67	53	76	44	39	71	58	67	71	68	74	59	74	56	74	46	71	55	70	50	72	73	71	73	71	71	52	64	73	73	66	60	73	74	74
	9:30 AM	67	67	66	52	75	33	22	72	60	66	71	65	74	58	74	41	74	44	71	59	71	54	72	73	71	73	71	73	49	67	74	74	67	62	73	73	74
	9:45 AM	69	69	66	49	57	28	21	71	61	66	71	65	74	54	74	54	74	45	67	53	71	52	72	73	71	73	71	74	53	67	74	74	68	65	73	74	74
	10:00 AM	69	70	64	41	42	24	20	72	63	66	71	67	74	58	75	59	75	45	70	51	70	50	72	74	70	73	72	74	56	69	74	74	69	66	74	74	75

Figure 9-22: Speed contour with CACC with 90% penetration rate compared with the baseline case under Operational Condition 3

If we compare network-wide traffic performance measures with CACC with different penetration rates with the baseline condition (Table 9-19, Table 9-20 and Table 9-21), we can notice that CACC shows a positive impact in terms of increase of throughput and reduction of travel time under this operational condition, which has severe congestion throughout the corridor. This benefit is significant already at the lowest penetration rate, and increases as the penetration rate increases.

Table 9-19: Performance measures with CACC with 25% penetration rate compared with the baseline case under Operational Condition 3

Network Statistics	CACC	Base	Difference
Vehicles Miles Travelled (miles)	2,581,645	2,518,604	2.5%
Total Travel Time (h)	70,387	76,531	-8.0%
Passenger Hourly Travel Time (h)	91,541	99,052	-7.6%
VMT/VHT (miles/h)	36.68	32.91	11.5%

Table 9-20: Performance measures with CACC with 50% penetration rate compared with the baseline case under Operational Condition 3

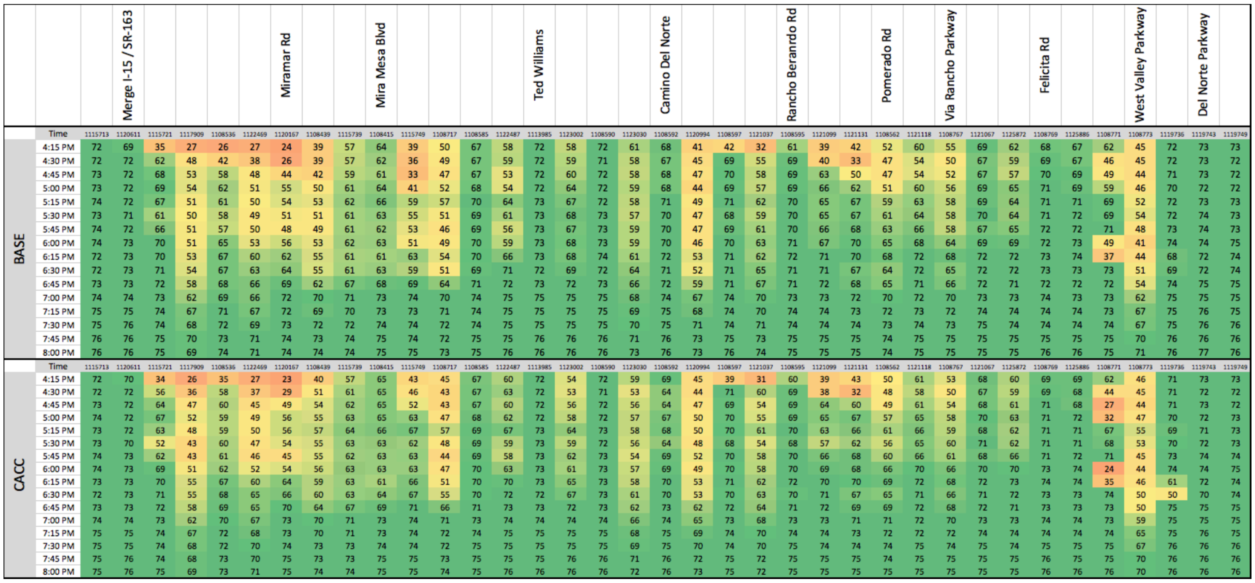
Network Statistics	CACC	Base	Difference
Vehicles Miles Travelled (miles)	2,501,073	2,518,604	-0.7%
Total Travel Time (h)	60,244	76,531	-21.3%
Passenger Hourly Travel Time (h)	79,302	99,052	-19.9%
VMT/VHT (miles/h)	41.52	32.91	26.2%

Table 9-21: Performance measures with CACC with 90% penetration rate compared with the baseline case under Operational Condition 3

Network Statistics	CACC	Base	Difference
Vehicles Miles Travelled (miles)	2,669,605	2,518,604	6.0%
Total Travel Time (h)	65,410	76,531	-14.5%
Passenger Hourly Travel Time (h)	85,564	99,052	-13.6%
VMT/VHT (miles/h)	40.81	32.91	24.0%

9.2.2.4 Operational condition 4 (PM4)

A comparison of the speed contour on I-15 in the northbound direction with the baseline conditions shows that under this operational condition, in which there is no significant congestion, CACC adoption doesn't improve significantly the average speed along the corridor (Figure 9-23, Figure 9-24 and Figure 9-25). In fact, at 50% penetration rate the application seems to have a counterproductive effect at the merge into I-15 from SR-163; this is because CACC lanes start after the merge, so at that location connected vehicles move to the leftmost lanes, while traffic from SR-163 merges from the left, thus producing significant conflicts.



			Merge I-15 / SR-163					Miramar Rd			Mira Mesa Blvd					Ted Williams				Camino Del Norte				Rancho Berarndo Rd			Pomerado Rd		Via Rancho Parkway			Felicita Rd			West Valley Parkway		Del Norte Parkway	
	Time	1115713	1120611	1115721	1117909	1108536	1122469	1120167	1108439	1115739	1108415	1115749	1108717	1108585	1122487	1113985	1123002	1108590	1123030	1108592	1120994	1108597	1121037	1108595	1121099	1121131	1108562	1121118	1108767	1121067	1125872	1108769	1125886	1108771	1108773	1119736	1119743	1119749
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	4:30 PM	72	72	62	48	42	38	26	39	57	62	36	49	67	59	72	59	71	58	67	45	69	55	69	40	33	47	54	50	67	59	69	67	46	45	72	73	72
	4:45 PM	73	72	68	53	58	48	44	42	59	61	33	47	67	53	72	60	72	58	68	47	70	58	69	63	50	47	54	52	67	57	70	69	49	44	71	73	72
	5:00 PM	73	72	69	54	62	51	55	50	61	64	41	52	68	54	72	64	72	59	68	44	69	57	69	66	62	51	60	56	69	65	71	69	59	46	70	72	72
	5:15 PM	74	72	67	51	61	50	54	53	62	66	59	57	70	64	73	67	72	58	71	49	71	62	70	65	67	59	63	58	69	64	71	71	69	52	72	73	73
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	5:45 PM	74	72	66	51	57	50	48	49	61	62	53	46	69	56	73	67	73	59	70	47	69	61	70	66	68	63	66	58	67	65	72	72	71	48	73	74	73
	6:00 PM	74	73	70	51	65	53	56	53	62	63	51	49	70	59	73	68	73	59	70	46	70	63	71	67	70	65	68	64	69	69	72	73	49	41	74	74	75
	6:15 PM	72	73	70	53	67	60	62	55	61	61	63	54	70	66	73	68	74	61	72	53	71	62	72	71	70	68	72	68	72	72	73	74	37	44	68	72	74
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	6:45 PM	73	73	72	58	68	66	69	62	67	68	69	64	71	72	73	72	73	66	72	59	71	67	71	72	68	65	71	66	72	71	72	72	72	54	74	75	75
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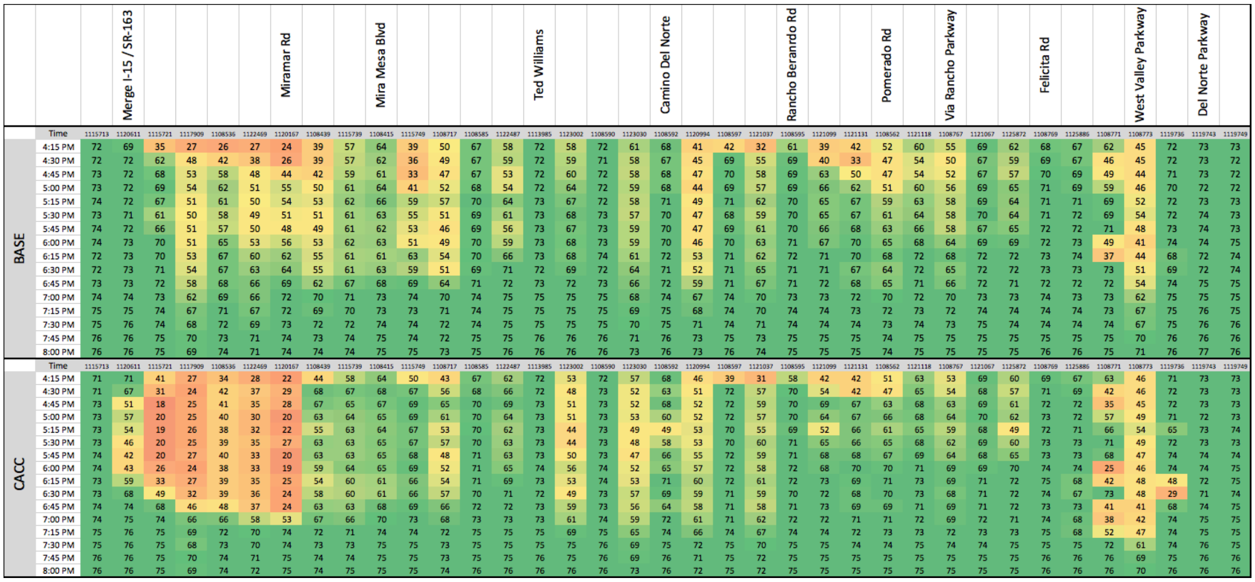
	7:30 PM	75	76	74	68	72	69	73	72	72	74	74	72	74	75	75	75	75	70	75	71	74	71	74	74	74	73	74	73	75	74	74	74	74	67	75	76	76
	7:45 PM	76	76	75	70	73	71	74	73	74	75	74	72	75	75	76	76	76	71	76	73	75	73	75	75	75	74	75	75	75	75	75	75	75	70	76	76	76
	8:00 PM	76	76	75	69	74	71	74	74	74	75	75	73	75	76	76	76	76	73	76	73	76	74	75	75	75	74	75	75	75	75	76	76	75	71	76	77	76
	Time	1115713	1120611	1115721	1117909	1108536	1122469	1120167	1108439	1115739	1108415	1115749	1108717	1108585	1122487	1113985	1123002	1108590	1123030	1108592	1120994	1108597	1121037	1108595	1121099	1121131	1108562	1121118	1108767	1121067	1125872	1108769	1125886	1108771	1108773	1119736	1119743	1119749
CACC	4:15 PM	72	70	34	26	35	27	23	40	57	65	43	45	67	60	72	54	72	59	69	45	39	31	60	39	43	50	61	53	68	60	69	69	62	46	71	73	73
	4:30 PM	72	72	56	36	58	37	29	51	61	65	46	43	67	63	72	53	71	53	64	44	71	60	69	38	32	48	58	50	67	59	69	68	44	45	71	72	72
	4:45 PM	73	72	64	47	60	45	49	54	62	65	52	43	67	60	72	56	72	56	64	47	69	54	69	64	60	49	61	54	68	61	71	68	27	44	71	73	72
	5:00 PM	74	72	67	52	59	49	56	55	63	65	63	47	68	62	72	58	72	57	67	50	70	55	69	65	67	57	65	58	70	63	71	72	32	47	70	72	73
	5:15 PM	73	72	63	48	59	50	56	57	64	66	67	57	69	67	73	64	73	58	68	50	70	61	70	63	66	61	66	59	68	62	71	71	67	55	69	71	73
	5:30 PM	73	70	52	43	60	47	54	55	63	63	62	48	69	59	73	59	72	56	64	48	68	54	68	57	62	56	65	60	71	62	71	71	68	53	70	72	73
	5:45 PM	74	73	62	43	61	46	45	55	62	63	63	44	69	58	73	62	73	54	69	52	70	58	70	66	68	60	66	61	68	66	71	72	71	45	73	74	74
	6:00 PM	74	73	69	51	62	52	54	56	63	63	63	47	70	63	73	61	73	57	69	49	70	58	70	69	68	66	70	66	70	70	73	74	24	44	74	74	75
	6:15 PM	73	73	70	55	67	60	64	59	63	61	66	51	70	70	73	65	73	58	70	53	71	62	72	70	70	69	72	68	72	73	74	74	35	46	61	72	74
	6:30 PM	72	73	71	55	68	65	66	60	63	64	67	55	70	72	72	67	73	61	70	53	70	63	70	71	67	65	71	66	71	72	73	73	74	50	50	70	74
	6:45 PM	73	73	72	58	69	65	70	64	67	69	71	66	71	73	73	72	73	62	73	62	72	64	71	72	69	69	72	68	72	71	73	73	73	50	75	75	75
	7:00 PM	74	74	73	62	70	67	73	70	71	73	74	71	73	74	74	74	74	66	74	65	73	68	73	73	71	71	72	70	73	73	74	74	73	59	75	75	75
	7:15 PM	75	75	74	67	72	68	73	70	71	73	74	72	74	75	75	75	75	68	75	69	74	70	74	74	73	72	72	72	74	74	74	74	74	65	75	76	75
	7:30 PM	75	75	74	68	72	70	74	73	73	74	74	72	75	75	75	75	75	69	75	70	74	70	75	74	74	74	75	74	75	74	75	75	75	67	76	76	76
	7:45 PM	75	76	74	68	73	70	75	73	73	75	75	73	75	75	75	76	76	71	76	72	75	72	75	75	75	74	75	75	75	75	76	75	75	70	76	76	76
	8:00 PM	75	76	75	69	73	71	75	74	74	75	75	74	75	76	76	76	76	72	76	73	75	72	75	75	75	75	75	75	75	75	76	76	76	70	76	76	76

Figure 9-23: Speed contour with CACC with 25% penetration rate compared with the baseline case under Operational Condition 4



			Merge I-15 / SR-163					Miramar Rd			Mira Mesa Blvd					Ted Williams				Camino Del Norte				Rancho Berarndo Rd			Pomerado Rd		Via Rancho Parkway			Felicita Rd			West Valley Parkway		Del Norte Parkway	
	Time	1115713	1120611	1115721	1117909	1108536	1122469	1120167	1108439	1115739	1108415	1115749	1108717	1108585	1122487	1113985	1123002	1108590	1123030	1108592	1120994	1108597	1121037	1108595	1121099	1121131	1108562	1121118	1108767	1121067	1125872	1108769	1125886	1108771	1108773	1119736	1119743	1119749
BASE	4:15 PM	72	69	35	27	26	27	24	39	57	64	39	50	67	58	72	58	72	61	68	41	42	32	61	39	42	52	60	55	69	62	68	67	62	45	72	73	73
	4:30 PM	72	72	62	48	42	38	26	39	57	62	36	49	67	59	72	59	71	58	67	45	69	55	69	40	33	47	54	50	67	59	69	67	46	45	72	73	72
	4:45 PM	73	72	68	53	58	48	44	42	59	61	33	47	67	53	72	60	72	58	68	47	70	58	69	63	50	47	54	52	67	57	70	69	49	44	71	73	72
	5:00 PM	73	72	69	54	62	51	55	50	61	64	41	52	68	54	72	64	72	59	68	44	69	57	69	66	62	51	60	56	69	65	71	69	59	46	70	72	72
	5:15 PM	74	72	67	51	61	50	54	53	62	66	59	57	70	64	73	67	72	58	71	49	71	62	70	65	67	59	63	58	69	64	71	71	69	52	72	73	73
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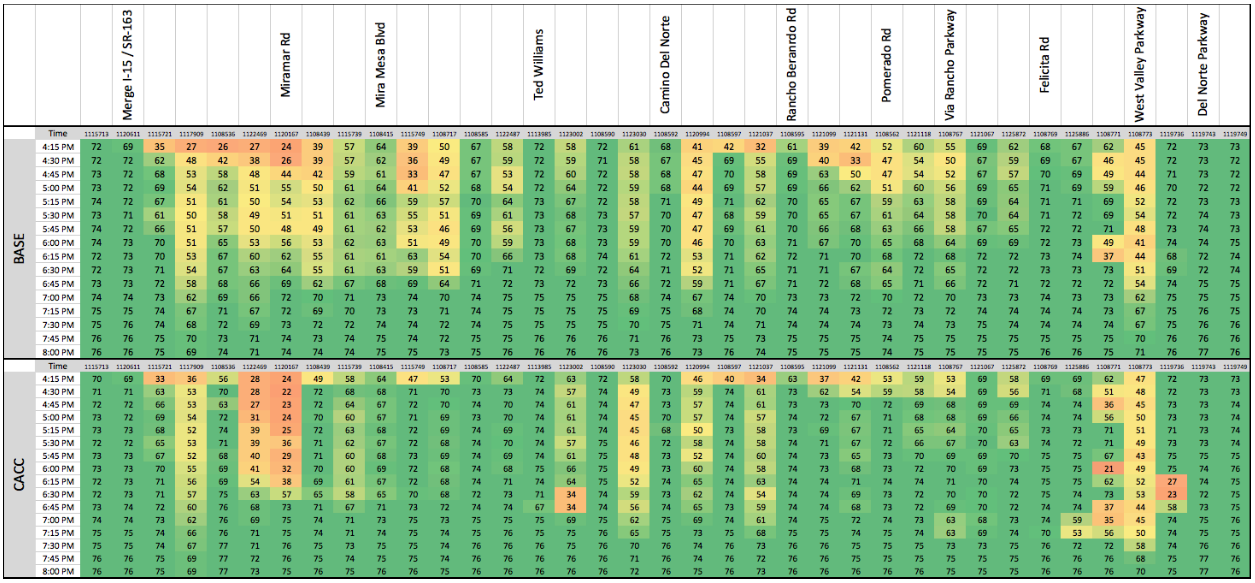
	5:45 PM	74	72	66	51	57	50	48	49	61	62	53	46	69	56	73	67	73	59	70	47	69	61	70	66	68	63	66	58	67	65	72	72	71	48	73	74	73
	6:00 PM	74	73	70	51	65	53	56	53	62	63	51	49	70	59	73	68	73	59	70	46	70	63	71	67	70	65	68	64	69	69	72	73	49	41	74	74	75
	6:15 PM	72	73	70	53	67	60	62	55	61	61	63	54	70	66	73	68	74	61	72	53	71	62	72	71	70	68	72	68	72	72	73	74	37	44	68	72	74
	6:30 PM	72	73	71	54	67	63	64	55	61	63	59	51	69	71	72	69	72	64	71	52	71	65	71	71	67	64	72	65	72	72	73	73	73	51	69	72	74
	6:45 PM	73	73	72	58	68	66	69	62	67	68	69	64	71	72	73	72	73	66	72	59	71	67	71	72	68	65	71	66	72	71	72	72	72	54	74	75	75
	7:00 PM	74	74	73	62	69	66	72	70	71	73	74	70	74	75	75	75	75	68	74	67	74	70	73	73	72	70	72	70	73	73	74	73	73	62	75	75	75
	7:15 PM	75	75	74	67	71	67	72	69	70	73	73	71	74	75	75	75	75	69	75	68	74	70	74	74	73	72	73	72	74	74	74	74	73	67	75	76	75
	7:30 PM	75	76	74	68	72	69	73	72	72	74	74	72	74	75	75	75	75	70	75	71	74	71	74	74	74	73	74	73	75	74	74	74	74	67	75	76	76
	7:45 PM	76	76	75	70	73	71	74	73	74	75	74	72	75	75	76	76	76	71	76	73	75	73	75	75	75	74	75	75	75	75	75	75	75	70	76	76	76
	8:00 PM	76	76	75	69	74	71	74	74	74	75	75	73	75	76	76	76	76	73	76	73	76	74	75	75	75	74	75	75	75	75	76	76	75	71	76	77	76
	Time	1115713	1120611	1115721	1117909	1108536	1122469	1120167	1108439	1115739	1108415	1115749	1108717	1108585	1122487	1113985	1123002	1108590	1123030	1108592	1120994	1108597	1121037	1108595	1121099	1121131	1108562	1121118	1108767	1121067	1125872	1108769	1125886	1108771	1108773	1119736	1119743	1119749
CACC	4:15 PM	71	71	41	27	34	28	22	44	58	64	50	43	67	62	72	53	72	57	68	46	39	31	58	42	42	51	63	53	69	60	69	67	63	46	71	73	73
	4:30 PM	71	67	31	24	42	37	29	68	67	68	67	56	68	66	72	48	73	52	63	51	72	57	70	54	42	47	65	54	68	57	71	69	42	46	72	73	73
	4:45 PM	73	51	18	25	41	35	28	67	65	67	69	65	70	69	73	51	73	52	68	52	72	59	70	69	67	63	68	63	69	61	72	72	35	45	72	73	73
	5:00 PM	73	57	20	25	40	30	20	63	64	65	69	61	70	64	73	51	73	53	60	52	72	57	70	64	67	66	68	64	70	62	73	72	57	49	71	72	73
	5:15 PM	73	54	19	26	38	32	22	55	63	64	67	53	70	62	73	44	73	49	49	53	70	55	69	52	66	61	65	59	68	49	72	71	66	54	65	73	74
	5:30 PM	73	46	20	25	39	35	27	63	63	65	67	57	70	63	73	44	73	48	58	53	70	60	71	65	66	65	68	62	69	60	73	73	71	49	72	73	73
	5:45 PM	74	42	20	27	40	33	20	63	63	65	68	48	71	63	73	50	73	47	66	55	72	59	71	68	68	67	69	64	68	65	73	73	68	47	74	74	74
	6:00 PM	74	43	26	24	38	33	19	59	64	65	69	52	71	65	74	56	74	52	65	57	72	58	72	68	70	70	71	69	69	70	74	74	25	46	74	74	75
	6:15 PM	73	59	33	27	39	35	25	54	60	61	66	54	71	69	73	53	74	53	71	60	72	61	72	73	69	71	73	69	71	72	75	68	42	48	48	72	75
	6:30 PM	73	68	49	32	39	36	24	58	60	61	66	57	70	71	72	49	73	57	69	59	71	59	70	72	68	70	73	68	71	72	74	67	73	48	29	71	74
	6:45 PM	74	74	68	46	48	37	24	63	63	68	69	66	72	72	73	59	73	56	64	58	71	58	71	73	69	69	71	69	71	72	73	73	41	41	68	74	75
	7:00 PM	74	75	74	66	66	58	53	67	66	70	73	68	73	73	73	61	74	59	72	61	71	62	72	72	71	71	72	69	72	71	74	68	38	42	74	75	75
	7:15 PM	75	76	75	69	72	70	74	72	71	74	74	72	75	75	75	69	75	65	74	66	74	67	74	74	72	73	73	72	73	73	75	68	52	47	74	75	75
	7:30 PM	75	76	75	68	73	70	74	73	73	75	75	73	75	75	75	75	76	69	75	72	75	70	75	75	74	74	75	74	74	75	75	75	72	61	74	76	75
	7:45 PM	76	76	75	70	74	71	75	74	74	75	75	73	75	75	76	75	76	69	76	71	75	72	75	75	75	75	75	75	75	75	76	76	76	69	75	76	76
	8:00 PM	76	76	75	69	74	72	75	74	75	75	75	74	76	76	76	76	76	73	76	72	75	72	75	75	75	75	75	75	75	75	76	76	76	70	76	76	76

Figure 9-24: Speed contour with CACC with 50% penetration rate compared with the baseline case under Operational Condition 4



			Merge I-15 / SR-163					Miramar Rd			Mira Mesa Blvd					Ted Williams				Camino Del Norte				Rancho Berarndo Rd			Pomerado Rd		Via Rancho Parkway			Felicita Rd			West Valley Parkway		Del Norte Parkway	
	Time	1115713	1120611	1115721	1117909	1108536	1122469	1120167	1108439	1115739	1108415	1115749	1108717	1108585	1122487	1113985	1123002	1108590	1123030	1108592	1120994	1108597	1121037	1108595	1121099	1121131	1108562	1121118	1108767	1121067	1125872	1108769	1125886	1108771	1108773	1119736	1119743	1119749
BASE	4:15 PM	72	69	35	27	26	27	24	39	57	64	39	50	67	58	72	58	72	61	68	41	42	32	61	39	42	52	60	55	69	62	68	67	62	45	72	73	73
	4:30 PM	72	72	62	48	42	38	26	39	57	62	36	49	67	59	72	59	71	58	67	45	69	55	69	40	33	47	54	50	67	59	69	67	46	45	72	73	72
	4:45 PM	73	72	68	53	58	48	44	42	59	61	33	47	67	53	72	60	72	58	68	47	70	58	69	63	50	47	54	52	67	57	70	69	49	44	71	73	72
	5:00 PM	73	72	69	54	62	51	55	50	61	64	41	52	68	54	72	64	72	59	68	44	69	57	69	66	62	51	60	56	69	65	71	69	59	46	70	72	72
	5:15 PM	74	72	67	51	61	50	54	53	62	66	59	57	70	64	73	67	72	58	71	49	71	62	70	65	67	59	63	58	69	64	71	71	69	52	72	73	73
	5:30 PM	73	71	61	50	58	49	51	51	61	63	55	51	69	61	73	68	73	57	70	47	68	59	70	65	67	61	64	58	70	64	71	72	69	54	72	74	73
	5:45 PM	74	72	66	51	57	50	48	49	61	62	53	46	69	56	73	67	73	59	70	47	69	61	70	66	68	63	66	58	67	65	72	72	71	48	73	74	73
	6:00 PM	74	73	70	51	65	53	56	53	62	63	51	49	70	59	73	68	73	59	70	46	70	63	71	67	70	65	68	64	69	69	72	73	49	41	74	74	75
	6:15 PM	72	73	70	53	67	60	62	55	61	61	63	54	70	66	73	68	74	61	72	53	71	62	72	71	70	68	72	68	72	72	73	74	37	44	68	72	74
	6:30 PM	72	73	71	54	67	63	64	55	61	63	59	51	69	71	72	69	72	64	71	52	71	65	71	71	67	64	72	65	72	72	73	73	73	51	69	72	74
	6:45 PM	73	73	72	58	68	66	69	62	67	68	69	64	71	72	73	72	73	66	72	59	71	67	71	72	68	65	71	66	72	71	72	72	72	54	74	75	75
	7:00 PM	74	74	73	62	69	66	72	70	71	73	74	70	74	75	75	75	75	68	74	67	74	70	73	73	72	70	72	70	73	73	74	73	73	62	75	75	75
	7:15 PM	75	75	74	67	71	67	72	69	70	73	73	71	74	75	75	75	75	69	75	68	74	70	74	74	73	72	73	72	74	74	74	74	73	67	75	76	75
	7:30 PM	75	76	74	68	72	69	73	72	72	74	74	72	74	75	75	75	75	70	75	71	74	71	74	74	74	73	74	73	75	74	74	74	74	67	75	76	76
	7:45 PM	76	76	75	70	73	71	74	73	74	75	74	72	75	75	76	76	76	71	76	73	75	73	75	75	75	74	75	75	75	75	75	75	75	70	76	76	76
	8:00 PM	76	76	75	69	74	71	74	74	74	75	75	73	75	76	76	76	76	73	76	73	76	74	75	75	75	74	75	75	75	75	76	76	75	71	76	77	76
	Time	1115713	1120611	1115721	1117909	1108536	1122469	1120167	1108439	1115739	1108415	1115749	1108717	1108585	1122487	1113985	1123002	1108590	1123030	1108592	1120994	1108597	1121037	1108595	1121099	1121131	1108562	1121118	1108767	1121067	1125872	1108769	1125886	1108771	1108773	1119736	1119743	1119749
CACC	4:15 PM	70	69	33	36	56	28	24	49	58	64	47	53	70	64	72	63	72	58	70	46	40	34	63	37	42	53	59	53	69	58	69	69	62	47	72	73	73
	4:30 PM	71	71	63	53	70	28	22	72	68	68	71	70	73	73	74	57	74	49	73	59	74	61	73	62	54	59	58	54	69	56	71	68	51	48	72	73	73
	4:45 PM	72	72	66	53	63	27	23	72	64	67	72	70	74	70	74	61	74	47	73	57	74	61	73	73	70	72	69	68	69	69	74	74	36	45	73	73	74
	5:00 PM	73	72	69	54	72	31	24	70	60	67	71	69	73	70	74	61	74	45	70	57	74	57	74	72	67	71	68	68	69	66	74	74	56	50	73	73	74
	5:15 PM	73	73	68	52	74	39	25	72	63	68	72	69	74	69	74	61	74	45	68	50	73	58	73	69	67	71	65	64	70	65	73	73	71	51	71	73	74
	5:30 PM	72	72	65	53	71	39	36	71	62	67	72	68	74	70	74	57	75	46	72	58	74	58	74	71	67	72	66	67	70	63	74	72	71	49	73	73	74
	5:45 PM	73	73	67	52	68	40	29	71	60	68	73	69	74	69	74	61	75	48	73	52	74	60	74	73	65	73	70	69	69	70	75	75	67	43	75	75	75
	6:00 PM	73	73	70	55	69	41	32	70	60	69	72	68	74	68	75	66	75	49	73	60	74	58	74	73	68	73	72	70	69	73	75	75	21	49	75	74	76
	6:15 PM	72	73	71	56	69	54	38	69	61	67	72	68	74	71	74	64	75	52	74	65	74	63	74	74	71	74	74	71	70	74	75	75	62	52	27	74	75
	6:30 PM	72	73	71	57	75	63	57	65	58	65	70	68	72	73	71	34	74	59	73	62	74	54	74	74	69	73	72	70	70	72	75	74	73	53	23	72	75
	6:45 PM	73	74	72	60	76	68	73	71	67	71	73	72	74	74	67	34	74	56	74	65	73	59	74	74	68	73	72	69	70	72	74	74	37	44	58	73	75
	7:00 PM	74	74	73	62	76	69	75	74	71	73	75	73	75	75	75	69	75	62	75	69	74	61	74	75	72	74	73	63	68	73	74	59	35	45	74	75	76
	7:15 PM	75	75	74	66	76	71	75	74	71	74	75	74	75	76	75	75	76	65	75	73	75	68	75	75	74	75	74	63	69	74	70	53	56	50	74	75	75
	7:30 PM	75	75	74	67	77	71	76	75	73	75	75	74	76	76	76	75	76	70	76	74	76	73	76	76	75	75	75	73	73	75	76	72	72	58	74	76	76
	7:45 PM	76	76	75	69	77	72	76	75	74	75	75	74	76	76	76	76	76	71	76	74	76	72	76	76	75	75	75	75	75	75	76	76	76	68	75	77	76
	8:00 PM	76	76	75	69	77	73	75	76	75	76	76	75	76	76	76	76	76	72	76	75	76	73	76	76	76	76	76	75	75	75	76	76	76	70	75	77	76

Figure 9-25: Speed contour with CACC with 90% penetration rate compared with the baseline case under Operational Condition 4

If we compare network-wide traffic performance measures with CACC with different penetration rates with the baseline condition (Table 9-22, Table 9-23 and Table 9-24), we can notice that CACC shows a positive impact in terms of increase of throughput, though less significant compared to all the other operational conditions. Additionally, at 50% penetration rate, the lane-changing conflicts between connected and non-connected vehicles at some locations seem to create a slight overall reduction of speed.

Table 9-22: Performance measures with CACC with 25% penetration rate compared with the baseline case under Operational Condition 4

Network Statistics	CACC	Base	Difference
Vehicles Miles Travelled (miles)	2,331,255	2,302,897	1.2%
Total Travel Time (h)	57,219	57,547	-0.6%
Passenger Hourly Travel Time (h)	75,512	75,856	-0.5%
VMT/VHT (miles/h)	40.74	40.02	1.8%

Table 9-23: Performance measures with CACC with 50% penetration rate compared with the baseline case under Operational Condition 4

Network Statistics	CACC	Base	Difference
Vehicles Miles Travelled (miles)	2,355,252	2,302,897	2.3%
Total Travel Time (h)	59,482	57,547	3.4%
Passenger Hourly Travel Time (h)	77,872	75,856	2.7%
VMT/VHT (miles/h)	39.60	40.02	-1.1%

Table 9-24: Performance measures with CACC with 90% penetration rate compared with the baseline case under Operational Condition 4

Network Statistics	CACC	Base	Difference
Vehicles Miles Travelled (miles)	2,364,616	2,302,897	2.7%
Total Travel Time (h)	58,247	57,547	1.2%
Passenger Hourly Travel Time (h)	76,468	75,856	0.8%
VMT/VHT (miles/h)	40.60	40.02	1.4%

9.2.2.5 Comparison between operational conditions

A comparison of the performance measures under different operational conditions and different penetration rates shows that CACC is more effective in congested situations (Figure 9-26): PM3, which has congestion distributed throughout the corridor, shows the highest increase of throughput and reduction of travel time, even at lower penetration rates.

When congestion is low, at some penetration rates even a slight reduction of traffic performance can be observed; this is because CACC platoons may cause an obstacle for non-connected vehicle that want to change lane, which may have to reduce their speed and look for a gap between platoons.

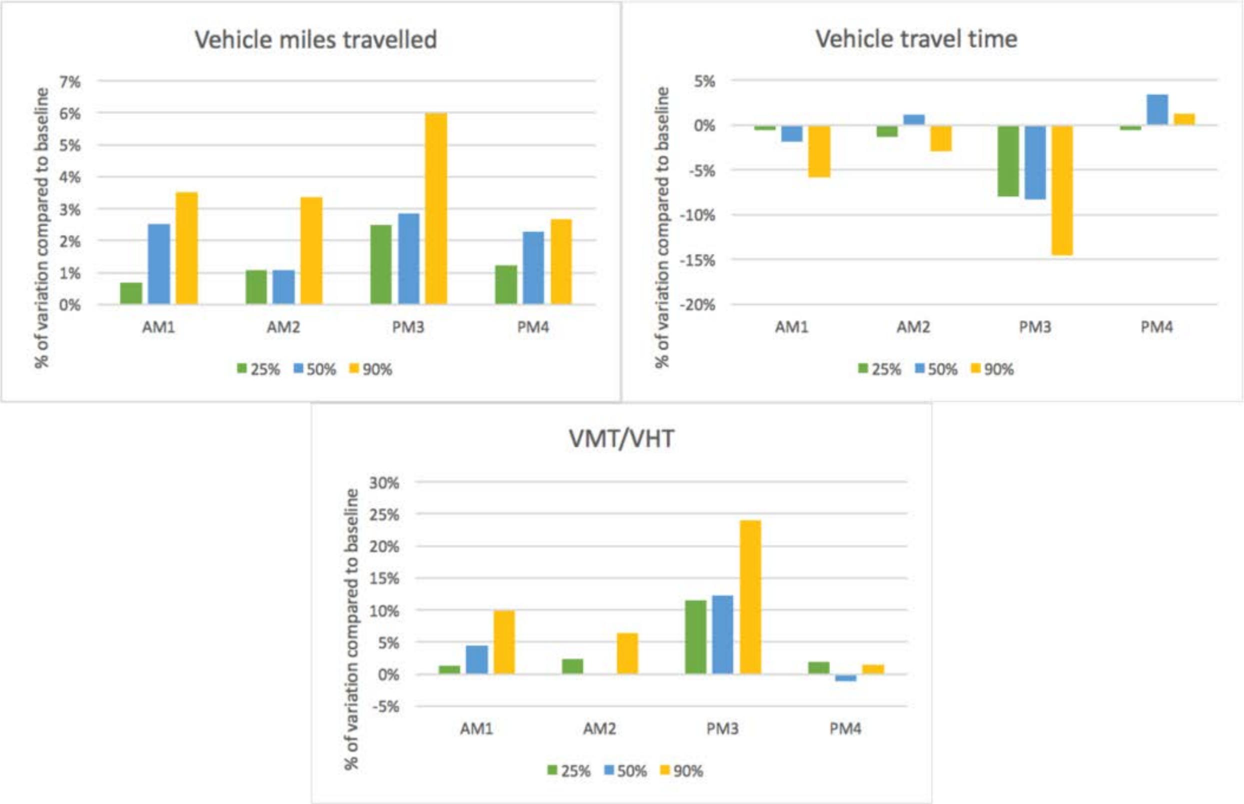


Figure 9-26: Change of the performance measures with CACC with different penetration rates compared with the baseline case under the different operational conditions

The analysis of the simulations with CACC suggest also the following observations:

- Most CACC algorithms available today only deal with car-following in a single lane and with an already formed platoon:
  - Care should be taken in selecting the parameters of the CACC algorithm (for example, the gain coefficients of the controller logic, the target headway, the update frequency), as only some combinations produce a stable car-following regime.
- To produce tangible benefits in real-world conditions, CACC algorithms should deal also with other aspects of vehicle movement:
  - Managing the transition (vehicles joining or leaving the platoon) is key to avoid instabilities.
  - Managing the vehicle distribution across multiple lanes is key with multiple reserved lanes (higher penetration rates).
  - Managing the length of the platoon is key with mixed traffic, to prevent blocking non-connected vehicles.

  - Managing the lane changing is key to allow connected vehicles take the exit they need to take and to prevent blocking non-connected vehicles.
- The results presented in this report should not be taken as an evaluation of the impact of CACC technology in general, but only of one specific implementation of this technology, based on the algorithm described in Section 6.2.1.

Additional considerations regarding the impact of penetration rates are provided in Chapter 12.

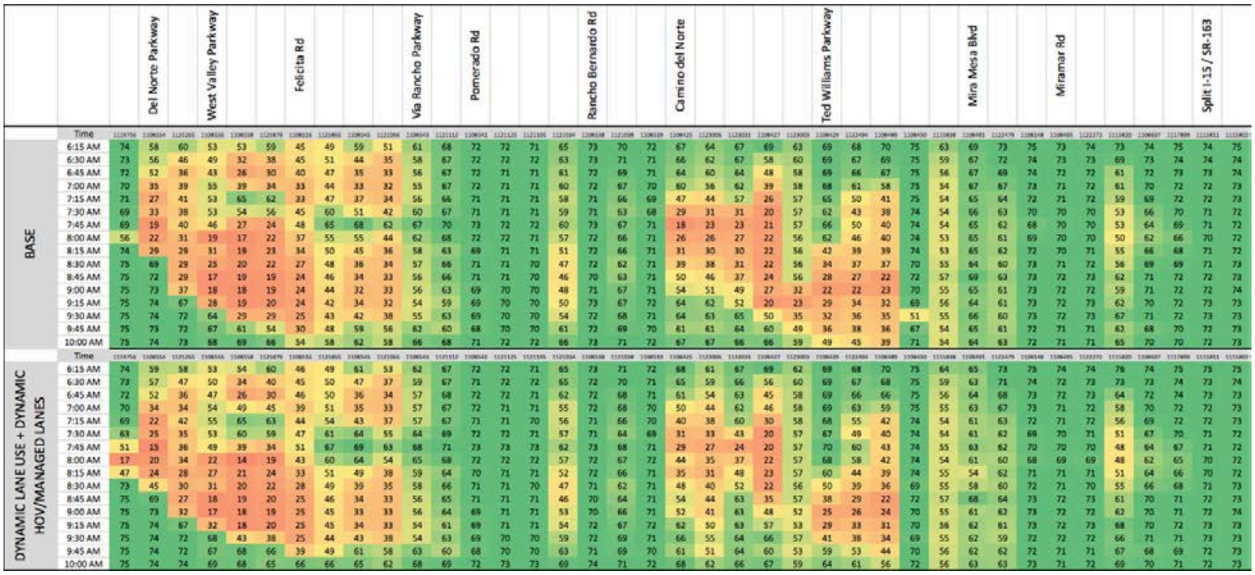
9.2.3 Dynamic Lane Use and Dynamic HOV/Managed Lanes

Dynamic Lane Use was modelled as a change from the standard 2 northbound and 2 southbound HOV lane configurations to 1 northbound and 3 southbound lanes for Operational Conditions 1 and 2 (AM) or 3 northbound and 1 southbound lanes for Operational Conditions 3 and 4 (PM). See 7.1.1 for further details. To promote the usage of the additional HOV lane, Dynamic HOV/Managed Lanes was concurrently modelled as the possibility for SOVs to access to the HOV lanes for free in the southbound direction for Operational Conditions 1 and 2 (AM) and in the northbound direction for Operational Conditions 3 and 4 (PM). See Section 7.2.2 for further details.

Both strategies are activated throughout the simulation.

9.2.3.1 Operational condition 1 (AM1)

A comparison of the speed contour on I-15 in the southbound direction with the baseline conditions shows that Dynamic Lane Use and Dynamic HOV/Managed Lanes produce overall a slight reduction of congestion along the corridor, with some localized increase of congestion where the accesses to the HOV lanes are located (Figure 9-27). This is intuitive because this strategy increases the capacity of the corridor by providing an additional lane for southbound traffic and promotes the usage of HOV lanes.



	Time		Del Norte Parkway		West Valley Parkway			Felicita Rd				Via Rancho Parkway		Pomerado Rd				Rancho Bernardo Rd			Camino del Norte					Ted Williams Parkway					Mira Mesa Blvd			Miramar Rd					Split I-15 / SR-163	
BASE	6:15 AM	74	58	60	53	53	59	45	49	59	51	61	68	72	72	71	65	73	70	72	67	64	67	69	63	69	68	70	75	63	69	73	75	73	74	73	74	75	74	75
	6:30 AM	73	56	46	49	32	38	45	51	44	35	58	67	72	72	72	63	73	71	71	66	62	67	58	60	69	67	69	75	59	67	72	74	73	73	69	73	74	74	74
	6:45 AM	72	52	36	43	26	30	40	47	35	33	56	67	72	71	71	61	72	69	71	64	60	64	48	58	69	66	67	75	56	67	69	74	72	72	61	72	73	73	74
	7:00 AM	70	35	39	55	39	34	33	44	33	32	55	67	72	71	71	60	72	67	70	60	58	62	39	58	68	61	58	75	54	67	67	73	71	72	61	70	72	72	73
	7:15 AM	71	27	41	53	65	62	33	47	37	34	56	66	71	71	71	58	71	66	69	47	44	57	26	57	65	50	41	75	54	65	64	72	71	72	59	69	72	72	73
	7:30 AM	69	33	38	53	54	56	45	60	51	42	60	67	71	71	71	59	71	63	68	29	31	31	20	57	62	43	38	74	54	66	63	70	70	70	53	66	70	71	72
	7:45 AM	69	19	40	46	27	24	48	65	68	62	67	70	73	72	72	60	73	67	71	18	23	23	21	57	66	50	40	74	54	65	62	68	70	70	53	64	69	71	72
	8:00 AM	56	22	31	19	17	22	37	55	55	44	62	68	72	72	71	57	72	66	71	26	26	27	22	56	62	46	40	74	53	65	61	69	70	70	50	62	66	70	72
	8:15 AM	74	29	29	31	19	23	34	50	45	36	58	63	69	71	71	51	72	66	71	31	30	30	22	56	42	39	39	74	53	65	62	72	70	71	55	66	68	71	72
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	9:00 AM	75	73	37	18	18	19	24	44	32	33	56	63	69	70	70	48	71	67	71	54	51	49	27	32	22	22	23	70	55	65	61	73	72	72	59	71	72	72	74
	9:15 AM	75	74	67	28	19	20	24	42	34	32	54	59	69	70	70	50	73	67	72	64	62	52	20	23	29	34	32	69	56	64	61	73	72	73	62	70	72	73	73
	9:30 AM	75	74	72	64	29	29	25	43	42	38	55	63	69	70	70	54	72	68	71	64	63	65	50	35	32	36	35	51	55	66	60	73	72	73	67	71	72	73	73
	9:45 AM	75	73	72	67	61	54	30	48	59	56	62	60	68	70	70	61	72	69	70	61	61	64	60	49	36	38	36	67	54	65	61	72	71	71	62	68	70	72	73
	10:00 AM	75	74	73	68	69	66	54	58	62	58	66	68	71	72	72	66	73	71	72	67	67	66	66	59	49	45	39	71	54	64	63	72	71	71	65	70	70	72	73
DYNAMIC LANE USE + DYNAMIC HOV/MANAGED LANES	6:15 AM	74	59	58	53	54	60	46	49	61	53	62	67	72	72	71	65	73	71	72	68	61	67	69	62	69	68	70	75	64	65	73	75	74	74	76	74	75	75	75
	6:30 AM	73	57	47	50	34	40	45	50	47	37	59	67	71	72	72	65	72	70	71	65	59	66	56	60	69	67	68	75	59	63	71	74	72	73	73	73	74	73	74
	6:45 AM	72	52	36	47	26	30	46	50	36	34	57	68	72	72	71	62	72	68	71	61	54	63	45	58	69	66	66	75	56	64	68	73	72	73	64	72	74	73	73
	7:00 AM	70	34	34	54	49	45	39	51	35	33	57	67	72	71	71	55	72	68	70	50	44	62	46	58	69	63	59	75	55	63	67	73	71	72	58	70	72	72	73
	7:15 AM	69	22	42	55	65	63	44	54	43	37	57	67	71	71	70	56	71	66	70	40	38	60	30	58	68	55	42	74	54	61	63	72	71	72	56	69	72	72	73
	7:30 AM	63	25	35	53	60	59	47	61	64	55	64	69	72	72	71	57	71	64	69	31	33	43	20	57	67	49	40	74	54	61	62	69	70	71	51	67	70	71	72
	7:45 AM	51	15	36	49	39	34	51	67	69	63	68	71	73	73	73	62	73	68	71	29	27	24	20	57	70	60	43	74	55	63	62	70	70	70	48	64	67	71	72
	8:00 AM	17	20	34	22	14	19	43	60	64	54	65	68	72	72	72	57	72	67	72	44	35	37	22	57	68	58	42	74	54	61	60	68	69	69	48	62	65	70	72
	8:15 AM	47	24	28	27	21	24	33	51	49	38	59	64	70	71	71	52	72	66	71	35	31	48	23	57	60	44	39	74	55	54	62	71	71	71	51	64	66	70	72
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	8:45 AM	75	69	27	18	19	20	25	46	34	33	56	65	71	71	71	46	70	64	71	54	44	63	35	57	38	29	22	72	57	68	64	73	72	73	61	70	71	72	73
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	9:30 AM	75	74	72	68	43	38	25	44	43	38	54	63	69	70	70	59	72	69	71	66	55	64	66	57	41	38	34	69	55	62	59	72	72	72	66	71	71	73	73
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	10:00 AM	75	74	74	69	68	65	66	66	65	62	68	69	72	73	73	69	74	71	72	68	62	66	67	59	64	61	56	72	56	63	63	73	71	72	69	70	71	72	73

Figure 9-27: Speed contour with Dynamic Lane Use and Dynamic HOV/Managed Lanes compared with the baseline case under Operational Condition 1

However, if we compare network-wide traffic performance measures with Dynamic Lane Use and Dynamic HOV/Managed Lanes with the baseline condition (Table 9-25 and Figure 9-28), we can notice that the throughput is practically unchanged. The reason is that Dynamic Lane Use and Dynamic HOV/Managed Lanes do not increase the capacity of the access points to the express lanes, which create a bottleneck to the usage of the additional lane. Therefore, the additional lane produces a reduction of the density along the corridor, hence the reduction of travel time observed in the network-wide performance measures, rather than an increase of volume.

Table 9-25: Performance measures with Dynamic Lane Use and Dynamic HOV/Managed Lanes compared with the baseline case under Operational Condition 1

Network Statistics	Base	Dyn Lane Use and Dyn HOV/Managed Lanes	Difference
Vehicles Miles Travelled (miles)	2,320,947	2,325,470	0.2%
Total Travel Time (h)	61,946	60,953	-1.6%
Passenger Hourly Travel Time (h)	78,635	77,591	-1.3%
VMT/VHT (mi/h)	37.47	38.15	1.8%

Figure 9-28: Performance measures with Dynamic Lane Use and Dynamic HOV/Managed Lanes compared with the baseline case under Operational Condition 1

In summary, the results show a slight benefit in a condition in which there are several localized bottlenecks along the corridor, as the additional lane provides a way to bypass them. However, the benefit is limited because the incident in this operational condition is located at the first entrance of the HOV lanes, so this ATDM strategy doesn't offer a way to bypass the major bottleneck.

9.2.3.2 Operational condition 2 (AM2)

A comparison of the speed contour on I-15 in the southbound direction with the baseline conditions shows that Dynamic Lane Use and Dynamic HOV/Managed Lanes produce overall a slight reduction of congestion along the corridor (Figure 9-29). This is intuitive because this strategy increases the capacity of the corridor by providing an additional lane for southbound traffic and promotes the usage of HOV lanes.

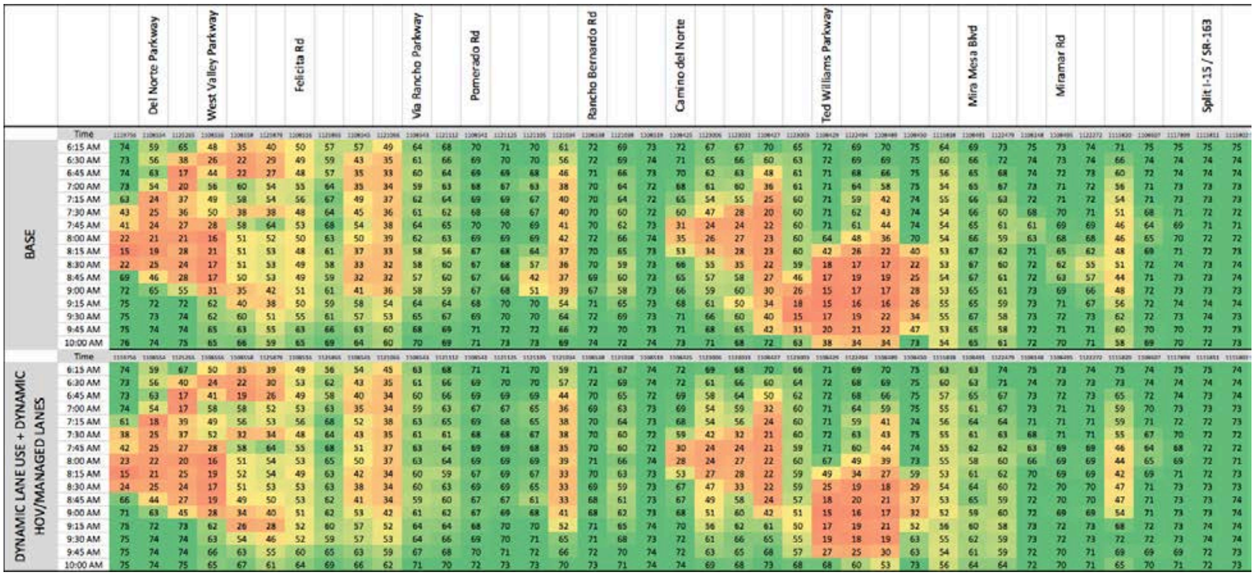


Figure 9-29: Speed contour with Dynamic Lane Use and Dynamic HOV/Managed Lanes compared with the baseline case under Operational Condition 2

If we compare network-wide traffic performance measures with Dynamic Lane Use and Dynamic HOV/Managed Lanes with the baseline condition (Table 9-26 and Figure 9-30), we can notice that the throughput is practically unchanged, but the travel time improves slightly.

Table 9-26: Performance measures with Dynamic Lane Use and Dynamic HOV/Managed Lanes compared with the baseline case under Operational Condition 2

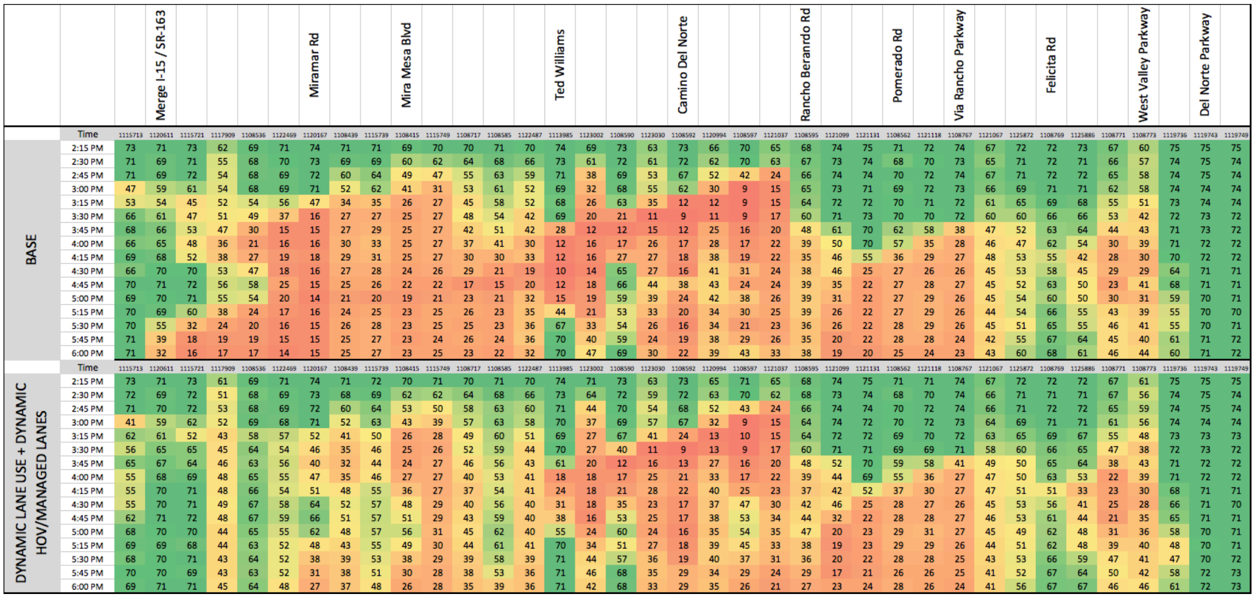
Network Statistics	Base	Dyn Lane Use and Dyn HOV/Managed Lanes	Difference
Vehicles Miles Travelled (miles)	2,304,353	2,313,228	0.4%
Total Travel Time (h)	61,509	60,683	-1.3%
Passenger Hourly Travel Time (h)	78,853	77,762	-1.4%
VMT/VHT (mi/h)	37.46	38.12	1.8%

Figure 9-30: Performance measures with Dynamic Lane Use and Dynamic HOV/Managed Lanes compared with the baseline case under Operational Condition 2

In summary, the results show a slight benefit in a condition in which there are several localized bottlenecks along the corridor, as the additional lane provides a way to bypass them. However, the benefit is limited because the incident in this operational condition is located just downstream of the first entrance of the HOV lanes, and causes a congestion that at some times spills back to the HOV entrance, so this ATDM strategy doesn’t offer a way to bypass the major bottleneck.

9.2.3.3 Operational condition 3 (PM3)

A comparison of the speed contour on I-15 in the northbound direction with the baseline conditions shows that Dynamic Lane Use and Dynamic HOV/Managed Lanes produce a reduction of congestion along the corridor (Figure 9-31). This is intuitive because this strategy increases the capacity of the corridor by providing an additional lane for northbound traffic and promotes the usage of HOV lanes.



			Merge I-15 / SR-163					Miramar Rd			Mira Mesa Blvd					Ted Williams				Camino Del Norte				Rancho Berarndo Rd			Pomerado Rd		Via Rancho Parkway			Felicita Rd			West Valley Parkway		Del Norte Parkway	
	Time	1115713	1120611	1115721	1117909	1108536	1122469	1120167	1108439	1115739	1108415	1115749	1108717	1108585	1122487	1113985	1123002	1108590	1123030	1108592	1120994	1108597	1121037	1108595	1121099	1121131	1108562	1121118	1108767	1121067	1125872	1108769	1125886	1108771	1108773	1119736	1119743	1119749
BASE	2:15 PM	73	71	73	62	69	71	74	71	71	69	70	70	71	70	74	69	73	63	73	66	70	65	68	74	75	71	72	74	67	72	72	73	67	60	75	75	75
	2:30 PM	71	69	71	55	68	70	73	69	69	60	62	64	68	66	73	61	72	61	72	62	70	63	67	73	74	68	70	73	65	71	72	71	66	57	74	75	74
	2:45 PM	71	69	72	54	68	69	72	60	64	49	47	55	63	59	71	38	69	53	67	52	42	24	66	74	74	70	72	74	67	71	72	72	65	58	74	75	74
	3:00 PM	47	59	61	54	68	69	71	52	62	41	31	53	61	52	69	32	68	55	62	30	9	15	65	73	71	69	72	73	66	69	71	71	62	58	74	74	74
	3:15 PM	53	54	45	52	54	56	47	34	35	26	27	45	58	52	68	26	63	35	12	12	9	15	64	72	72	70	71	72	61	65	69	68	55	51	73	74	74
	3:30 PM	66	61	47	51	49	37	16	27	27	25	27	48	54	42	69	20	21	11	9	11	9	17	60	71	73	70	70	72	60	60	66	66	53	42	72	73	72
	3:45 PM	68	66	53	47	30	15	15	27	29	25	27	42	51	42	28	12	12	15	12	25	16	20	48	61	70	62	58	38	47	52	63	64	44	43	71	73	72
	4:00 PM	66	65	48	36	21	16	16	30	33	25	27	37	41	30	12	16	17	26	17	28	17	22	39	50	70	57	35	28	46	47	62	54	30	39	71	72	72
	4:15 PM	69	68	52	38	27	19	18	29	31	25	27	30	30	33	12	16	27	27	18	38	19	22	35	46	55	36	29	27	48	53	55	42	28	30	70	72	72
	4:30 PM	66	70	70	53	47	18	16	27	28	24	26	29	21	19	10	14	65	27	16	41	31	24	38	46	25	27	26	26	45	53	58	45	29	29	64	71	71
	4:45 PM	70	71	72	56	58	25	15	25	26	22	22	17	15	20	12	18	66	44	38	43	24	24	39	35	22	27	28	27	45	52	63	50	23	41	68	71	71
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	5:15 PM	70	69	60	38	24	17	16	24	25	23	25	26	23	35	44	21	53	33	20	34	30	25	39	26	22	27	29	26	44	54	66	55	43	39	55	70	70
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	6:00 PM	71	32	16	17	17	14	15	25	27	23	25	23	22	32	70	47	69	30	22	39	43	33	38	19	20	25	24	23	43	60	68	61	46	44	60	71	72
	Time	1115713	1120611	1115721	1117909	1108536	1122469	1120167	1108439	1115739	1108415	1115749	1108717	1108585	1122487	1113985	1123002	1108590	1123030	1108592	1120994	1108597	1121037	1108595	1121099	1121131	1108562	1121118	1108767	1121067	1125872	1108769	1125886	1108771	1108773	1119736	1119743	1119749
DYNAMIC LANE USE + DYNAMIC HOV/MANAGED LANES	2:15 PM	73	71	73	61	69	71	74	71	72	70	71	70	71	70	74	71	73	63	73	65	71	65	68	74	75	71	71	74	67	72	72	72	67	61	75	75	75
	2:30 PM	72	69	72	51	68	69	73	68	69	62	62	64	68	66	73	64	72	59	72	63	70	62	68	73	74	68	70	74	66	71	71	71	67	56	74	75	74
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	3:00 PM	41	59	62	52	69	68	71	52	63	43	39	57	63	58	70	37	69	57	67	32	9	15	64	74	72	70	72	73	64	69	71	71	61	56	74	74	74
	3:15 PM	62	61	52	43	58	57	52	41	50	26	28	49	60	51	69	27	67	41	24	13	10	15	64	72	72	69	70	72	63	65	69	67	55	48	73	73	73
	3:30 PM	56	65	65	45	64	54	46	35	46	25	26	52	59	44	70	27	40	11	9	13	9	17	60	71	71	69	69	71	58	60	66	65	47	38	72	73	72
	3:45 PM	65	67	64	46	63	56	40	32	44	24	27	46	56	43	61	20	12	16	13	27	16	20	48	52	70	59	58	41	49	50	65	64	38	43	71	72	72
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	5:15 PM	69	69	68	44	63	52	48	43	55	49	30	44	61	41	70	34	51	27	18	39	45	33	38	19	23	29	29	26	44	51	62	48	39	40	48	70	71
	5:30 PM	68	70	71	43	64	52	38	39	53	38	29	39	58	39	71	44	57	36	19	40	37	31	36	20	22	28	28	25	43	53	66	59	47	41	47	70	72
	5:45 PM	70	70	69	43	63	52	31	38	51	30	28	38	53	36	71	46	68	35	29	34	29	24	29	17	21	26	26	25	41	52	67	64	50	42	58	72	73
	6:00 PM	69	71	71	45	64	48	27	37	48	26	28	35	39	36	71	42	68	33	29	35	26	21	27	23	24	28	26	24	41	56	67	67	46	46	61	72	73

Figure 9-31: Speed contour with Dynamic Lane Use and Dynamic HOV/Managed Lanes compared with the baseline case under Operational Condition 3

If we compare network-wide traffic performance measures with Dynamic Lane Use and Dynamic HOV/Managed Lanes with the baseline condition (Table 9-27 and Figure 9-32), we can notice that the throughput is practically unchanged, but the travel time improves slightly.

Table 9-27: Performance measures with Dynamic Lane Use and Dynamic HOV/Managed Lanes compared with the baseline case under Operational Condition 3

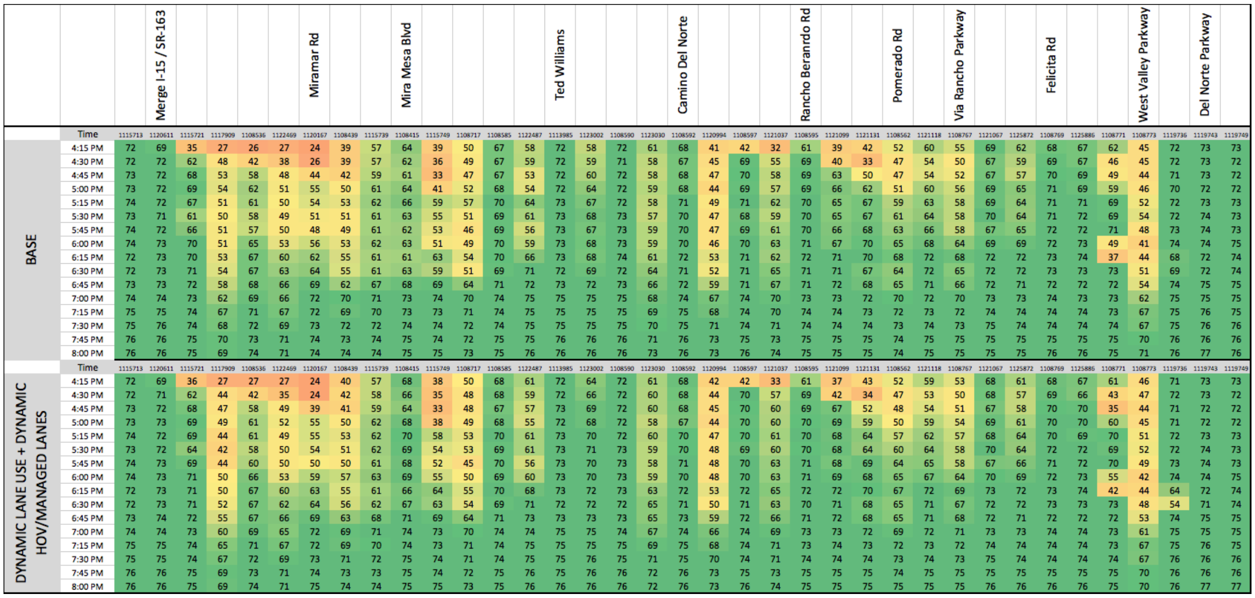
Network Statistics	Base	Dyn Lane Use and Dyn HOV/Managed Lanes	Difference
Vehicles Miles Travelled (miles)	2,518,604	2,531,493	0.5%
Total Travel Time (h)	76,531	73,529	-3.9%
Passenger Hourly Travel Time (h)	99,052	95,937	-3.1%
VMT/VHT (mi/h)	32.91	34.43	4.6%

Figure 9-32: Performance measures with Dynamic Lane Use and Dynamic HOV/Managed Lanes compared with the baseline case under Operational Condition 3

In summary, the results show a slight benefit in a condition in which there is congestion throughout the corridor, as the additional lane provides a way to bypass it. In this operational condition the benefit is more significant compared to the previous because the incident doesn't affect any entrances to the HOV lanes.

9.2.3.4 Operational condition 4 (PM4)

A comparison of the speed contour on I-15 in the northbound direction with the baseline conditions shows that Dynamic Lane Use and Dynamic HOV/Managed Lanes produce no significant change on congestion along the corridor (Figure 9-33). This is intuitive because since under this operational condition there is no significant congestion, so the additional lane for northbound traffic doesn't provide much value.



			Merge I-15 / SR-163					Miramar Rd			Mira Mesa Blvd					Ted Williams			
	Time	1115713	1120611	1115721	1117909	1108536	1122469	1120167	1108439	1115739	1108415	1115749	1106717	1108585	1122487	1113985	1123002	1108590	1123030
BASE	4:15 PM	72	69	35	27	26	27	24	39	57	64	39	50	67	58	72	58	72	61
	4:30 PM	72	72	62	48	42	38	26	39	57	62	36	49	67	59	72	59	71	58
	4:45 PM	73	72	68	53	58	48	44	42	59	61	33	47	67	53	72	60	72	58
	5:00 PM	73	72	69	54	62	51	55	50	61	64	41	52	68	54	72	64	72	59
	5:15 PM	74	72	67	51	61	50	54	53	62	66	59	57	70	64	73	67	72	58
	5:30 PM	73	71	61	50	58	49	51	51	61	63	55	51	69	61	73	68	73	57
	5:45 PM	74	72	66	51	57	50	48	49	61	62	53	46	69	56	73	67	73	59
	6:00 PM	74	73	70	51	65	53	56	53	62	63	51	49	70	59	73	68	73	59
	6:15 PM	72	73	70	53	67	60	62	55	61	61	63	54	70	66	73	68	74	61
	6:30 PM	72	73	71	54	67	63	64	55	61	63	59	51	69	71	72	69	72	64
	6:45 PM	73	73	72	58	68	66	69	62	67	68	69	64	71	72	73	72	73	66
	7:00 PM	74	74	73	62	69	66	72	70	71	73	74	70	74	75	75	75	75	68
	7:15 PM	75	75	74	67	71	67	72	69	70	73	73	71	74	75	75	75	75	69
	7:30 PM	75	76	74	68	72	69	73	72	72	74	74	72	74	75	75	75	75	70
	7:45 PM	76	76	75	70	73	71	74	73	74	75	74	72	75	75	76	76	76	71
	8:00 PM	76	76	75	69	74	71	74	74	74	75	75	73	75	76	76	76	76	73
	Time	1115713	1120611	1115721	1117909	1108536	1122469	1120167	1108439	1115739	1108415	1115749	1106717	1108585	1122487	1113985	1123002	1108590	1123030
DYNAMIC LANE USE + DYNAMIC HOV/MANAGED LANES	4:15 PM	72	69	36	27	27	27	24	40	57	68	38	50	68	61	72	64	72	61
	4:30 PM	72	71	62	44	42	35	24	42	58	66	35	48	68	59	72	66	72	60
	4:45 PM	73	72	68	47	58	49	39	41	59	64	33	48	67	57	73	69	72	60
	5:00 PM	73	73	69	49	61	52	55	50	62	68	38	49	68	55	72	68	72	58
	5:15 PM	74	72	69	44	61	49	55	53	62	70	58	53	70	61	73	70	72	60
	5:30 PM	73	72	64	42	58	50	54	51	62	69	54	53	69	61	73	71	73	59
	5:45 PM	74	73	69	44	60	50	50	50	61	68	52	45	70	56	73	70	73	58
	6:00 PM	74	73	71	50	66	53	59	57	63	69	55	50	69	60	73	70	73	59
	6:15 PM	72	73	71	50	67	60	63	55	61	66	64	55	70	68	73	72	73	63
	6:30 PM	72	73	71	52	67	62	64	56	62	67	63	54	69	71	72	72	72	65
	6:45 PM	73	74	72	55	67	66	69	63	68	71	69	64	71	73	73	73	73	65
	7:00 PM	74	74	73	60	69	65	72	69	71	74	73	70	74	74	75	75	74	67
	7:15 PM	75	75	74	65	71	67	72	69	70	74	73	71	74	75	75	75	75	69
	7:30 PM	75	75	74	67	72	69	73	71	72	75	74	71	74	75	75	76	75	71
	7:45 PM	76	76	75	69	73	71	74	73	73	75	74	72	75	76	75	76	76	72
	8:00 PM	76	76	75	69	74	71	75	74	74	75	75	73	75	76	76	76	76	72

		Camino Del Norte				Rancho Beranrdo Rd			Pomerado Rd		Via Rancho Parkway			Felicita Rd			West Valley Parkway		Del Norte Parkway	
	Time	1108592	1120994	1108597	1121037	1106595	1121099	1121131	1108562	1121118	1108767	1121067	1125872	1108769	1125886	1108771	1108773	1119736	1119743	1119749
BASE	4:15 PM	68	41	42	32	61	39	42	52	60	55	69	62	68	67	62	45	72	73	73
	4:30 PM	67	45	69	55	69	40	33	47	54	50	67	59	69	67	46	45	72	73	72
	4:45 PM	68	47	70	58	69	63	50	47	54	52	67	57	70	69	49	44	71	73	72
	5:00 PM	68	44	69	57	69	66	62	51	60	56	69	65	71	69	59	46	70	72	72
	5:15 PM	71	49	71	62	70	65	67	59	63	58	69	64	71	71	69	52	72	73	73
	5:30 PM	70	47	68	59	70	65	67	61	64	58	70	64	71	72	69	54	72	74	73
	5:45 PM	70	47	69	61	70	66	68	63	66	58	67	65	72	72	71	48	73	74	73
	6:00 PM	70	46	70	63	71	67	70	65	68	64	69	69	72	73	49	41	74	74	75
	6:15 PM	72	53	71	62	72	71	70	68	72	68	72	72	73	74	37	44	68	72	74
	6:30 PM	71	52	71	65	71	71	67	64	72	65	72	72	73	73	73	51	69	72	74
	6:45 PM	72	59	71	67	71	72	68	65	71	66	72	71	72	72	72	54	74	75	75
	7:00 PM	74	67	74	70	73	73	72	70	72	70	73	73	74	73	73	62	75	75	75
	7:15 PM	75	68	74	70	74	74	73	72	73	72	74	74	74	74	73	67	75	76	75
	7:30 PM	75	71	74	71	74	74	74	73	74	73	75	74	74	74	74	67	75	76	76
	7:45 PM	76	73	75	73	75	75	75	74	75	75	75	75	75	75	75	70	76	76	76
	8:00 PM	76	73	76	74	75	75	75	74	75	75	75	75	76	76	75	71	76	77	76
	Time	1108592	1120994	1108597	1121037	1106595	1121099	1121131	1108562	1121118	1108767	1121067	1125872	1108769	1125886	1108771	1108773	1119736	1119743	1119749
DYNAMIC LANE USE + DYNAMIC HOV/MANAGED LANES	4:15 PM	68	42	42	33	61	37	43	52	59	53	68	61	68	67	61	46	71	73	73
	4:30 PM	68	44	70	57	69	42	34	47	53	50	68	57	69	66	43	47	72	73	72
	4:45 PM	68	45	70	60	69	67	52	48	54	51	67	58	70	70	35	44	71	72	72
	5:00 PM	67	44	70	60	70	69	59	50	59	54	69	61	70	70	60	45	71	72	72
	5:15 PM	70	47	70	61	70	68	64	57	62	57	68	64	70	69	70	51	72	73	73
	5:30 PM	70	48	69	60	70	68	64	60	64	58	70	64	72	72	69	52	72	74	73
	5:45 PM	71	48	70	63	71	68	69	64	65	58	67	66	71	72	70	49	73	74	73
	6:00 PM	70	48	70	63	71	69	68	65	67	64	70	69	72	73	55	42	74	74	75
	6:15 PM	72	53	72	65	72	72	70	67	72	69	73	72	73	74	42	44	64	72	74
	6:30 PM	71	50	71	63	70	71	68	65	71	67	72	72	73	73	73	48	54	71	74
	6:45 PM	73	59	72	66	71	72	68	65	71	68	72	71	72	72	72	53	74	75	75
	7:00 PM	74	66	74	69	73	73	72	69	72	71	73	73	74	74	73	61	75	75	75
	7:15 PM	75	68	74	71	73	74	73	72	73	72	74	74	74	74	73	67	75	76	75
	7:30 PM	75	70	74	71	74	74	74	73	74	73	75	74	74	74	74	67	76	76	76
	7:45 PM	76	73	75	73	75	75	75	74	75	75	75	75	75	75	75	70	76	76	76
	8:00 PM	76	73	76	74	75	75	75	75	75	75	76	76	76	76	75	70	76	77	77

Figure 9-33: Speed contour with Dynamic Lane Use and Dynamic HOV/Managed Lanes compared with the baseline case under Operational Condition 4

If we compare network-wide traffic performance measures with Dynamic Lane Use and Dynamic HOV/Managed Lanes with the baseline condition (Table 9-28 and Figure 9-32), we can notice that all the indicators are practically unchanged.

Table 9-28: Performance measures with Dynamic Lane Use and Dynamic HOV/Managed Lanes compared with the baseline case under Operational Condition 4

Network Statistics	Base	Dyn Lane Use and Dyn HOV/Managed Lanes	Difference
Vehicles Miles Travelled (miles)	2,302,897	2,301,997	0.0%
Total Travel Time (h)	57,547	57,589	0.1%
Passenger Hourly Travel Time (h)	75,856	75,918	0.1%
VMT/VHT (mi/h)	40.02	39.97	-0.1%

Figure 9-34: Performance measures with Dynamic Lane Use and Dynamic HOV/Managed Lanes compared with the baseline case under Operational Condition 4

In summary, the results show that in a condition in which there is no congestion throughout the corridor, this ATDM strategy doesn’t produce any significant benefit nor detrimental effect. However, the slight worsening of the performance indicators suggests that the additional demand using the HOV lanes may cause a slight increase of localized congestion at the access and egress points.

9.2.3.5 Comparison between operational conditions

A comparison of the performance measures under different operational conditions shows that Dynamic Lane Use and Dynamic HOV/Managed Lanes are effective only in congested situations. Additionally, the location of incidents and bottlenecks may reduce the effectiveness of this ATDM strategy, because if the congestion caused by them affects the access points to the HOV lanes, vehicles have difficulty in reaching the additional lane that allows bypassing the bottlenecks.

9.2.4 Dynamic Speed Limits

Dynamic Speed Limits was modelled as a reduction of the speed limit of each road segment depending on congestion in the southbound direction for Operational Conditions 1 and 2 (AM) and in the northbound direction for Operational Conditions 3 and 4 (PM). See Section 7.1.2 for further details about the algorithm. The strategy is active throughout the simulation.

9.2.4.1 Operational condition 1 (AM1)

A comparison of the speed contour on I-15 in the southbound direction with the baseline conditions shows that Dynamic Speed Limits produce a “dilution” of the congestion over space and time (Figure 9-35), which corresponds to an increase of safety as the speed drop between adjacent road segments diminishes.

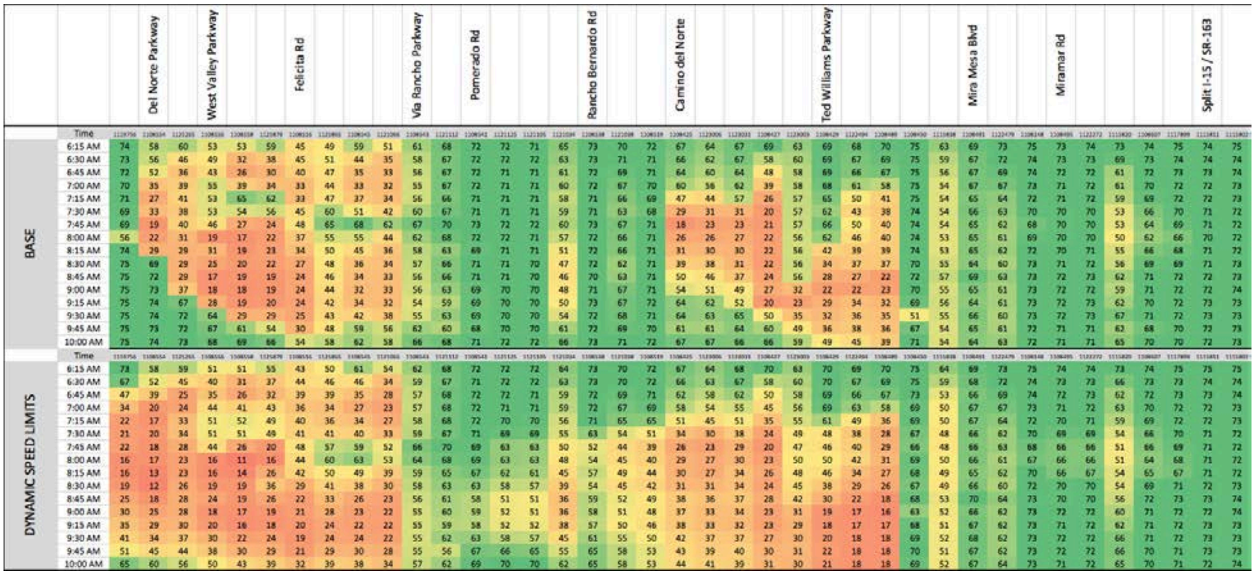
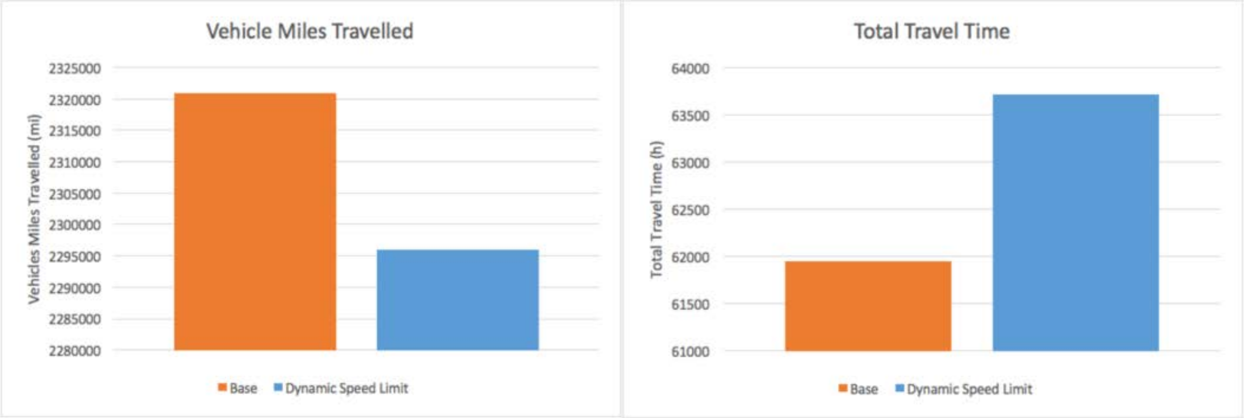


Figure 9-35: Speed contour with Dynamic Speed Limits compared with the baseline case under Operational Condition 1

If we compare network-wide traffic performance measures with Dynamic Speed Limits with the baseline condition (Table 9-29 and Figure 9-36), we can notice that it produces a slight decrease of throughput with some decrease of the overall speed.

Table 9-29: Performance measures with Dynamic Speed Limits compared with the baseline case under Operational Condition 1

Network Statistics	Base	Dynamic Speed Limit	Difference
Vehicles Miles Travelled (miles)	2,320,947	2,295,970	-1.1%
Total Travel Time (h)	61,946	63,713	2.9%
Passenger Hourly Travel Time (h)	78,635	80,972	3.0%
VMT/VHT (mi/h)	37.47	36.04	-3.8%



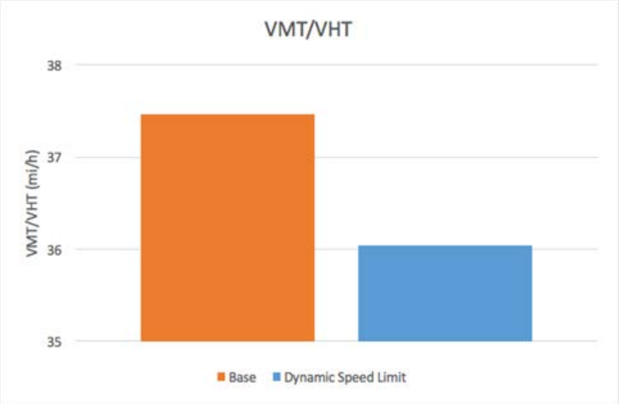
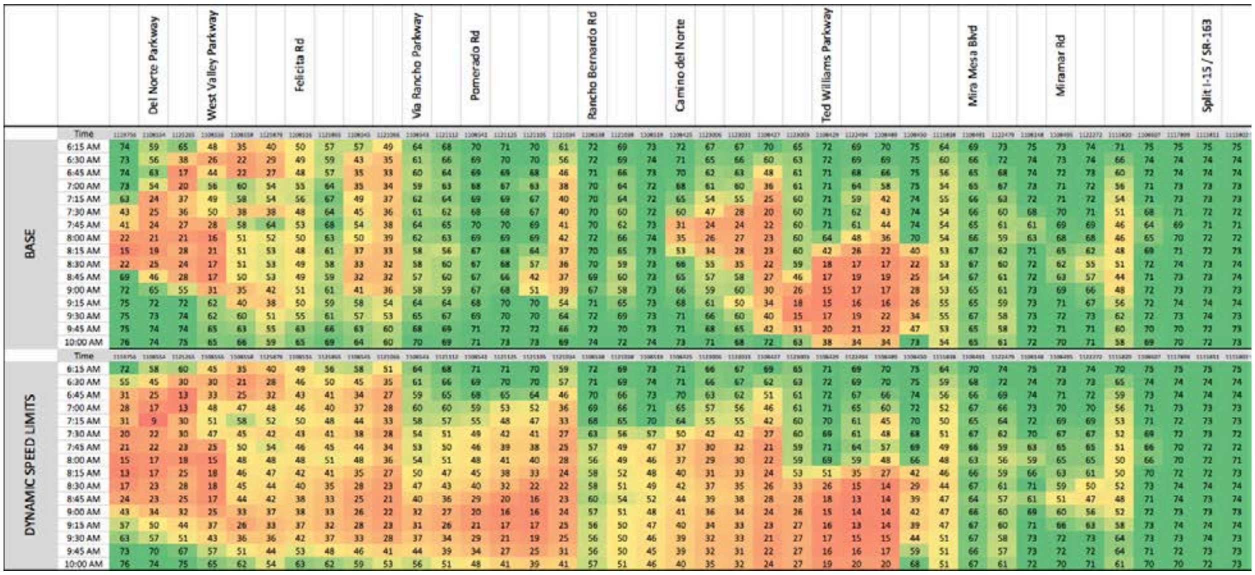


Figure 9-36: Performance measures with Dynamic Speed Limits compared with the baseline case under Operational Condition 1

In summary, the results show that in a condition in which there are several localized bottlenecks along the corridor this ATDM strategy reduces the speed drops, with an increase of safety at the price of a little increase of the overall travel time.

9.2.4.2 Operational condition 2 (AM2)

A comparison of the speed contour on I-15 in the southbound direction with the baseline conditions shows that Dynamic Speed Limits produce a "dilution" of the congestion over space and time (Figure 9-37), which corresponds to an increase of safety as the speed drop between adjacent road segments diminishes.



	Time		Del Norte Parkway		West Valley Parkway			Felicita Rd				Via Rancho Parkway		Pomerado Rd				Rancho Bernardo Rd			Camino del Norte					Ted Williams Parkway					Mira Mesa Blvd			Miramar Rd					Split I-15 / SR-163	
BASE	6:15 AM	74	59	65	48	35	40	50	57	57	49	64	68	70	71	70	61	72	69	73	72	67	67	70	65	72	69	70	75	64	69	73	75	73	74	71	75	75	75	75
	6:30 AM	73	56	38	26	22	29	49	59	43	35	61	66	69	70	70	56	72	69	74	71	65	66	60	63	72	69	69	75	60	66	72	74	73	74	66	74	74	74	74
	6:45 AM	74	63	17	44	22	27	48	57	35	33	60	64	69	69	68	46	71	66	73	70	62	63	48	61	71	68	66	75	56	65	68	74	72	73	60	72	74	74	74
	7:00 AM	73	54	20	56	60	54	55	64	35	34	59	63	68	67	63	38	70	64	72	68	61	60	36	61	71	64	58	75	54	65	67	73	71	72	56	71	73	73	73
	7:15 AM	63	24	37	49	58	54	56	67	49	37	62	64	69	69	67	40	70	64	72	65	54	55	25	60	71	59	42	74	55	66	63	72	71	72	54	71	73	73	73
	7:30 AM	43	25	36	50	38	38	48	64	45	36	61	62	68	68	67	40	70	60	72	60	47	28	20	60	71	62	43	74	54	66	60	68	70	71	51	68	71	72	72
	7:45 AM	41	24	27	28	58	64	53	68	54	38	64	65	70	70	69	41	70	62	73	31	24	24	22	60	71	61	44	74	54	65	61	61	69	69	46	64	69	71	71
	8:00 AM	22	21	21	16	51	52	50	63	50	39	62	63	69	69	69	42	72	66	74	35	26	27	23	60	64	48	36	70	54	66	59	63	68	68	46	65	70	72	72
	8:15 AM	15	19	28	21	51	53	48	61	37	33	58	56	67	68	64	37	70	65	73	53	34	28	23	60	42	26	22	40	53	67	62	71	65	62	48	69	71	72	73
	8:30 AM	22	25	24	17	51	53	49	58	33	32	58	60	67	68	57	36	70	59	73	66	55	35	22	59	18	17	17	22	53	67	60	72	62	55	51	72	74	73	74
	8:45 AM	69	46	28	17	50	53	49	59	32	32	57	60	67	66	42	37	69	60	73	65	57	58	27	46	17	19	19	25	54	67	61	72	63	57	44	71	73	73	74
	9:00 AM	72	65	55	31	35	42	51	61	41	36	58	59	67	68	51	39	67	58	73	66	59	60	30	26	15	17	17	28	53	65	61	73	69	66	48	72	73	73	73
	9:15 AM	75	72	72	62	40	38	50	59	58	54	64	64	68	70	70	54	71	65	73	68	61	50	34	18	15	16	16	26	55	65	59	73	71	67	56	72	74	74	74
	9:30 AM	75	73	74	62	60	51	55	61	57	53	65	67	69	70	70	64	72	69	73	71	66	60	40	15	17	19	22	34	55	67	58	73	72	73	62	72	73	74	73
	9:45 AM	75	74	74	65	63	55	63	66	63	60	68	69	71	72	72	66	72	70	73	71	68	65	42	31	20	21	22	47	53	65	58	72	71	71	60	70	70	72	73
	10:00 AM	76	74	75	65	66	59	65	69	64	60	70	69	71	73	73	69	74	72	74	73	71	68	72	63	38	34	34	73	54	65	61	72	70	71	58	69	70	72	73
DYNAMIC SPEED LIMITS	6:15 AM	72	58	60	45	35	40	49	56	58	51	64	68	71	71	70	59	72	69	73	71	66	67	69	65	71	69	70	75	64	70	74	75	73	74	70	75	75	75	75
	6:30 AM	55	45	30	30	21	28	46	50	45	35	61	66	69	70	70	57	71	69	74	71	66	67	62	63	72	69	70	75	59	68	72	74	73	73	65	74	74	74	74
	6:45 AM	31	25	13	33	25	32	43	41	34	27	59	65	68	65	64	46	70	66	73	70	63	62	51	61	72	67	66	74	56	66	69	74	71	72	59	73	74	74	74
	7:00 AM	28	17	13	48	47	48	46	40	37	28	60	60	59	53	52	36	69	66	71	65	57	56	46	61	71	65	60	72	52	67	66	73	70	70	56	71	73	73	73
	7:15 AM	31	9	30	51	58	52	50	48	44	33	58	57	55	48	47	33	68	65	70	64	55	55	42	60	70	61	45	70	50	65	64	72	69	69	53	71	72	73	73
	7:30 AM	20	22	30	47	45	42	43	41	38	28	54	51	49	42	41	27	63	56	57	50	42	42	27	60	69	61	48	68	51	67	62	70	67	67	52	69	72	73	72
	7:45 AM	21	22	23	25	50	54	46	45	44	34	53	50	46	39	38	25	57	49	47	37	30	32	21	59	71	64	57	69	49	66	59	63	65	65	51	66	70	72	72
	8:00 AM	15	17	18	15	48	48	48	51	48	36	54	51	48	41	40	28	56	49	46	37	29	30	22	59	69	59	48	66	48	63	56	59	65	65	50	66	70	72	71
	8:15 AM	13	17	25	18	46	47	42	41	35	27	50	47	45	38	33	24	58	52	48	40	31	33	24	53	51	35	27	42	46	66	59	66	63	61	50	70	72	72	73
	8:30 AM	17	23	28	18	45	44	40	35	28	23	47	43	40	32	22	22	58	51	49	42	37	35	26	33	26	15	14	29	44	67	61	71	59	50	52	73	74	74	74
	8:45 AM	24	23	25	17	44	42	38	33	25	21	40	36	29	20	16	23	60	54	52	44	39	38	28	28	18	13	14	39	47	64	57	61	51	47	48	71	74	73	74
	9:00 AM	43	34	32	25	33	37	38	33	26	22	32	27	20	16	16	24	57	51	48	41	36	34	24	26	15	14	14	42	47	66	60	69	60	56	52	72	73	73	73
	9:15 AM	57	50	44	37	26	33	37	32	28	23	31	26	21	17	17	25	56	50	47	40	34	33	23	27	16	13	14	39	47	67	60	71	66	63	58	73	74	74	74
	9:30 AM	63	57	51	43	36	36	42	37	33	28	37	34	29	21	19	25	56	50	46	39	32	33	21	27	17	15	15	44	51	67	58	73	72	73	64	73	73	74	73
	9:45 AM	73	70	67	57	51	44	53	48	46	41	44	39	34	27	25	31	56	50	45	39	32	31	22	27	16	16	17	59	51	66	57	73	72	72	64	71	72	73	73
	10:00 AM	76	74	75	65	62	54	63	62	59	53	56	51	48	41	39	41	57	51	46	40	35	32	24	27	19	20	20	68	51	67	61	72	70	71	61	70	70	72	73

Figure 9-37: Speed contour with Dynamic Speed Limits compared with the baseline case under Operational Condition 2

If we compare network-wide traffic performance measures with Dynamic Speed Limits with the baseline condition (Table 9-30 and Figure 9-38), we can notice that it produces a slight decrease of throughput with some decrease of the overall speed.

Table 9-30: Performance measures with Dynamic Speed Limits compared with the baseline case under Operational Condition 2

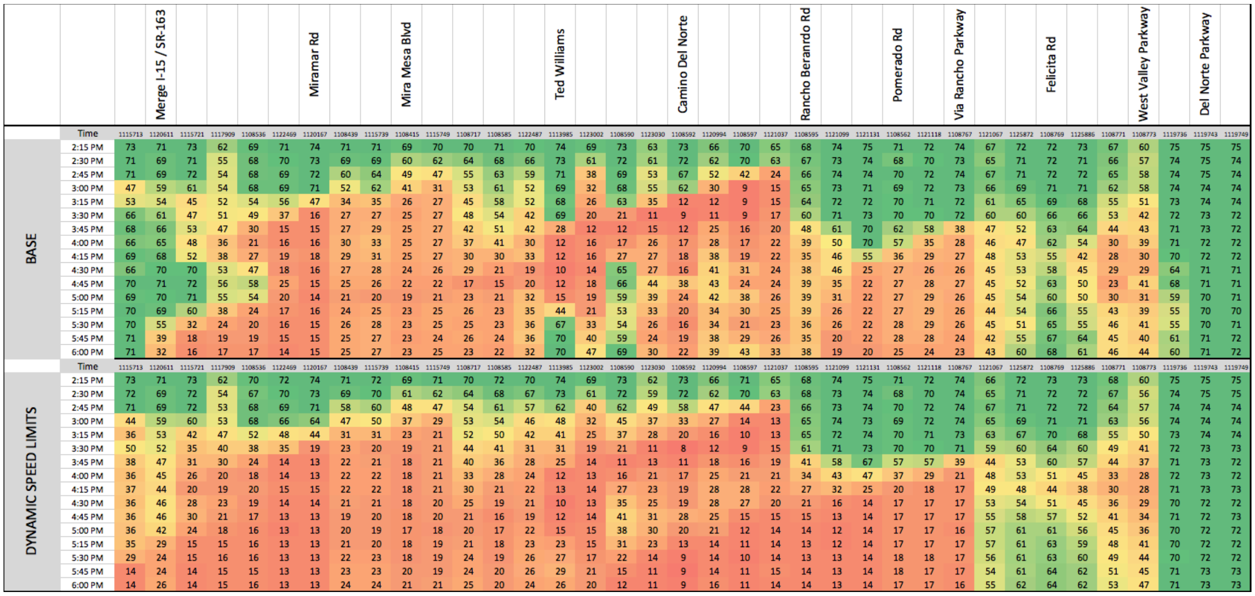
Network Statistics	Base	Dynamic Speed Limit	Difference
Vehicles Miles Travelled (miles)	2,304,353	2,281,850	-1.0%
Total Travel Time (h)	61,509	63,446	3.1%
Passenger Hourly Travel Time (h)	78,853	81,278	3.1%
VMT/VHT (mi/h)	37.46	35.97	-4.0%

Figure 9-38: Performance measures with Dynamic Speed Limits compared with the baseline case under Operational Condition 2

In summary, as in the previous operational condition, the results show that in a condition in which there are several localized bottlenecks along the corridor this ATDM strategy reduces the speed drops, with an increase of safety at the price of a little increase of the overall travel time.

9.2.4.3 Operational condition 3 (PM3)

A comparison of the speed contour on I-15 in the northbound direction with the baseline conditions shows that Dynamic Speed Limits produce a “dilution” of the congestion over space and time (Figure 9-39), which corresponds to an increase of safety as the speed drop between adjacent road segments diminishes.



			Merge I-15 / SR-163					Miramar Rd			Mira Mesa Blvd					Ted Williams				Camino Del Norte				Rancho Berandro Rd			Pomerado Rd		Via Rancho Parkway			Felicita Rd			West Valley Parkway		Del Norte Parkway	
	Time	1115713	1120611	1115721	1117909	1108536	1122469	1120167	1108439	1115739	1108415	1115749	1108717	1108585	1122487	1113985	1123002	1108590	1123030	1108592	1120994	1108597	1121037	1108595	1121099	1121131	1108562	1121118	1108767	1121067	1125872	1108769	1125886	1108771	1108773	1119736	1119743	1119749
BASE	2:15 PM	73	71	73	62	69	71	74	71	71	69	70	70	71	70	74	69	73	63	73	66	70	65	68	74	75	71	72	74	67	72	72	73	67	60	75	75	75
	2:30 PM	71	69	71	55	68	70	73	69	69	60	62	64	68	66	73	61	72	61	72	62	70	63	67	73	74	68	70	73	65	71	72	71	66	57	74	75	74
	2:45 PM	71	69	72	54	68	69	72	60	64	49	47	55	63	59	71	38	69	53	67	52	42	24	66	74	74	70	72	74	67	71	72	72	65	58	74	75	74
	3:00 PM	47	59	61	54	68	69	71	52	62	41	31	53	61	52	69	32	68	55	62	30	9	15	65	73	71	69	72	73	66	69	71	71	62	58	74	74	74
	3:15 PM	53	54	45	52	54	56	47	34	35	26	27	45	58	52	68	26	63	35	12	12	9	15	64	72	72	70	71	72	61	65	69	68	55	51	73	74	74
	3:30 PM	66	61	47	51	49	37	16	27	27	25	27	48	54	42	69	20	21	11	9	11	9	17	60	71	73	70	70	72	60	60	66	66	53	42	72	73	72
	3:45 PM	68	66	53	47	30	15	15	27	29	25	27	42	51	42	28	12	12	15	12	25	16	20	48	61	70	62	58	38	47	52	63	64	44	43	71	73	72
	4:00 PM	66	65	48	36	21	16	16	30	33	25	27	37	41	30	12	16	17	26	17	28	17	22	39	50	70	57	35	28	46	47	62	54	30	39	71	72	72
	4:15 PM	69	68	52	38	27	19	18	29	31	25	27	30	30	33	12	16	27	27	18	38	19	22	35	46	55	36	29	27	48	53	55	42	28	30	70	72	72
	4:30 PM	66	70	70	53	47	18	16	27	28	24	26	29	21	19	10	14	65	27	16	41	31	24	38	46	25	27	26	26	45	53	58	45	29	29	64	71	71
	4:45 PM	70	71	72	56	58	25	15	25	26	22	22	17	15	20	12	18	66	44	38	43	24	24	39	35	22	27	28	27	45	52	63	50	23	41	68	71	71
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	5:45 PM	71	39	18	19	19	15	15	25	27	23	24	26	24	36	70	40	59	24	19	38	29	26	35	20	22	28	28	24	42	55	67	64	45	40	61	71	72
	6:00 PM	71	32	16	17	17	14	15	25	27	23	25	23	22	32	70	47	69	30	22	39	43	33	38	19	20	25	24	23	43	60	68	61	46	44	60	71	72
	Time	1115713	1120611	1115721	1117909	1108536	1122469	1120167	1108439	1115739	1108415	1115749	1108717	1108585	1122487	1113985	1123002	1108590	1123030	1108592	1120994	1108597	1121037	1108595	1121099	1121131	1108562	1121118	1108767	1121067	1125872	1108769	1125886	1108771	1108773	1119736	1119743	1119749
DYNAMIC SPEED LIMITS	2:15 PM	73	71	73	62	70	72	74	71	72	69	71	70	72	70	74	69	73	62	73	66	71	65	68	74	75	71	72	74	66	72	73	73	68	60	75	75	75
	2:30 PM	72	69	72	54	67	70	73	69	70	61	62	64	68	67	73	61	72	59	72	62	70	63	68	73	74	68	70	74	65	71	72	72	67	56	74	75	75
	2:45 PM	71	69	72	53	68	69	71	58	60	48	47	54	61	57	62	40	62	49	58	47	44	23	66	73	74	70	72	74	67	71	72	72	64	57	74	74	74
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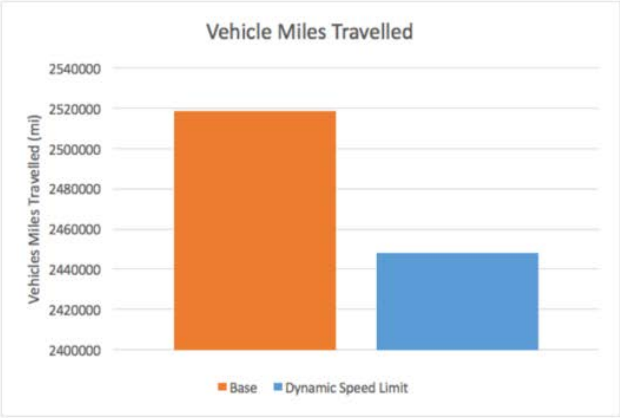
	3:15 PM	36	53	42	47	52	48	44	31	31	23	21	52	50	42	41	25	37	28	20	16	10	13	65	72	74	70	71	73	63	67	70	68	55	50	73	74	74
	3:30 PM	50	52	35	40	38	35	19	23	20	19	21	44	41	31	31	19	21	11	8	12	9	15	61	71	73	70	70	71	59	60	64	60	49	41	72	73	73
	3:45 PM	38	47	31	30	24	14	13	22	21	18	21	40	36	28	25	14	11	13	11	18	16	19	41	58	67	57	57	39	44	53	60	57	44	37	71	73	72
	4:00 PM	36	45	26	20	18	14	13	22	22	18	21	33	28	24	12	13	16	21	17	25	21	21	34	43	47	37	29	21	48	53	51	45	33	28	72	73	72
	4:15 PM	37	44	20	19	20	15	15	22	22	18	21	30	21	22	13	14	27	23	19	28	28	22	27	32	25	20	18	17	49	48	44	38	30	28	71	73	73
	4:30 PM	36	46	28	23	19	14	14	21	21	18	20	25	19	21	10	13	35	25	19	28	27	20	21	16	14	17	17	17	53	54	51	45	36	29	70	72	72
	4:45 PM	36	46	30	21	17	13	13	19	20	18	20	21	16	19	12	14	41	31	28	25	15	15	15	13	14	17	17	17	55	58	57	52	41	34	71	72	73
	5:00 PM	36	42	24	18	16	13	13	20	19	17	18	20	17	22	15	15	38	30	20	21	12	14	14	12	14	17	17	16	57	61	61	56	45	36	70	72	72
	5:15 PM	35	29	15	15	16	13	13	21	20	18	19	21	18	23	23	15	31	23	13	14	11	14	13	12	14	17	17	17	57	61	63	59	48	41	70	72	72
	5:30 PM	29	24	15	16	16	13	13	22	23	18	19	24	19	26	27	17	22	14	9	14	10	14	13	13	14	18	18	17	56	61	63	60	49	44	70	72	72
	5:45 PM	14	24	14	15	15	13	13	23	23	20	19	24	20	26	29	21	15	11	9	14	11	15	14	13	14	18	17	17	54	61	64	62	51	45	71	73	73
	6:00 PM	14	26	14	15	16	13	13	24	24	21	21	25	20	24	26	20	12	11	9	16	11	14	14	13	14	17	17	16	55	62	64	62	53	47	71	73	73

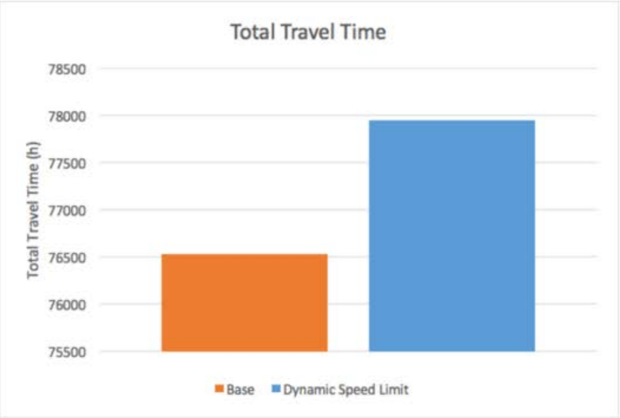
Figure 9-39: Speed contour with Dynamic Speed Limits compared with the baseline case under Operational Condition 3

If we compare network-wide traffic performance measures with Dynamic Speed Limits with the baseline condition (Table 9-31 and Figure 9-40), we can notice that it produces a little decrease of throughput with some decrease of the overall speed.

Table 9-31: Performance measures with Dynamic Speed Limits compared with the baseline case under Operational Condition 3

Network Statistics	Base	Dynamic Speed Limit	Difference
Vehicles Miles Travelled (miles)	2,518,604	2,447,851	-2.8%
Total Travel Time (h)	76,531	77,953	1.9%
Passenger Hourly Travel Time (h)	99,052	100,604	1.6%
VMT/VHT (mi/h)	32.91	31.40	-4.6%





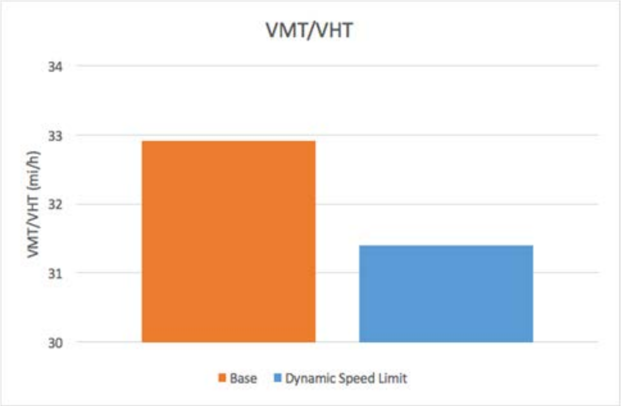
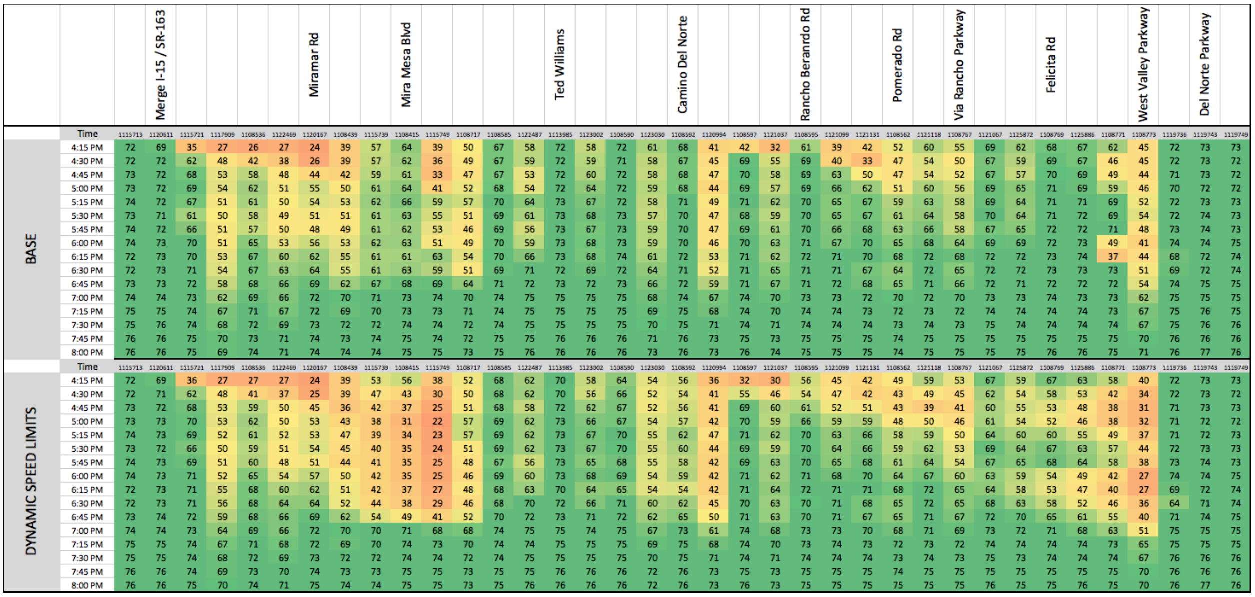


Figure 9-40: Performance measures with Dynamic Speed Limits compared with the baseline case under Operational Condition 3

In summary, the results show that in a condition in which there is high congestion throughout the corridor this ATDM strategy reduces the speed drops, with an increase of safety at the price of an increase of the overall travel time.

9.2.4.4 Operational condition 4 (PM4)

A comparison of the speed contour on I-15 in the northbound direction with the baseline conditions shows that Dynamic Speed Limits produce a “dilution” of the congestion over space and time (Figure 9-41), which corresponds to an increase of safety as the speed drop between adjacent road segments diminishes.



			Merge I-15 / SR-163					Miramar Rd			Mira Mesa Blvd					Ted Williams				Camino Del Norte				Rancho Beranrdo Rd			Pomerado Rd		Via Rancho Parkway			Felicita Rd			West Valley Parkway		Del Norte Parkway	
	Time	1115713	1120611	1115721	1117909	1108536	1122469	1120167	1108439	1115739	1108415	1115749	1108717	1108585	1122487	1113985	1123002	1108590	1123030	1108592	1120994	1108597	1121037	1108595	1121099	1121131	1108562	1121118	1108767	1121067	1125872	1108769	1125886	1108771	1108773	1119736	1119743	1119749
BASE	4:15 PM	72	69	35	27	26	27	24	39	57	64	39	50	67	58	72	58	72	61	68	41	42	32	61	39	42	52	60	55	69	62	68	67	62	45	72	73	73
	4:30 PM	72	72	62	48	42	38	26	39	57	62	36	49	67	59	72	59	71	58	67	45	69	55	69	40	33	47	54	50	67	59	69	67	46	45	72	73	72
	4:45 PM	73	72	68	53	58	48	44	42	59	61	33	47	67	53	72	60	72	58	68	47	70	58	69	63	50	47	54	52	67	57	70	69	49	44	71	73	72
	5:00 PM	73	72	69	54	62	51	55	50	61	64	41	52	68	54	72	64	72	59	68	44	69	57	69	66	62	51	60	56	69	65	71	69	59	46	70	72	72
	5:15 PM	74	72	67	51	61	50	54	53	62	66	59	57	70	64	73	67	72	58	71	49	71	62	70	65	67	59	63	58	69	64	71	71	69	52	72	73	73
	5:30 PM	73	71	61	50	58	49	51	51	61	63	55	51	69	61	73	68	73	57	70	47	68	59	70	65	67	61	64	58	70	64	71	72	69	54	72	74	73
	5:45 PM	74	72	66	51	57	50	48	49	61	62	53	46	69	56	73	67	73	59	70	47	69	61	70	66	68	63	66	58	67	65	72	72	71	48	73	74	73
	6:00 PM	74	73	70	51	65	53	56	53	62	63	51	49	70	59	73	68	73	59	70	46	70	63	71	67	70	65	68	64	69	69	72	73	49	41	74	74	75
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	8:00 PM	76	76	75	69	74	71	74	74	74	75	75	73	75	76	76	76	76	73	76	73	76	74	75	75	75	74	75	75	75	75	76	76	75	71	76	77	76
	Time	1115713	1120611	1115721	1117909	1108536	1122469	1120167	1108439	1115739	1108415	1115749	1108717	1108585	1122487	1113985	1123002	1108590	1123030	1108592	1120994	1108597	1121037	1108595	1121099	1121131	1108562	1121118	1108767	1121067	1125872	1108769	1125886	1108771	1108773	1119736	1119743	1119749
DYNAMIC SPEED LIMITS	4:15 PM	72	69	36	27	27	27	24	39	53	56	38	52	68	62	70	58	64	54	56	36	32	30	56	45	42	49	59	53	67	59	67	63	58	40	72	73	73
	4:30 PM	72	71	62	48	41	37	25	39	47	43	30	50	68	62	70	56	66	52	54	41	55	46	54	47	42	43	49	45	62	54	58	53	42	34	72	73	72
	4:45 PM	73	72	68	53	59	50	45	36	42	37	25	51	68	58	72	62	67	52	56	41	69	60	61	52	51	43	39	41	60	55	53	48	38	31	71	73	73
	5:00 PM	73	73	70	53	62	50	53	43	38	31	22	57	69	62	73	66	67	54	57	42	70	59	66	59	59	48	50	46	61	54	52	46	38	32	71	72	72
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	5:30 PM	73	72	66	50	59	51	54	45	40	35	24	51	69	62	73	67	70	55	60	44	69	59	70	64	66	59	62	53	69	64	67	63	57	44	72	73	73
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	7:45 PM	76	76	74	69	73	70	74	73	73	75	75	73	75	75	76	76	76	72	76	73	75	73	75	75	75	74	75	75	75	75	75	75	75	70	76	76	76
	8:00 PM	76	76	75	70	74	71	75	74	74	75	75	73	75	76	76	76	76	72	76	73	76	73	75	75	75	75	75	75	76	75	75	76	75	70	76	77	76

Figure 9-41: Speed contour with Dynamic Speed Limits compared with the baseline case under Operational Condition 4

If we compare network-wide traffic performance measures with Dynamic Speed Limits with the baseline condition (Table 9-32 and Figure 9-42), we can notice that it doesn’t affect the throughput but produces a slight decrease of the overall speed.

Table 9-32: Performance measures with Dynamic Speed Limits compared with the baseline case under Operational Condition 4

Network Statistics	Base	Dynamic Speed Limit	Difference
Vehicles Miles Travelled (miles)	2,302,897	2,302,937	0.0%
Total Travel Time (h)	57,547	58,476	1.6%
Passenger Hourly Travel Time (h)	75,856	76,910	1.4%
VMT/VHT (mi/h)	40.02	39.38	-1.6%

Figure 9-42: Performance measures with Dynamic Speed Limits compared with the baseline case under Operational Condition 4

In summary, the results show that in a condition in which there is little congestion throughout the corridor this ATDM strategy reduces the speed drops, with an increase of safety at the price of a slight increase of the overall travel time.

9.2.4.5 Comparison between operational conditions

Dynamic Speed Limits reduce the speed change between consecutive road segments, at the expense of reducing the overall speed along the corridor. With little congestion the impact in terms of increase of delay is negligible, while as congestion increases the increase of delay increases, too, and is coupled with a slight decrease of throughput.

It’s worth noting that the Dynamic Speed Limits algorithm that has been adopted for this evaluation is not recent nor very sophisticated. It is therefore expected that other algorithms could produce different results. However, studies available in literature show that Dynamic Speed Limits are most effective when there are heavy localized bottlenecks, in which case they can produce benefits in terms of travel time in addition to safety, while when congestion is distributed over a long segment they can produce an increase of travel time.

9.2.5 Dynamic Merge Control

Since the only location that has been selected to test Dynamic Merge Control is at the entrance into I-15 from SR-78 in the southbound direction, this ATDM strategy has been assessed only under the two operational conditions in which the prevailing traffic demand is in the southbound direction: AM1 and AM2.

The simulations were run with the rightmost lane of I-15 upstream of the ramp from SR-78 closed throughout the analysis interval (see Section 7.1.3), rather than activating the closure based on traffic conditions, because during the whole period traffic from I-15 is constantly high, so there is no simple rule to define when it should be penalized to favor the entrance from SR-78. Additionally, this setting allows assessing the maximum impact of this ATDM strategy.

9.2.5.1 Operational condition 1 (AM1)

A comparison of the speed contour on I-15 in the southbound direction with the baseline conditions shows that the Dynamic Merge Control produces an increase of congestion upstream of the location where it is applied (Figure 9-43). This is intuitive because this strategy closes one lane on I-15 at that location.

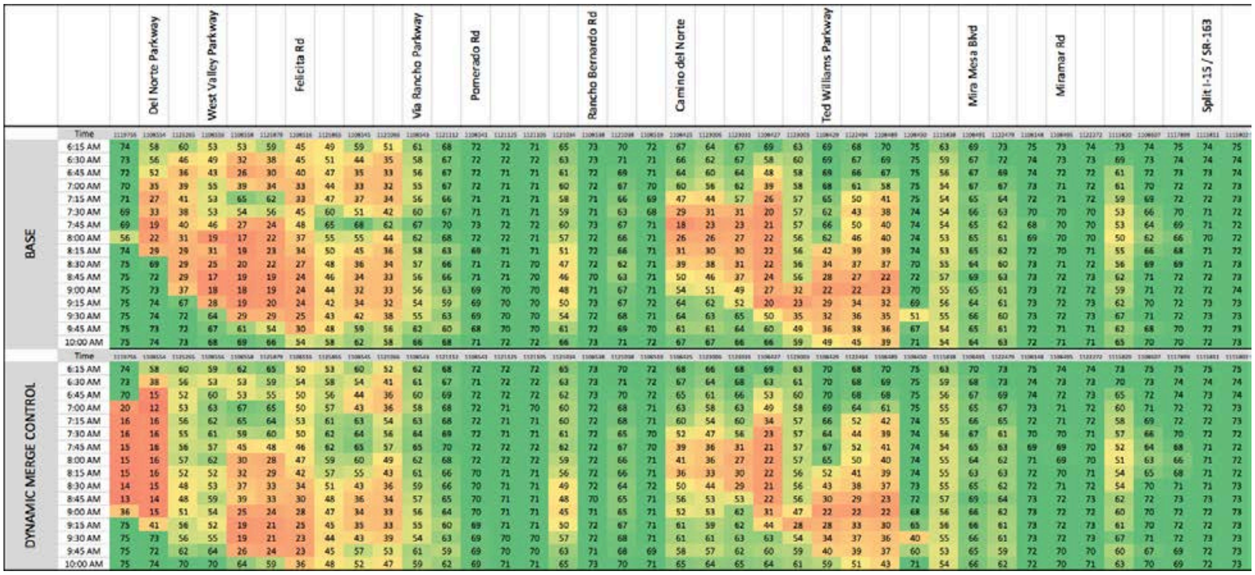


Figure 9-43: Speed contour with Dynamic Merge Control compared with the baseline case under Operational Condition 1

If we compare network-wide traffic performance measures with Dynamic Merge Control with the baseline condition (Table 9-33 and Figure 9-44), we can notice an almost negligible decrease of throughput with a slight increase of travel time.

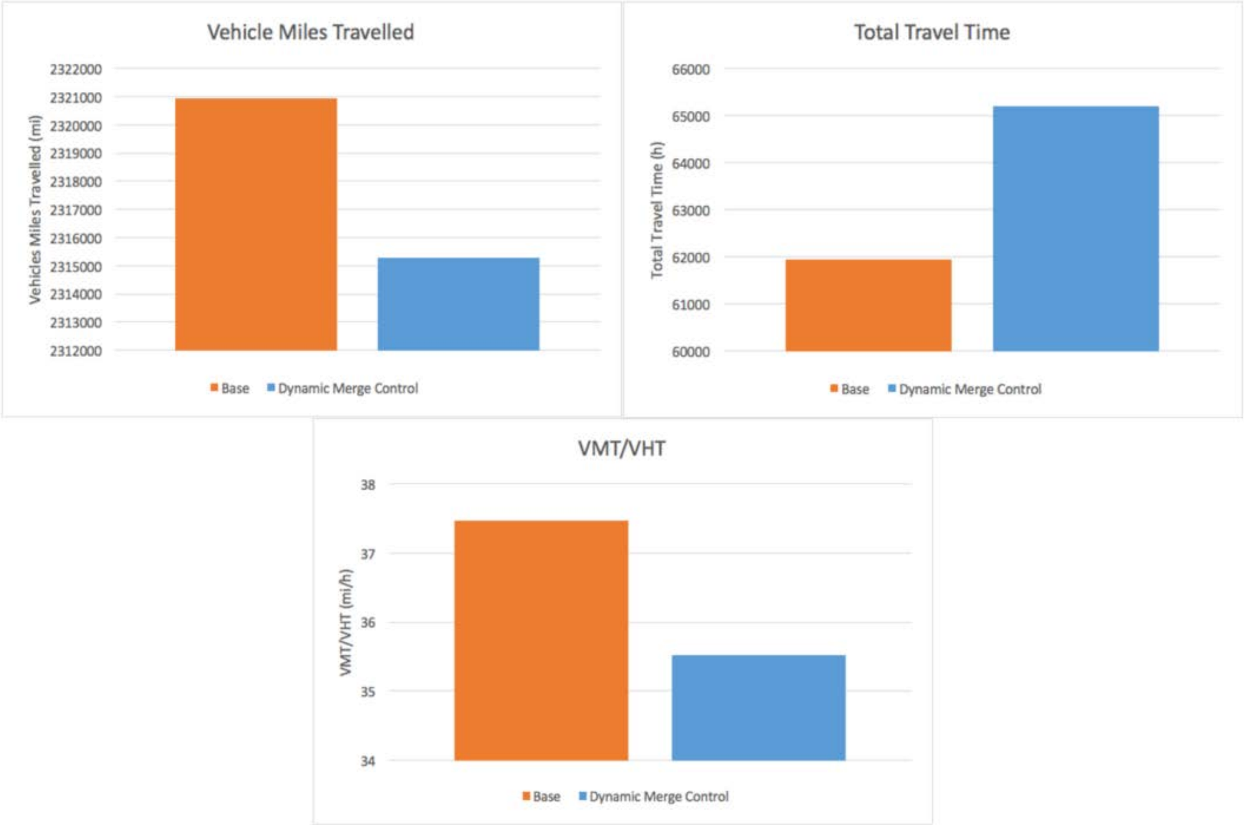


Figure 9-44: Performance measures with Dynamic Merge Control compared with the baseline case under Operational Condition 1

Table 9-33: Performance measures with Dynamic Merge Control compared with the baseline case under Operational Condition 1

Network Statistics	Base	Dynamic Merge Control	Difference
Vehicles Miles Travelled (miles)	2,320,947	2,315,264	-0.2%
Total Travel Time (h)	61,946	65,191	5.2%
Passenger Hourly Travel Time (h)	78,635	83,511	6.2%
VMT/VHT (mi/h)	37.47	35.52	-5.2%

If we look at the total count over the analysis period at the merge, on the upstream road section of I-15 and on the ramp coming from SR-78 (Table 9-34) we can notice that Dynamic Merge Control leaves the throughput of the merge essentially unchanged, but redistributes the inflow differently between I-15 and SR-78, promoting the entrance from the latter.

Table 9-34: Throughput at the merge with Dynamic Merge Control compared with the baseline case under Operational Condition 1

Total Count (veh)	Base	Dynamic Merge Control	Difference
Merging Section	35,551	34,838	-713
I-15 Upstream Section	23,669	21,981	-1688
SR-78 Ramp	11,867	12,841	974

In summary, the results show a slightly negative effect in terms of traffic performance caused by Dynamic Merge Control, which facilitates the entrance from SR-78, at the expense of penalizing traffic coming from the northern boundary of the I-15 corridor in the southbound direction.

9.2.5.2 Operational condition 2 (AM2)

A comparison of the speed contour on I-15 in the southbound direction with the baseline conditions shows that the Dynamic Merge Control produces a slight increase of congestion upstream of the location where it is applied (Figure 9-45). This is intuitive because this strategy closes one lane on I-15 at that location.

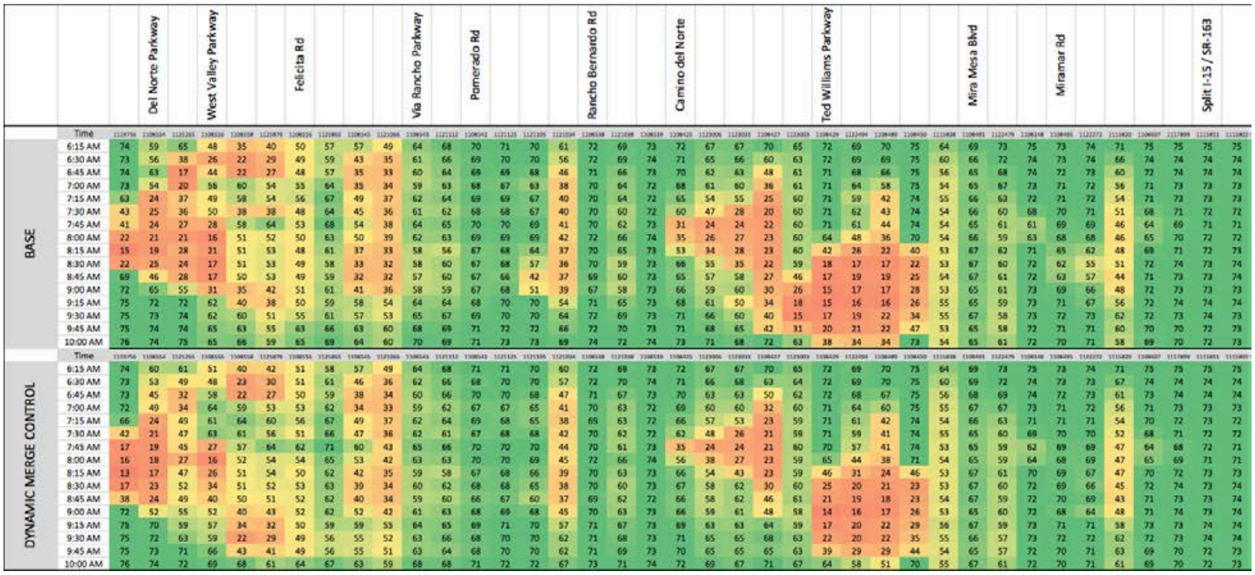


Figure 9-45: Speed contour with Dynamic Merge Control compared with the baseline case under Operational Condition 2

If we compare network-wide traffic performance measures with Dynamic Merge Control with the baseline condition (Table 9-35 and Figure 9-46), we can notice no change of throughput with a slight increase of travel time.

Table 9-35: Performance measures with Dynamic Merge Control compared with the baseline case under Operational Condition 2

Network Statistics	Base	Dynamic Merge Control	Difference
Vehicles Miles Travelled (miles)	2,304,353	2,305,441	0.0%
Total Travel Time (h)	61,509	64,540	4.9%
Passenger Hourly Travel Time (h)	78,853	82,905	5.1%
VMT/VHT (mi/h)	37.46	35.72	-4.7%

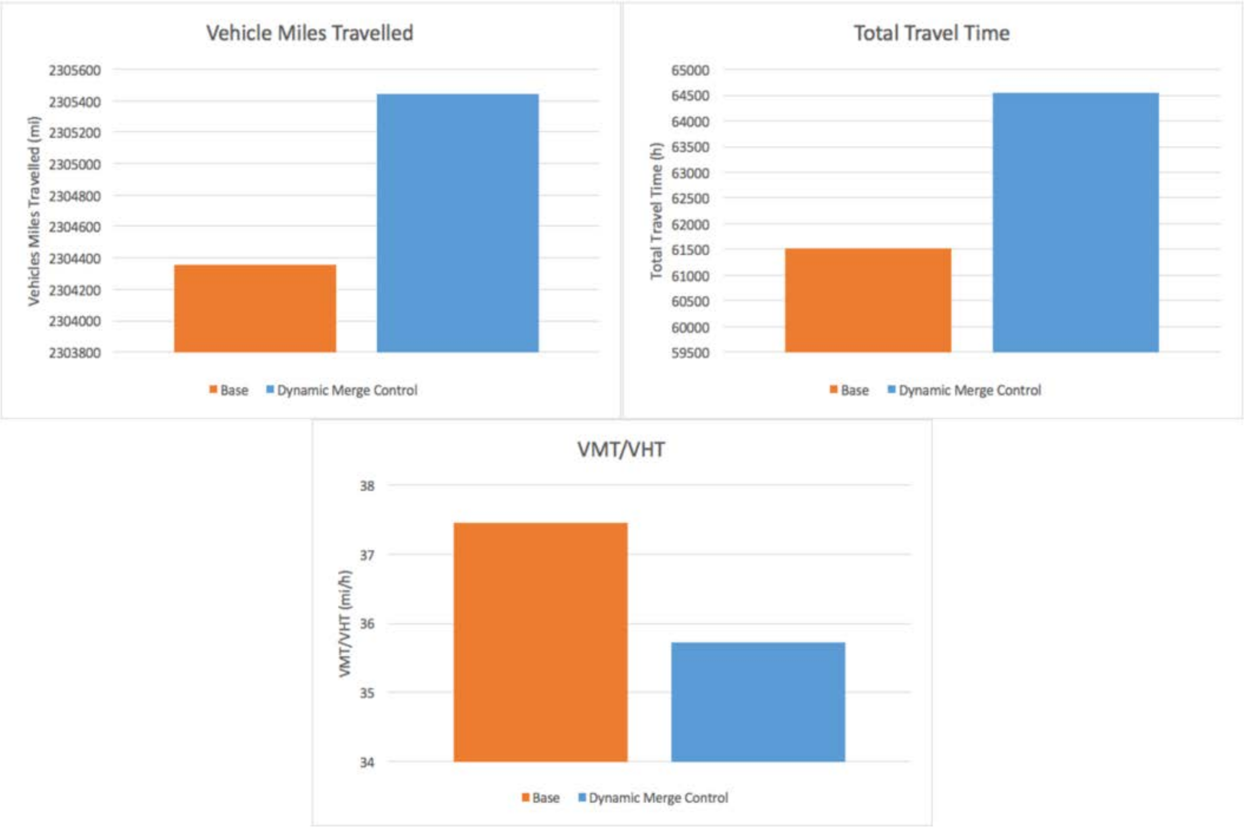


Figure 9-46: Performance measures with Dynamic Merge Control compared with the baseline case under Operational Condition 2

If we look at the total count over the analysis period at the merge, on the upstream road section of I-15 and on the ramp coming from SR-78 (Table 9-36) we can notice that Dynamic Merge Control leaves the throughput of the merge essentially unchanged, but redistributes the inflow differently between I-15 and SR-78, promoting the entrance from the latter.

Table 9-36: Throughput at the merge with Dynamic Merge Control compared with the baseline case under Operational Condition 2

Total Count (veh)	Base	Dynamic Merge Control	Difference
Merging Section	33,899	33,813	-87
I-15 Upstream Section	22,157	21,842	-316
SR-78 Ramp	11,723	11,955	232

In summary, the results show a slightly negative effect in terms of traffic performance caused by Dynamic Merge Control, which facilitates the entrance from SR-78, at the expense of penalizing traffic coming from the northern boundary of the I-15 corridor in the southbound direction.

9.2.5.3 Comparison between operational conditions

Dynamic Merge Control facilitates the entrance from SR-78, at the expense of penalizing traffic coming from the northern boundary of the I-15 corridor in the southbound direction. Under both operational conditions the traffic coming from I-15 is constantly high, and higher than that coming from SR-78, so there is no evident benefit from the activation of this ATDM strategy. It is expected however than when the southbound I-15 traffic gets lower, this strategy will have positive overall impact on the corridor, because it will reduce conflicts at the merge.

9.2.6 Predictive Traveler Information with Dynamic Routing

A simulation framework to produce simulation-based travel time predictions was built. This framework emulates the ICM capabilities provided by Aimsun Online in reality. It was used to test how vehicles would reroute if having access to predictive travel time information with two time horizons: 15 and 30 minutes. For further details see Sections 7.2.1 and 7.2.3.

Considering that in the I-15 corridor an ICM application that predicts travel times is already in existence, and that the baseline scenario features response plans that have been activated based on it, the comparison between baseline and Predictive Traveler Information with Dynamic Routing should be considered to validate the capability of the Predictive Traveler Information testing framework of reproducing the real ICM application.

In addition to the baseline conditions, the performance of this application has been compared with the do-nothing scenario, which consists in the baseline case without any response plan applied. This comparison evaluates the effectiveness of Predictive Traveler Information with respect to a situation without any predictive capabilities.

9.2.6.1 Operational condition 1 (AM1)

An analysis of the speed contour on I-15 in the southbound direction shows that the Predictive Traveler Information produces no significant difference in terms of congestion both compared to do-nothing and to the baseline (Figure 9-47).

30 min prediction horizon

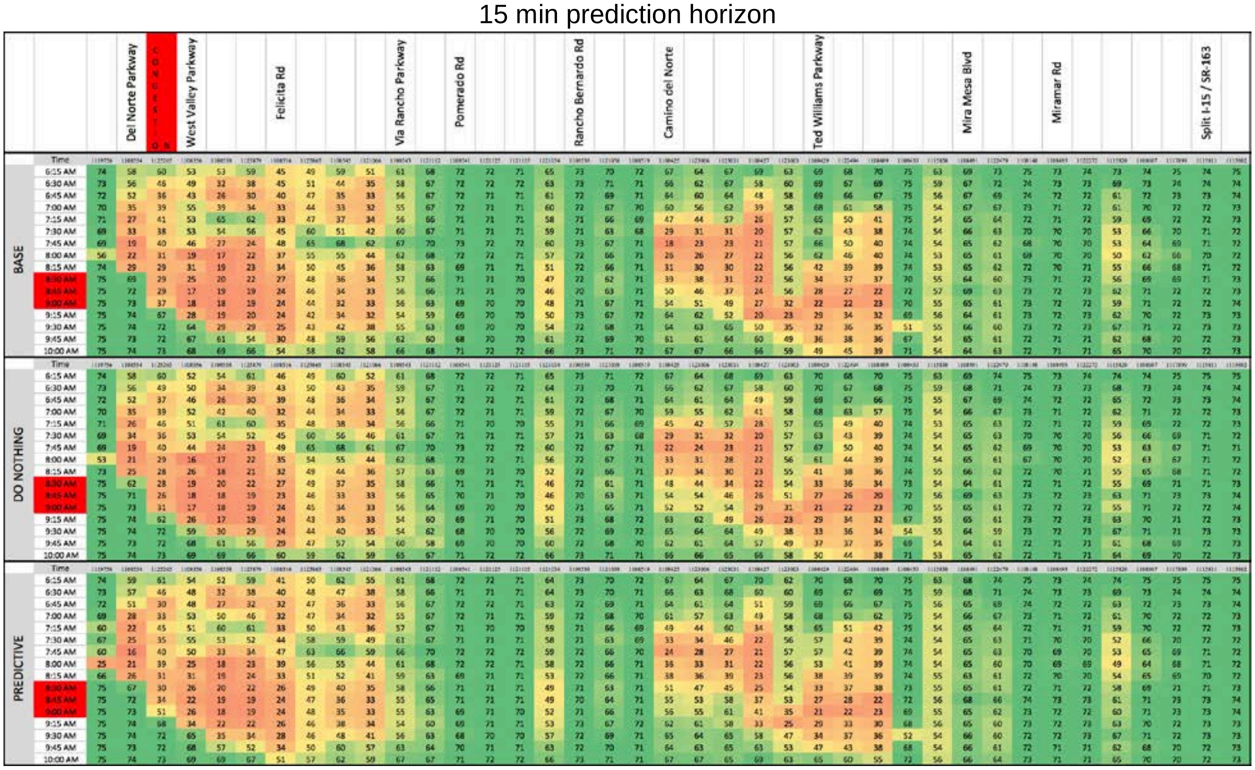


Figure 9-47: Speed contour with Predictive Traveler Information compared with the do-nothing and the baseline case under Operational Condition 1; the red boxes mark the location and duration of the incident

If we compare network-wide traffic performance measures with Predictive Traveler Information with the do-nothing and the baseline condition (Table 9-37 and Table 9-38), we can notice that the difference with the baseline is negligible and that, probably because of rerouting, there is a slight increase of travel time and distance travelled compared with do-nothing. The difference is higher with the longer prediction horizon.

Table 9-37: Performance measures with Predictive Traveler Information with 30 min prediction horizon compared with the do-nothing and the baseline case under Operational Condition 1

Network Statistics	Predictive	Do Nothing	Difference	Base	Difference
Vehicles Miles Travelled (miles)	2,321,980	2,305,327	0.7%	2,320,947	0.0%
Total Travel Time (h)	62,128	60,912	2.0%	61,946	0.3%
Passenger Hourly Travel Time (h)	79,053	78,172	1.1%	78,635	0.5%
VMT/VHT (miles/h)	37.37	37.85	-1.3%	37.47	-0.2%

Table 9-38: Performance measures with Predictive Traveler Information with 15 min prediction horizon compared with the do-nothing and the baseline case under Operational Condition 1

Network Statistics	Predictive	Do Nothing	Difference	Base	Difference
Vehicles Miles Travelled (miles)	2,322,078	2,305,327	0.7%	2,320,947	0.0%
Total Travel Time (h)	61,920	60,912	1.7%	61,946	0.0%
Passenger Hourly Travel Time (h)	78,727	78,172	0.7%	78,635	0.1%
VMT/VHT (miles/h)	37.50	37.85	-0.9%	37.47	0.1%

9.2.6.2 Operational condition 2 (AM2)

An analysis of the speed contour on I-15 in the southbound direction shows that the Predictive Traveler Information produces a slight reduction of some congestion points both compared to do-nothing and to the baseline (Figure 9-48). The reduction is more significant with the longer prediction horizon.

30 min prediction horizon

15 min prediction horizon

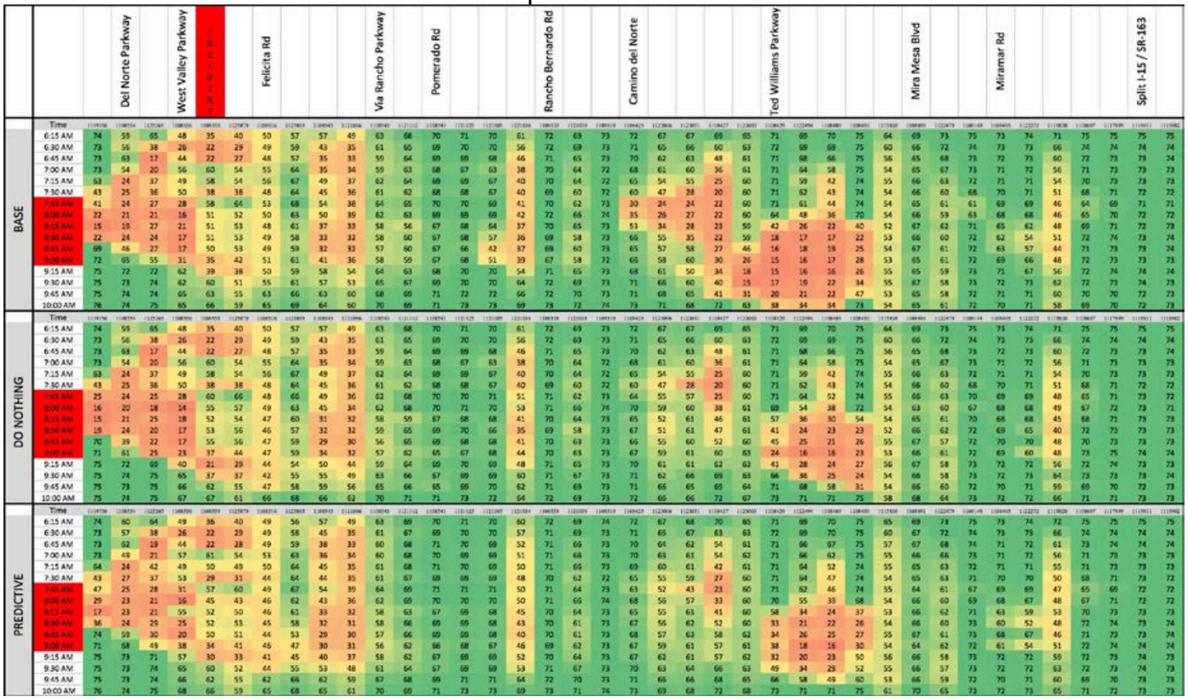


Figure 9-48: Speed contour with Predictive Traveler Information compared with the do-nothing and the baseline case under Operational Condition 2; the red boxes mark the location and duration of the incident

If we compare network-wide traffic performance measures with Predictive Traveler Information with the do-nothing and the baseline condition (Table 9-39 and Table 9-40), we can notice that the difference with the baseline is negligible and that there is a slight increase of travel time with similar distance travelled compared with do-nothing. The difference is similar with both prediction horizons.

Table 9-39: Performance measures with Predictive Traveler Information with 30 min prediction horizon compared with the do-nothing and the baseline case under Operational Condition 2

Network Statistics	Predictive	Do Nothing	Difference	Base	Difference
Vehicles Miles Travelled (miles)	2,299,074	2,305,327	-0.3%	2,304,353	-0.2%
Total Travel Time (h)	61,867	60,912	1.6%	61,509	0.6%
Passenger Hourly Travel Time (h)	79,466	78,172	1.7%	78,853	0.8%
VMT/VHT (miles/h)	37.16	37.85	-1.8%	37.46	-0.8%

Table 9-40: Performance measures with Predictive Traveler Information with 15 min prediction horizon compared with the do-nothing and the baseline case under Operational Condition 2

Network Statistics	Predictive	Do Nothing	Difference	Base	Difference
Vehicles Miles Travelled (miles)	2,300,027	2,305,327	-0.2%	2,304,353	-0.2%
Total Travel Time (h)	61,773	60,912	1.4%	61,509	0.4%
Passenger Hourly Travel Time (h)	79,267	78,172	1.4%	78,853	0.5%
VMT/VHT (miles/h)	37.23	37.85	-1.6%	37.46	-0.6%

9.2.6.3 Operational condition 3 (PM3)

An analysis of the speed contour on I-15 in the northbound direction shows that the Predictive Traveler Information produces no significant difference in terms of congestion both compared to do-nothing and to the baseline (Figure 9-49).

30 min prediction horizon

15 min prediction horizon

Figure 9-49: Speed contour with Predictive Traveler Information compared with the do-nothing and the baseline case under Operational Condition 3; the red boxes mark the location and the duration of the incident

If we compare network-wide traffic performance measures with Predictive Traveler Information with the do-nothing and the baseline condition (Table 9-41 and Table 9-42), we can notice that the difference with the baseline is negligible and that there is a slight decrease of travel time with similar distance travelled compared with do-nothing. The difference is similar with both prediction horizons.

Table 9-41: Performance measures with Predictive Traveler Information with 30 min prediction horizon compared with the do-nothing and the baseline case under Operational Condition 3

Network Statistics	Predictive	Do Nothing	Difference	Base	Difference
Vehicles Miles Travelled (miles)	2,525,928	2,536,662	-0.4%	2,518,604	0.3%
Total Travel Time (h)	76,612	77,486	-1.1%	76,531	0.1%
Passenger Hourly Travel Time (h)	99,168	100,193	-1.0%	99,052	0.1%
VMT/VHT (miles/h)	32.97	32.74	0.7%	32.91	0.2%

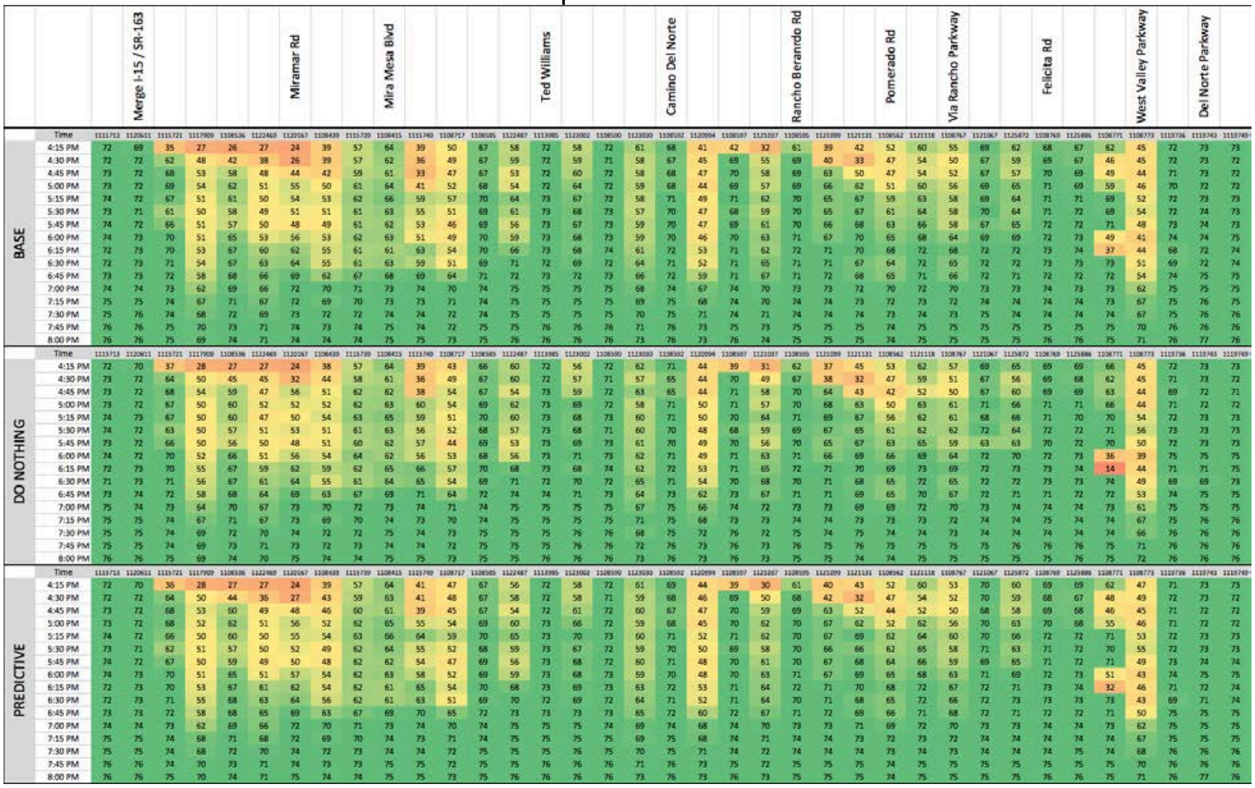
Table 9-42: Performance measures with Predictive Traveler Information with 15 min prediction horizon compared with the do-nothing and the baseline case under Operational Condition 3

Network Statistics	Predictive	Do Nothing	Difference	Base	Difference
Vehicles Miles Travelled (miles)	2,536,005	2,536,662	0.0%	2,518,604	0.7%
Total Travel Time (h)	76,378	77,486	-1.4%	76,531	-0.2%
Passenger Hourly Travel Time (h)	98,927	100,193	-1.3%	99,052	-0.1%
VMT/VHT (miles/h)	33.20	32.74	1.4%	32.91	0.9%

9.2.6.4 Operational condition 4 (PM4)

An analysis of the speed contour on I-15 in the northbound direction shows that the Predictive Traveler Information produces no significant difference in terms of congestion both compared to do-nothing and to the baseline (Figure 9-50).

30 min prediction horizon



15 min prediction horizon

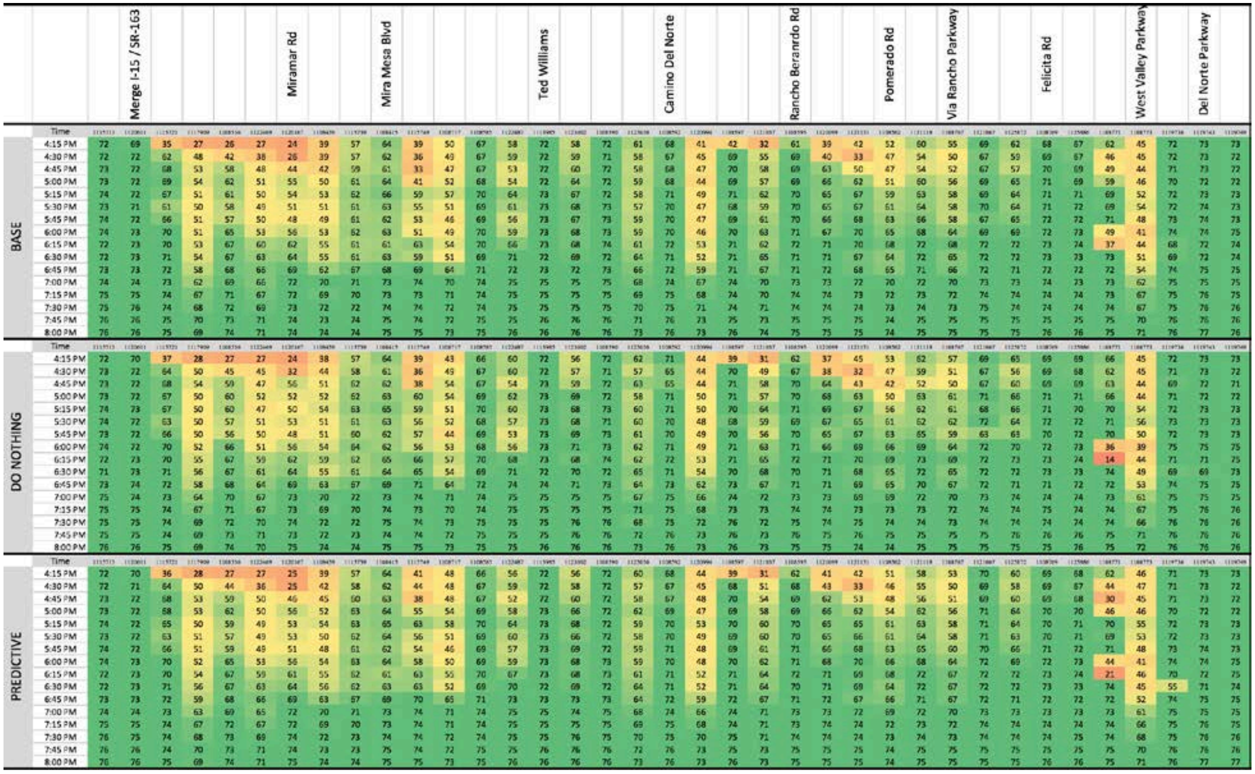


Figure 9-50: Speed contour with Predictive Traveler Information compared with the do-nothing and the baseline case under Operational Condition 4; the incident is located on a ramp outside of the corridor

If we compare network-wide traffic performance measures with Predictive Traveler Information with the do-nothing and the baseline condition (Table 9-43 and Table 9-44), we can notice that the difference with both the baseline and the do-nothing case is negligible with both prediction horizons.

Table 9-43: Performance measures with Predictive Traveler Information with 30 min prediction horizon compared with the do-nothing and the baseline case under Operational Condition 4

Network Statistics	Predictive	Do Nothing	Difference	Base	Difference
Vehicles Miles Travelled (miles)	2,303,573	2,309,503	-0.3%	2,302,897	0.0%
Total Travel Time (h)	57,523	57,576	-0.1%	57,547	0.0%
Passenger Hourly Travel Time (h)	75,870	75,909	-0.1%	75,856	0.0%
VMT/VHT (miles/h)	40.05	40.11	-0.2%	40.02	0.1%

Table 9-44: Performance measures with Predictive Traveler Information with 15 min prediction horizon compared with the do-nothing and the baseline case under Operational Condition 4

Network Statistics	Predictive	Do Nothing	Difference	Base	Difference
Vehicles Miles Travelled (miles)	2,303,303	2,309,503	-0.3%	2,302,897	0.0%
Total Travel Time (h)	57,607	57,576	0.1%	57,547	0.1%
Passenger Hourly Travel Time (h)	75,987	75,909	0.1%	75,856	0.2%
VMT/VHT (miles/h)	39.98	40.11	-0.3%	40.02	-0.1%

9.2.6.5 Comparison between operational conditions

A comparison of the speed contours, which focus on the performance of the I-15 corridor, under different operational conditions and different prediction horizons shows that Predictive Traveler Information is more effective with higher demand and with more severe incidents: AM2, which has several bottlenecks scattered throughout the corridor, shows the highest reduction of congestion, even with the shorter prediction horizon; AM1, which has a similar congestion pattern but a less severe incident, shows a slightly less improvement. PM4, which has no significant congestion, shows no significant effect.

If we look at the traffic performance measures, which adopt a network-wide perspective, we can notice that in some operational condition the positive impact on the speed along the I-15 corridor is in fact counterbalanced by a slight increase of travel time along the nearby arterials, which absorb the additional traffic that gets diverted from I-15.

9.3 Summary of Results

The results confirm the hypotheses: the benefits of DMA applications and ATDM strategies depend on the congestion level and operational conditions.

SPD-HARM generally does not produce significant benefits in terms of traffic performance, but a benefit in terms of safety. Its effectiveness is more evident in congested situations, when it can be appreciated already at lower penetration rates, while when the congestion is low, high penetration rates are required to produce a reduction of shockwaves. The benefit in terms of safety comes at the cost of a slight increase of travel time under all operational conditions.

CACC is more effective in congested situations, where it can produce a significant increase of throughput and reduction of travel time, even at lower penetration rates. When congestion is low, at 50% penetration rate even a slight reduction of traffic performance can be observed, because CACC platoons may cause an obstacle for non-connected vehicle that want to change lane.

The analysis of the simulations with CACC suggest also the following observations:

- Most CACC algorithms available today only deal with car-following in a single lane and with an already formed platoon:
    - Care should be taken in selecting the parameters of the CACC algorithm (for example, the gain coefficients of the controller logic, the target headway, the update frequency), as only some combinations produce a stable car-following regime.
- To produce tangible benefits in real-world conditions, CACC algorithms should deal also with other aspects of vehicle movement:
    - Managing the transition (vehicle joining or leaving the platoon) is key to avoid instabilities.
    - Managing the vehicle distribution across multiple lanes is key with multiple reserved lanes (higher penetration rates).
    - Managing the length of the platoon is key with mixed traffic, to prevent blocking non-connected vehicles.
    - Managing the lane changing is key to allow connected vehicles take the exit they need to take and to prevent blocking non-connected vehicles.

Dynamic Lane Use and Dynamic HOV/Managed Lanes are effective only in congested situations. Additionally, the location of incidents and bottlenecks may reduce the effectiveness of this ATDM strategy, because if the congestion caused by them affects the access points to the HOV lanes, vehicles have difficulty in reaching the additional lane that allows bypassing the bottlenecks.

Dynamic Speed Limits reduce the speed change between consecutive road segments, at the expense of reducing the overall speed along the corridor. With little congestion the impact in terms of increase of delay is negligible, while as congestion increases the increase of delay increases, too, and is coupled with a slight decrease of throughput.

Dynamic Merge Control facilitates the entrance from SR-78, at the expense of penalizing traffic coming from the northern boundary of the I-15 corridor in the southbound direction. When the I-15 traffic is lower than that entering from SR-78, this strategy has a positive overall impact on the corridor, because it reduces conflicts at the merge.

Predictive Traveler Information with Dynamic Routing is more effective with higher demand and with more severe incidents. The benefit is evident if we focus on the I-15 corridor, while if we adopt a network-wide perspective, we can notice that in some operational condition the positive impact on the speed along the I-15 corridor is in fact counterbalanced by an overall slight increase of travel time because or rerouting along the arterials.

Chapter 10. Communication Latency and Errors

The San Diego testbed also features a communications emulator to assess some of the communication-related sensitivity analysis as far as connected vehicle applications are concerned. Please note that the communications modeling performed within the scope of this project does not assume physical characteristics of wireless communication such as channel congestion, environmental impacts, hidden nodes, and retransmission.

10.1 Research Questions

This chapter addresses the following research questions:

1. What are the impacts of communication latency on benefits?
2. How effective are the DMA bundles when there are errors or loss in communication?

The following hypotheses were made to design this analysis:

1. Applications such as CACC rely on low-latency communication, whereas applications such as SPD-HARM could work with higher-than-one-second latency.
2. The effectiveness of DMA bundles will be reduced by errors and loss in communication.

10.2 Analysis Approach

Operational condition 1 was used to evaluate the impact of latency and message loss on SPD-HARM. In the scenarios to assess latency, all connected vehicles have the same latency value. Two latency values were evaluated:

- 1 second
- 3 seconds

In the scenarios to assess message loss, all messages sent or received by all connected vehicles have the same probability of being dropped. Two values of probability of dropping a message have been evaluated:

- 10%
- 20%

The same set of simulations run to evaluate SPD-HARM in isolation under operational condition 1 (see 9.2.1.1) were rerun first applying latency and then applying message loss. The concurrent impact of latency and message loss was not evaluated. The results obtained were compared with those produced under perfect communication to assess the impact of these communication issues.

Previous research analyzed the minimum communication delay to be in terms of few milliseconds for the CACC application[16] and assessed the impact the impact of data loss on CACC's performance[17]. All these studies agree that low-latency and robust communication are very important to ensure the stability of the platoon and avoid collisions, given the reliance of CACC on V2V communication at high rate. Since literature on the topic was available, no specific evaluation was conducted in the San Diego testbed.

10.2.1 SPD-HARM and Latency

Simulations were run with different penetration rates of connected vehicles (25%, 50% and 90%) and two latency values (1s and 3s).

10.2.1.1 1 second of latency

If we compare network-wide traffic performance measures with 1 second of latency with the results with perfect communication and those with the baseline condition (Table 10-1, Table 10-2 and Table 10-3), we can notice that the impact on SPD-HARM is minimal.

Table 10-1: Performance measures with SPD-HARM with 25% penetration rate with 1s latency compared with perfect communication and the baseline case under Operational Condition 1

Network Statistics	Base	SPD-HARM 25%, 1s latency	Difference	SPD-HARM 25%	Difference
Vehicle Miles Traveled (mi)	2,320,947	2,340,542	0.8%	2,340,587	0.8%
Total Travel Time (h)	61,946	63,711	2.8%	64,185	3.6%
Passenger Hourly Travel Time (h)	78,635	80,852	2.8%	81,499	3.6%
VMT/VHT (mi/h)	37.47	36.74	-1.9%	36.47	-2.7%
Spatial speed drop (mi/h)	15.0	12.6	-16.0%	12.6	-16.0%
Temporal speed drop (mi/h)	11.0	9.8	-10.9%	9.8	-10.9%

Table 10-2: Performance measures with SPD-HARM with 50% penetration rate with 1s latency compared with perfect communication and the baseline case under Operational Condition 1

Network Statistics	Base	SPD-HARM 50%, 1s latency	Difference	SPD-HARM 50%	Difference
Vehicle Miles Traveled (mi)	2,320,947	2,350,725	1.3%	2,350,332	1.3%
Total Travel Time (h)	61,946	66,307	7.0%	66,744	7.7%
Passenger Hourly Travel Time (h)	78,635	84,045	6.9%	84,659	7.7%
VMT/VHT (mi/h)	37.47	35.45	-5.4%	35.21	-6.0%
Spatial speed drop (mi/h)	15.0	10.4	-30.7%	10.4	-30.7%
Temporal speed drop (mi/h)	11.0	7.0	-36.4%	7.0	-36.4%

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[16] Xiangheng Liu at al., Effects of communication delay on string stability in vehicle platoons, accessed at: http://ieeexplore.ieee.org/document/948732/
Sinan Oncu et al., String stability of interconnected vehicles under communication constraints, accessed at: http://ieeexplore.ieee.org/abstract/document/6426042/

[17] C. Lei at al., Impact of packet loss on CACC string stability performance, accessed at: http://ieeexplore.ieee.org/abstract/document/6060086/

Table 10-3: Performance measures with SPD-HARM with 90% penetration rate with 1s latency compared with perfect communication and the baseline case under Operational Condition 1

Network Statistics	Base	SPD-HARM 90%, 1s latency	Difference	SPD-HARM 90%	Difference
Vehicle Miles Traveled (mi)	2,320,947	2,355,640	1.5%	2,351,385	1.3%
Total Travel Time (h)	61,946	68,682	10.9%	68,997	11.4%
Passenger Hourly Travel Time (h)	78,635	86,753	10.3%	87,306	11.0%
VMT/VHT (mi/h)	37.47	34.30	-8.5%	34.08	-9.0%
Spatial speed drop (mi/h)	15.0	10.0	-33.3%	10.0	-33.3%
Temporal speed drop (mi/h)	11.0	6.2	-43.6%	6.2	-43.6%

10.2.1.2 3 seconds of latency

If we compare network-wide traffic performance measures with 3 seconds of latency with the results with perfect communication and those with the baseline condition (Table 10-4, Table 10-5 and Table 10-6), we can notice that the impact on SPD-HARM is minimal.

Table 10-4: Performance measures with SPD-HARM with 25% penetration rate with 3s latency compared with perfect communication and the baseline case under Operational Condition 1

Network Statistics	Base	SPD-HARM 25%, 3s latency	Difference	SPD-HARM 25%	Difference
Vehicle Miles Traveled (mi)	2,320,947	2,340,457	0.8%	2,340,587	0.8%
Total Travel Time (h)	61,946	64,424	4.0%	64,185	3.6%
Passenger Hourly Travel Time (h)	78,635	81,756	4.0%	81,499	3.6%
VMT/VHT (mi/h)	37.47	36.33	-3.0%	36.47	-2.7%
Spatial speed drop (mi/h)	15.0	12.6	-16.0%	12.6	-16.0%
Temporal speed drop (mi/h)	11.0	9.8	-10.9%	9.8	-10.9%

Table 10-5: Performance measures with SPD-HARM with 50% penetration rate with 3s latency compared with perfect communication and the baseline case under Operational Condition 1

Network Statistics	Base	SPD-HARM 50%, 3s latency	Difference	SPD-HARM 50%	Difference
Vehicle Miles Traveled (mi)	2,320,947	2,349,121	1.2%	2,350,332	1.3%
Total Travel Time (h)	61,946	66,591	7.5%	66,744	7.7%
Passenger Hourly Travel Time (h)	78,635	84,447	7.4%	84,659	7.7%
VMT/VHT (mi/h)	37.47	35.28	-5.8%	35.21	-6.0%
Spatial speed drop (mi/h)	15.0	10.4	-30.7%	10.4	-30.7%
Temporal speed drop (mi/h)	11.0	7.0	-36.4%	7.0	-36.4%

Table 10-6: Performance measures with SPD-HARM with 90% penetration rate with 3s latency compared with perfect communication and the baseline case under Operational Condition 1

Network Statistics	Base	SPD-HARM 90%, 3s latency	Difference	SPD-HARM 90%	Difference
Vehicle Miles Traveled (mi)	2,320,947	2,351,966	1.3%	2,351,385	1.3%
Total Travel Time (h)	61,946	68,923	11.3%	68,997	11.4%
Passenger Hourly Travel Time (h)	78,635	87,148	10.8%	87,306	11.0%
VMT/VHT (mi/h)	37.47	34.12	-8.9%	34.08	-9.0%
Spatial speed drop (mi/h)	15.0	10.0	-33.3%	10.0	-33.3%
Temporal speed drop (mi/h)	11.0	6.2	-43.6%	6.2	-43.6%

10.2.1.3 Comparison between different latency values

A comparison of the performance measures with different values of latency shows that SPD-HARM is not sensitive to this communication issue (Figure 10-1). At all penetration rates, even a latency of 3 seconds has a minimal impact on the performance of this DMA application.

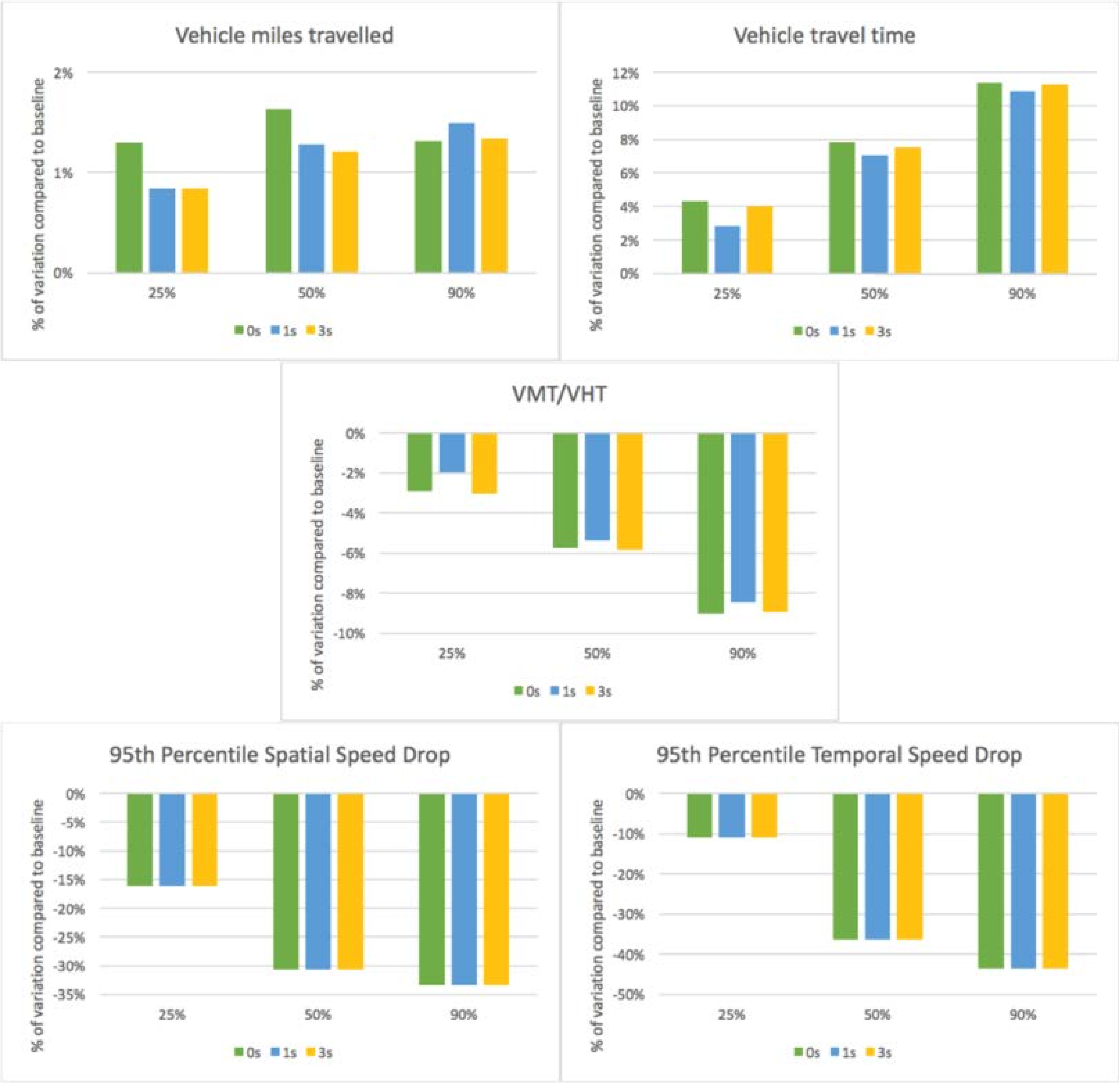


Figure 10-1: Change of the performance measures with SPD-HARM with different penetration rates compared with the baseline case with different communication latency

10.2.2 SPD-HARM and Message Loss

Simulations were run with different penetration rates of connected vehicles (25%, 50% and 90%) and two probabilities of dropping a message (10% and 20%).

10.2.2.1 10% of message loss

If we compare network-wide traffic performance measures with 10% message loss with the results with perfect communication and those with the baseline condition (Table 10-7, Table 10-8 and Table 10-9), we can notice that the impact on SPD-HARM can be only perceived at the lowest penetration rate. At 50% and 90% penetration rate the number of vehicles receiving SPD-HARM messages is high enough to compensate for the occasional drop of a message.

Table 10-7: Performance measures with SPD-HARM with 25% penetration rate with 10% message loss compared with perfect communication and the baseline case under Operational Condition 1

Network Statistics	Base	SPD-HARM 25%, 10% message loss	Difference	SPD-HARM 25%	Difference
Vehicle Miles Traveled (mi)	2,320,947	2,341,181	0.9%	2,340,587	0.8%
Total Travel Time (h)	61,946	64,009	3.3%	64,185	3.6%
Passenger Hourly Travel Time (h)	78,635	81,260	3.3%	81,499	3.6%
VMT/VHT (mi/h)	37.47	36.58	-2.4%	36.47	-2.7%
Spatial speed drop (mi/h)	15.0	13.0	-13.3%	12.6	-16.0%
Temporal speed drop (mi/h)	11.0	10.0	-9.1%	9.8	-10.9%

Table 10-8: Performance measures with SPD-HARM with 50% penetration rate with 10% message loss compared with perfect communication and the baseline case under Operational Condition 1

Network Statistics	Base	SPD-HARM 50%, 10% message loss	Difference	SPD-HARM 50%	Difference
Vehicle Miles Traveled (mi)	2,320,947	2,350,338	1.3%	2,350,332	1.3%
Total Travel Time (h)	61,946	66,561	7.5%	66,744	7.7%
Passenger Hourly Travel Time (h)	78,635	84,388	7.3%	84,659	7.7%
VMT/VHT (mi/h)	37.47	35.31	-5.8%	35.21	-6.0%
Spatial speed drop (mi/h)	15.0	10.4	-30.7%	10.4	-30.7%
Temporal speed drop (mi/h)	11.0	7.0	-36.4%	7.0	-36.4%

Table 10-9: Performance measures with SPD-HARM with 90% penetration rate with 10% message loss compared with perfect communication and the baseline case under Operational Condition 1

Network Statistics	Base	SPD-HARM 90%, 10% message loss	Difference	SPD-HARM 90%	Difference
Vehicle Miles Traveled (mi)	2,320,947	2,349,894	1.2%	2,351,385	1.3%
Total Travel Time (h)	61,946	68,655	10.8%	68,997	11.4%
Passenger Hourly Travel Time (h)	78,635	86,718	10.3%	87,306	11.0%
VMT/VHT (mi/h)	37.47	34.23	-8.6%	34.08	-9.0%
Spatial speed drop (mi/h)	15.0	10.0	-33.3%	10.0	-33.3%
Temporal speed drop (mi/h)	11.0	6.2	-43.6%	6.2	-43.6%

10.2.2.2 20% message loss

If we compare network-wide traffic performance measures with 20% message loss with the results with perfect communication and those with the baseline condition (Table 10-10, Table 10-11 and Table 10-12), we can notice that the impact on SPD-HARM diminishes with the increase of the penetration rate: at 25% penetration rate a 20% message loss is capable of almost neutralizing the benefit in terms of shockwave reduction; at 50% penetration rate the impact is less, and at 90% penetration rate it becomes insignificant, as the number of vehicles receiving SPD-HARM messages is high enough to compensate for the occasional drop of a message.

Table 10-10: Performance measures with SPD-HARM with 25% penetration rate with 20% message loss compared with perfect communication and the baseline case under Operational Condition 1

Network Statistics	Base	SPD-HARM 25%, 20% message loss	Difference	SPD-HARM 25%	Difference
Vehicle Miles Traveled (mi)	2,320,947	2,341,428	0.9%	2,340,587	0.8%
Total Travel Time (h)	61,946	63,911	3.2%	64,185	3.6%
Passenger Hourly Travel Time (h)	78,635	81,158	3.2%	81,499	3.6%
VMT/VHT (mi/h)	37.47	36.64	-2.2%	36.47	-2.7%
Spatial speed drop (mi/h)	15.0	14.0	-6.7%	12.6	-16.0%
Temporal speed drop (mi/h)	11.0	11.0	0.0%	9.8	-10.9%

Table 10-11: Performance measures with SPD-HARM with 50% penetration rate with 20% message loss compared with perfect communication and the baseline case under Operational Condition 1

Network Statistics	Base	SPD-HARM 50%, 20% message loss	Difference	SPD-HARM 50%	Difference
Vehicle Miles Traveled (mi)	2,320,947	2,350,797	1.3%	2,350,332	1.3%
Total Travel Time (h)	61,946	66,392	7.2%	66,744	7.7%
Passenger Hourly Travel Time (h)	78,635	84,139	7.0%	84,659	7.7%
VMT/VHT (mi/h)	37.47	35.41	-5.5%	35.21	-6.0%
Spatial speed drop (mi/h)	15.0	11.0	-26.7%	10.4	-30.7%
Temporal speed drop (mi/h)	11.0	8.0	-27.3%	7.0	-36.4%

Table 10-12: Performance measures with SPD-HARM with 90% penetration rate with 20% message loss compared with perfect communication and the baseline case under Operational Condition 1

Network Statistics	Base	SPD-HARM 90%, 20% message loss	Difference	SPD-HARM 90%	Difference
Vehicle Miles Traveled (mi)	2,320,947	2,351,426	1.3%	2,351,385	1.3%
Total Travel Time (h)	61,946	69,044	11.5%	68,997	11.4%
Passenger Hourly Travel Time (h)	78,635	87,255	11.0%	87,306	11.0%
VMT/VHT (mi/h)	37.47	34.06	-9.1%	34.08	-9.0%
Spatial speed drop (mi/h)	15.0	10.0	-33.3%	10.0	-33.3%
Temporal speed drop (mi/h)	11.0	6.2	-43.6%	6.2	-43.6%

10.2.2.3 Comparison between different message loss ratios

A comparison of the performance measures with different values of message loss shows that SPD-HARM is sensitive to this communication issue at lower penetration rates (Figure 10-2): at the highest penetration rate even 20% message loss doesn't alter the performance of this DMA application because the number of vehicles receiving SPD-HARM message is high; at 25% penetration rate instead the effect of just a 10% message loss can already be perceived, while at 50% penetration rate only 20% message loss can impact the shockwave reduction.

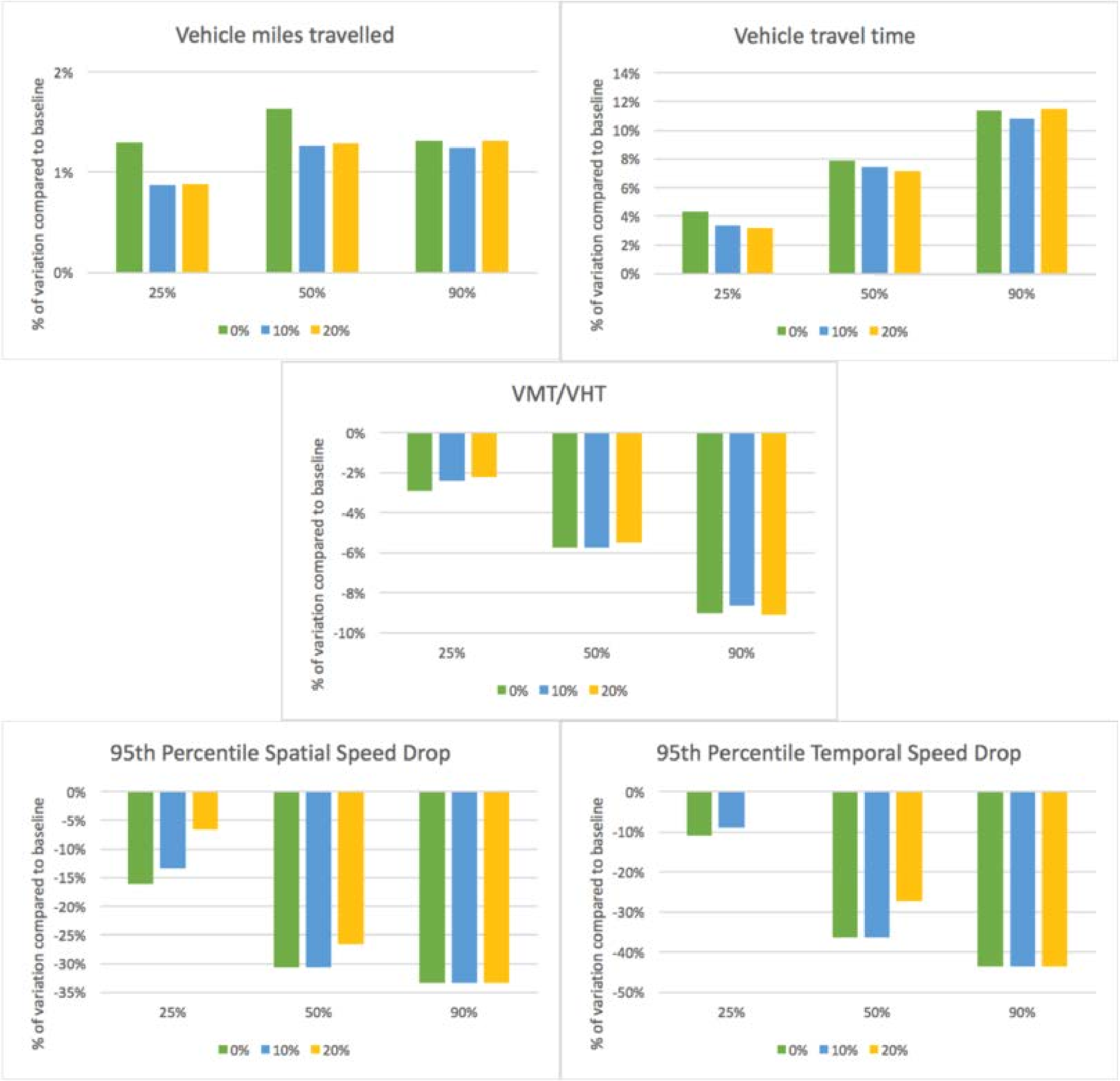


Figure 10-2: Change of the performance measures with SPD-HARM with different penetration rates compared with the baseline case with different message losses

10.3 Summary of Results

SPD-HARM doesn't seem to be sensitive to latency: at all penetration rates, even a latency of 3 seconds doesn't alter the performance of this DMA application. However, it is sensitive to packet loss at lower penetration rates of connected vehicles: at the highest penetration rate even 20% message loss doesn't alter the performance of this DMA application because the number of vehicles receiving SPD-HARM message is high; at 25% penetration rate instead the effect of just a 10% message loss can already be perceived, while at 50% penetration rate only 20% message loss can impact the shockwave reduction.

Chapter 11. Prediction and Active Management

This chapter analyses the impact of travel time prediction on the effectiveness of ATDM strategies and DMA applications.

11.1 Research Questions

The following research questions are answered using this analysis:

1. Can new applications that yield transformative benefits be deployed without a commensurate investment in prediction and active management (reduced control latency)? How cost-effective are DMA bundles when coupled with prediction and active management?
2. Which ATDM strategy or combination of strategies will benefit the most through increased prediction accuracy and under what operational conditions?
3. Are all forms of prediction equally valuable, i.e., which attributes of prediction quality are critical (e.g., length of prediction horizon, prediction accuracy, prediction speed, and geographic area covered by prediction) for each ATDM strategy?

To answer these questions, the following hypotheses were made:

1. DMA bundles (Q-WARN and SPD-HARM) will be most cost-effective only when coupled with prediction and active management.
2. Improvements in prediction accuracy will yield higher benefits for certain ATDM strategies and combinations of strategies than for others. An ATDM strategy or combinations of strategies will yield the most benefits with improvements in prediction accuracy only under certain operational conditions.
3. Increased prediction accuracy is more critical for certain ATDM strategies over others, with certain attributes (e.g., length of prediction horizon, prediction accuracy, prediction speed, and geographic area covered by prediction) of prediction quality being most critical.

11.2 Analysis Approach

The first question can be answered based on the results of the simulations run to assess synergies and conflicts between SPD-HARM and Predictive Traveler Information (see Chapter 8.2.7).

In those simulations, SPD-HARM and Predictive Traveler Information were run as two independent applications, with no interchange of information between them: predictions are made without considering what speeds SPD-HARM will suggest, and SPD-HARM operates without knowing what rerouting has been triggered by predictive travel time information.

Thus, with low penetration rates of connected vehicles, the shockwave reduction is limited, and the increase of throughput reduced compared to SPD-HARM alone. As the penetration rate of connected vehicles approaches 90%, the gain in terms of shockwave reduction doesn't increase as quickly as with SPD-HARM alone, but the travel time increases significantly more.

It can be concluded that a tighter integration between Predictive Traveler Information and DMA application[18], with some interchange of information, would produce significantly better results, by allowing the prediction of shockwaves and the dissemination of anticipatory speed harmonization messages, rather than reactive.

The other two questions were answered by running the Predictive Traveler Information framework, described in Chapter 7.2.1, with response plans based on the activation of ATDM strategies. This emulates the fact that the activation of each ATDM strategy is decided based on predicted traffic conditions in a radius of 10 miles around the incident location in an anticipatory rather than reactive fashion. The ATDM strategies that are evaluated each time a prediction is made are:

- Dynamic Lane Use and Dynamic HOV/Managed Lanes
- Dynamic Speed Limits
- Dynamic Merge Control
- Combinations of two of the above strategies
- Combination of the three of them

The evaluation was performed under all four different operational conditions (see Section 3.2).

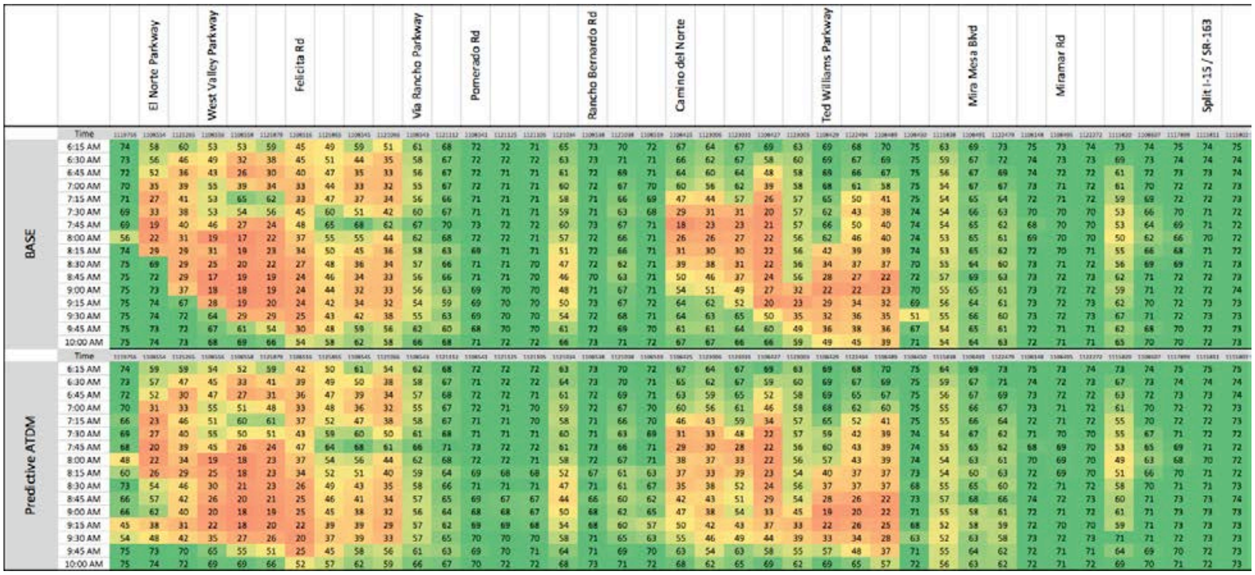
The performance measures obtained in these simulations have been compared both with the baseline case and with the scenarios evaluating the activation of each ATDM strategy in isolation.

11.2.1 Predictive Traveler Information and ATDM strategies

The simulation framework to produce simulation-based travel time predictions was configured with response plans based on the activation of individual ATDM strategies and combinations of them. Predictions were run every 5 minutes for a horizon of 30 minutes.

11.2.1.1 Operational condition 1 (AM1)

An analysis of the speed contour on I-15 in the southbound direction shows that the Predictive Traveler Information produces no significant difference in terms of congestion (Figure 11-1).



			El Norte Parkway		West Valley Parkway			Felicita Rd				Via Rancho Parkway		Pomerado Rd				Rancho Bernardo Rd			Camino del Norte					Ted Williams Parkway					Mira Mesa Blvd			Miramar Rd					Split I-15 / SR-163	
	Time	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
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	6:45 AM	72	52	36	43	26	30	40	47	35	33	56	67	72	71	71	61	72	69	71	64	60	64	48	58	69	66	67	75	56	67	69	74	72	72	61	72	73	73	74
	7:00 AM	70	35	39	55	39	34	33	44	33	32	55	67	72	71	71	60	72	67	70	60	56	62	39	58	68	61	58	75	54	67	67	73	71	72	61	70	72	72	73
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	7:30 AM	69	33	38	53	54	56	45	60	51	42	60	67	71	71	71	59	71	63	68	29	31	31	20	57	62	43	38	74	54	66	63	70	70	70	53	66	70	71	72
	7:45 AM	69	19	40	46	27	24	48	65	68	62	67	70	73	72	72	60	73	67	71	18	23	23	21	57	66	50	40	74	54	65	62	68	70	70	53	64	69	71	72
	8:00 AM	56	22	31	19	17	22	37	55	55	44	62	68	72	72	71	57	72	66	71	26	26	27	22	56	62	46	40	74	53	65	61	69	70	70	50	62	66	70	72
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	10:00 AM	75	74	72	69	69	66	52	57	62	59	66	67	70	72	72	68	73	71	72	68	62	65	69	62	69	65	57	72	56	63	62	72	71	72	69	70	71	72	73

Figure 11-1: Speed contour with Predictive Traveler Information compared with the baseline case under Operational Condition 1

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[18] This evaluation would require some change in the Windows application emulating INFLO.

If we compare network-wide traffic performance measures with Predictive Traveler Information with the baseline condition and with the activation of individual ATDM strategies (Table 11-1 and Figure 11-2), we can notice an improvement compared to the baseline, though less significant than with the constant activation of Dynamic Lane Use and Dynamic Managed Lanes alone. This is because the predictive engine in some time intervals recommended the concurrent activation of Dynamic Merge Control or Variable Speed Limit, which, as described in Chapter 8, have the effect of worsening the overall traffic performance to favor the merge from SR-78 or to reduce shockwaves.

Table 11-1: Performance measures with Predictive Traveler Information compared with the baseline case and with the activation of individual ATDM strategies under Operational Condition 1

Network Statistics	Base	Predictive ATDM	Difference	Dyn Lane Use + Dyn Managed Lanes	Difference	Dynamic Speed Limit	Difference	Dynamic Merge Control	Difference
Vehicle Miles Traveled (mi)	2,320,947	2,322,987	0.1%	2,325,470	0.2%	2,295,970	-1.1%	2,315,264	-0.2%
Total Travel Time (h)	61,946	61,362	-0.9%	60,953	-1.6%	63,713	2.9%	65,191	5.2%
Passenger Hourly Travel Time (h)	78,635	78,050	-0.7%	77,591	-1.3%	80,972	3.0%	83,511	6.2%
VMT/VHT (mi/h)	37.47	37.86	1.0%	38.15	1.8%	36.04	-3.8%	35.52	-5.2%

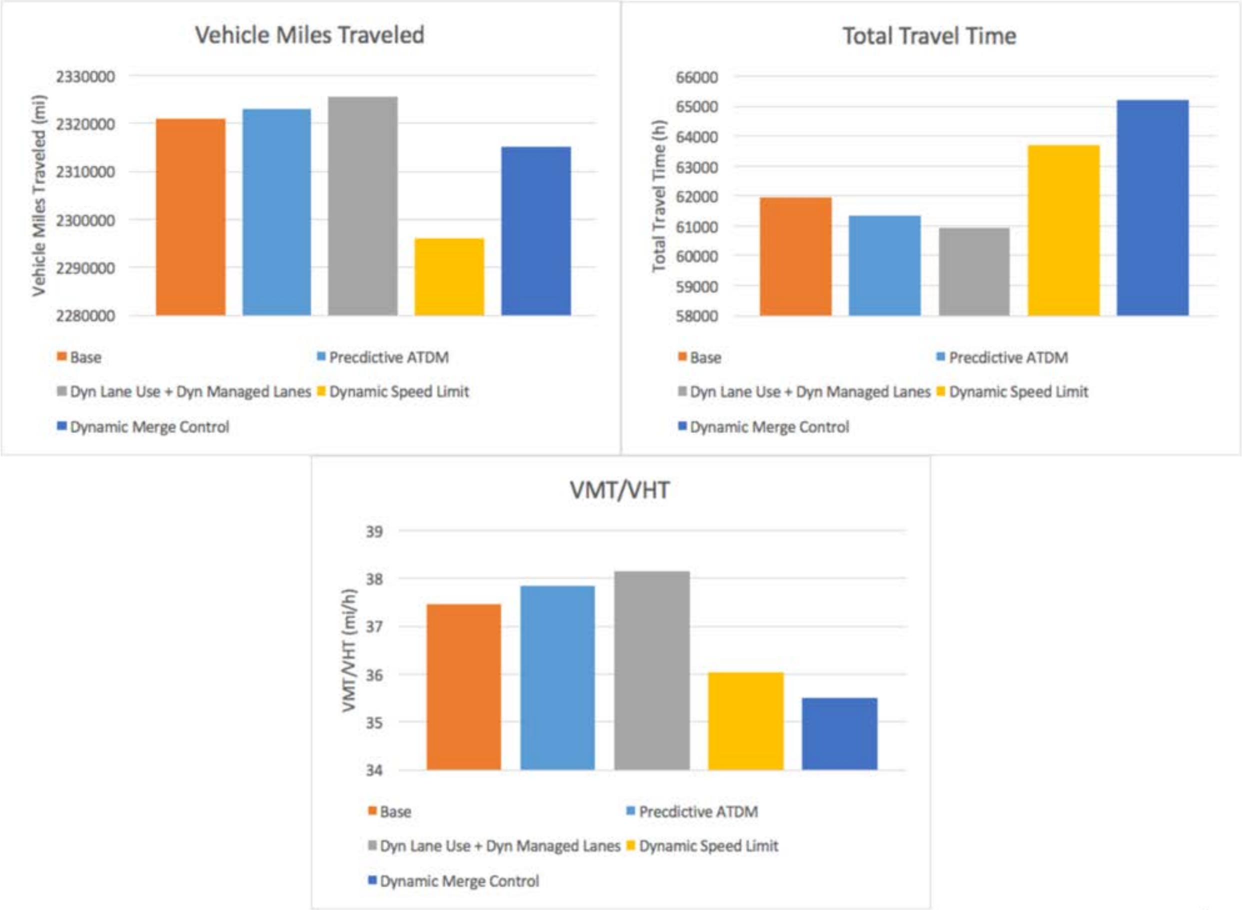


Figure 11-2: Performance measures with Predictive Traveler Information compared with the baseline case and with the activation of individual ATDM strategies under Operational Condition 1

11.2.1.2 Operational condition 2 (AM2)

An analysis of the speed contour on I-15 in the southbound direction shows that the Predictive Traveler Information slightly reduces the congestion in the southern part of the corridor (Figure 11-3).

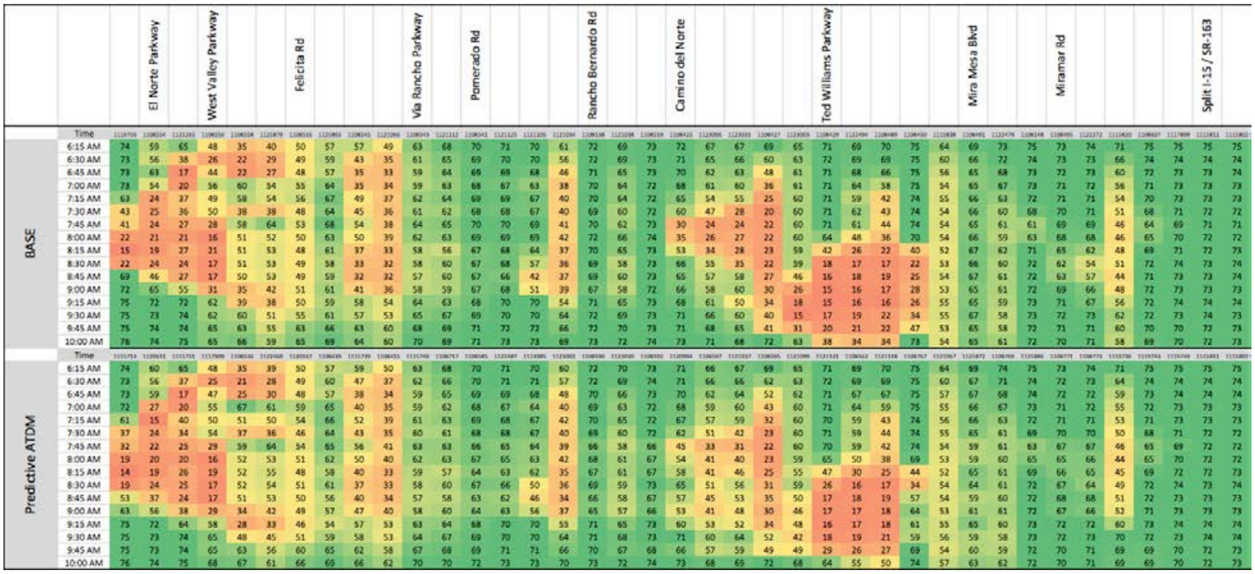


Figure 11-3: Speed contour with Predictive Traveler Information compared with the baseline case under Operational Condition 2

If we compare network-wide traffic performance measures with Predictive Traveler Information with the baseline condition and with the activation of individual ATDM strategies (Table 11-2 and Figure 11-4), we can notice that the difference with the baseline is negligible.

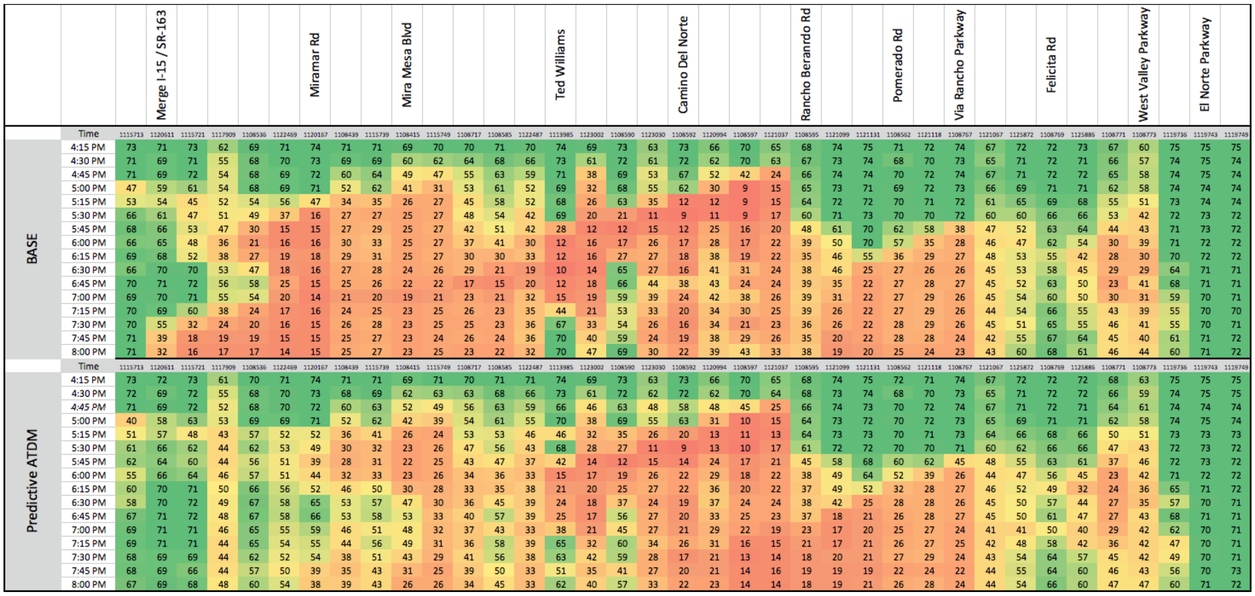
Table 11-2: Performance measures with Predictive Traveler Information compared with the baseline case and with the activation of individual ATDM strategies under Operational Condition 2

Network Statistics	Base	Predictive ATDM	Difference	Dyn Lane Use + Dyn Managed Lanes	Difference	Dynamic Speed Limit	Difference	Dynamic Merge Control	Difference
Vehicle Miles Traveled (mi)	2,304,353	2,309,786	0.2%	2,313,228	0.4%	2,281,850	-1.0%	2,305,441	0.0%
Total Travel Time (h)	61,509	61,462	-0.1%	60,683	-1.3%	63,446	3.1%	64,540	4.9%
Passenger Hourly Travel Time (h)	78,853	78,985	0.2%	77,762	-1.4%	81,278	3.1%	82,905	5.1%
VMT/VHT (mi/h)	37.46	37.58	0.3%	38.12	1.8%	35.97	-4.0%	35.72	-4.7%

Figure 11-4: Performance measures with Predictive Traveler Information compared with the baseline case and with the activation of individual ATDM strategies under Operational Condition 2

11.2.1.3 *Operational condition 3 (PM3)*

An analysis of the speed contour on I-15 in the southbound direction shows that the Predictive Traveler Information slightly reduces the congestion in the southern part of the corridor (Figure 11-5).



			Merge I-15 / SR-163					Miramar Rd			Mira Mesa Blvd					Ted Williams				Camino Del Norte			Rancho Berandro Rd			Pomerado Rd		Via Rancho Parkway			Felicita Rd			West Valley Parkway		El Norte Parkway	
	Time	1115713	1120611	1115721	1117909	1108536	1122469	1120167	1108439	1115739	1108415	1115749	1108717	1108585	1122487	1113985	1123002	1108590	1123030	1108592	1120994	1108597	1121037	1108595	1121099	1121131	1108562	1121118	1108767	1121067	1125872	1108769	1125886	1108771	1108773	1119736	1119743	1119749
BASE	4:15 PM	73	71	73	62	69	71	74	71	71	69	70	70	71	70	74	69	73	63	73	66	70	65	68	74	75	71	72	74	67	72	72	73	67	60	75	75	75
	4:30 PM	71	69	71	55	68	70	73	69	69	60	62	64	68	66	73	61	72	61	72	62	70	63	67	73	74	68	70	73	65	71	72	71	66	57	74	75	74
	4:45 PM	71	69	72	54	68	69	72	60	64	49	47	55	63	59	71	38	69	53	67	52	42	24	66	74	74	70	72	74	67	71	72	72	65	58	74	75	74
	5:00 PM	47	59	61	54	68	69	71	52	62	41	31	53	61	52	69	32	68	55	62	30	9	15	65	73	71	69	72	73	66	69	71	71	62	58	74	74	74
	5:15 PM	53	54	45	52	54	56	47	34	35	26	27	45	58	52	68	26	63	35	12	12	9	15	64	72	72	70	71	72	61	65	69	68	55	51	73	74	74
	5:30 PM	66	61	47	51	49	37	16	27	27	25	27	48	54	42	69	20	21	11	9	11	9	17	60	71	73	70	70	72	60	60	66	66	53	42	72	73	72
	5:45 PM	68	66	53	47	30	15	15	27	29	25	27	42	51	42	28	12	12	15	12	25	16	20	48	61	70	62	58	38	47	52	63	64	44	43	71	73	72
	6:00 PM	66	65	48	36	21	16	16	30	33	25	27	37	41	30	12	16	17	26	17	28	17	22	39	50	70	57	35	28	46	47	62	54	30	39	71	72	72
	6:15 PM	69	68	52	38	27	19	18	29	31	25	27	30	30	33	12	16	27	27	18	38	19	22	35	46	55	36	29	27	48	53	55	42	28	30	70	72	72
	6:30 PM	66	70	70	53	47	18	16	27	28	24	26	29	21	19	10	14	65	27	16	41	31	24	38	46	25	27	26	26	45	53	58	45	29	29	64	71	71
	6:45 PM	70	71	72	56	58	25	15	25	26	22	22	17	15	20	12	18	66	44	38	43	24	24	39	35	22	27	28	27	45	52	63	50	23	41	68	71	71
	7:00 PM	69	70	71	55	54	20	14	21	20	19	21	23	21	32	15	19	59	39	24	42	38	26	39	31	22	27	29	26	45	54	60	50	30	31	59	70	71
	7:15 PM	70	69	60	38	24	17	16	24	25	23	25	26	23	35	44	21	53	33	20	34	30	25	39	26	22	27	29	26	44	54	66	55	43	39	55	70	70
	7:30 PM	70	55	32	24	20	16	15	26	28	23	25	25	23	36	67	33	54	26	16	34	21	23	36	26	22	28	29	26	45	51	65	55	46	41	55	70	71
	7:45 PM	71	39	18	19	19	15	15	25	27	23	24	26	24	36	70	40	59	24	19	38	29	26	35	20	22	28	28	24	42	55	67	64	45	40	61	71	72
	8:00 PM	71	32	16	17	17	14	15	25	27	23	25	23	22	32	70	47	69	30	22	39	43	33	38	19	20	25	24	23	43	60	68	61	46	44	60	71	72
	Time	1115713	1120611	1115721	1117909	1108536	1122469	1120167	1108439	1115739	1108415	1115749	1108717	1108585	1122487	1113985	1123002	1108590	1123030	1108592	1120994	1108597	1121037	1108595	1121099	1121131	1108562	1121118	1108767	1121067	1125872	1108769	1125886	1108771	1108773	1119736	1119743	1119749
Predictive ATDM	4:15 PM	73	72	73	61	70	71	74	71	71	69	71	70	71	71	74	69	73	63	73	66	70	65	68	74	75	72	71	74	67	72	72	72	68	63	75	75	75
	4:30 PM	72	69	72	55	68	70	73	68	69	62	63	63	68	66	73	61	72	62	72	62	70	64	68	73	74	68	70	73	65	71	72	72	66	59	74	75	75
	4:45 PM	71	69	72	52	68	70	72	60	63	52	49	56	63	59	66	46	63	48	58	48	45	25	66	74	73	70	72	74	67	71	72	71	64	61	74	74	74
	5:00 PM	40	58	63	53	69	69	71	52	62	42	39	54	61	55	70	38	69	55	63	31	10	15	64	73	72	70	72	73	65	69	71	71	62	58	74	75	74
	5:15 PM	51	57	48	43	57	52	52	36	41	26	24	53	53	46	46	32	35	26	20	13	11	13	64	73	73	70	71	73	64	66	68	66	50	51	73	73	73
	5:30 PM	61	66	62	44	62	53	49	30	32	23	26	47	56	43	68	28	27	11	9	13	10	17	61	72	72	70	70	71	60	62	66	66	47	43	72	73	72
	5:45 PM	62	64	60	44	56	51	39	28	31	22	25	43	47	37	42	14	12	15	14	24	17	21	45	58	68	60	62	45	48	55	63	61	37	46	72	73	72
	6:00 PM	55	66	64	46	57	51	44	32	33	23	26	34	36	33	15	17	19	26	22	29	18	22	38	49	64	52	39	26	44	47	56	45	23	42	71	72	72
	6:15 PM	60	70	71	50	66	56	52	46	50	30	28	33	35	38	21	20	25	27	22	36	20	22	37	49	52	32	28	27	46	52	49	32	24	36	65	71	72
	6:30 PM	58	70	72	49	67	58	65	53	57	47	30	36	45	39	24	18	37	24	19	37	24	24	38	42	25	28	28	26	45	50	57	44	27	35	57	70	71
	6:45 PM	67	71	72	48	67	58	66	53	58	53	33	40	57	39	25	17	56	27	20	33	25	23	37	18	21	26	28	27	45	50	61	47	27	43	68	71	71
	7:00 PM	69	71	71	46	65	55	59	46	51	48	32	37	43	33	38	21	45	27	21	29	22	19	23	17	20	25	27	24	41	41	50	40	29	42	62	70	71
	7:15 PM	69	71	71	44	65	54	55	44	56	49	31	36	58	39	65	32	60	34	26	31	16	15	21	17	21	26	27	25	42	48	58	42	36	42	47	70	71
	7:30 PM	68	69	69	44	62	52	54	38	51	43	29	41	56	38	63	42	59	28	17	21	13	14	18	20	21	27	29	24	43	54	64	57	45	42	49	70	71
	7:45 PM	68	69	66	44	57	50	39	35	43	31	25	39	50	33	51	35	41	27	20	21	14	16	19	19	19	22	24	22	44	55	64	60	46	43	56	70	73
	8:00 PM	67	69	68	48	60	54	38	39	43	26	26	34	45	33	62	40	57	33	22	23	14	14	18	19	21	26	28	24	44	54	66	60	47	47	60	71	72

Figure 11-5: Speed contour with Predictive Traveler Information compared with the baseline case under Operational Condition 3

If we compare network-wide traffic performance measures with Predictive Traveler Information with the baseline condition and with the activation of individual ATDM strategies (Table 11-3 and Figure 11-6), we can notice that the difference with base can only be observed in terms of travel time and the order of magnitude is approximately half of what the constant activation of Dynamic Lane Use and Dynamic Managed Lanes. The reason is that Predictive Traveler Information activates Dynamic Lane Use and Dynamic Managed Lanes sometimes in concurrence with Variable Speed Limit, which has the effect of lowering the speed, hence compensating in part the benefit of Dynamic Lane Use and Dynamic Managed Lanes.

Table 11-3: Performance measures with Predictive Traveler Information compared with the baseline case and with the activation of individual ATDM strategies under Operational Condition 3

Network Statistics	**Base**	**Predictive ATDM**	**Difference**	**Dyn Lane Use + Dyn Managed Lanes**	**Difference**	**Dynamic Speed Limit**	**Difference**
Vehicle Miles Traveled (mi)	2,518,604	2,520,906	0.1%	2,531,493	0.5%	2,447,851	-2.8%
Total Travel Time (h)	76,531	75,043	-1.9%	73,529	-3.9%	77,953	1.9%
Passenger Hourly Travel Time (h)	99,052	97,794	-1.3%	95,937	-3.1%	100,604	1.6%
VMT/VHT (mi/h)	32.91	33.59	2.1%	34.43	4.6%	31.40	-4.6%

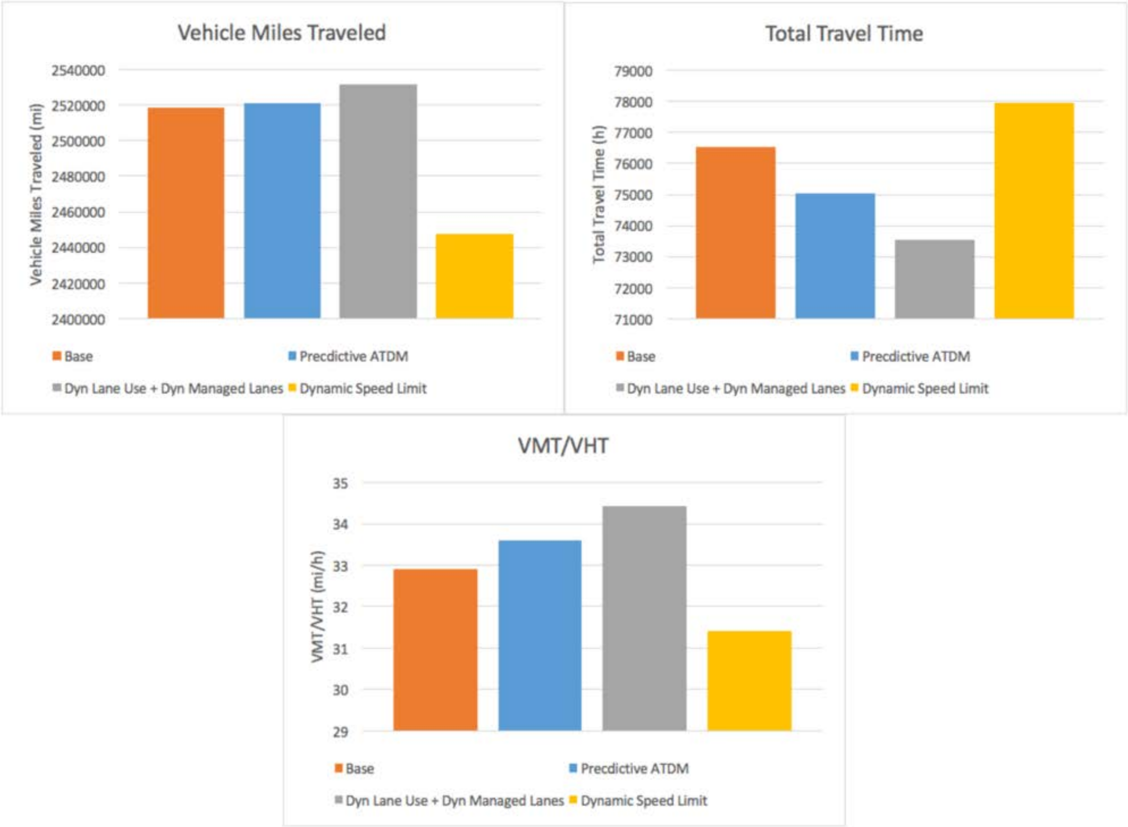
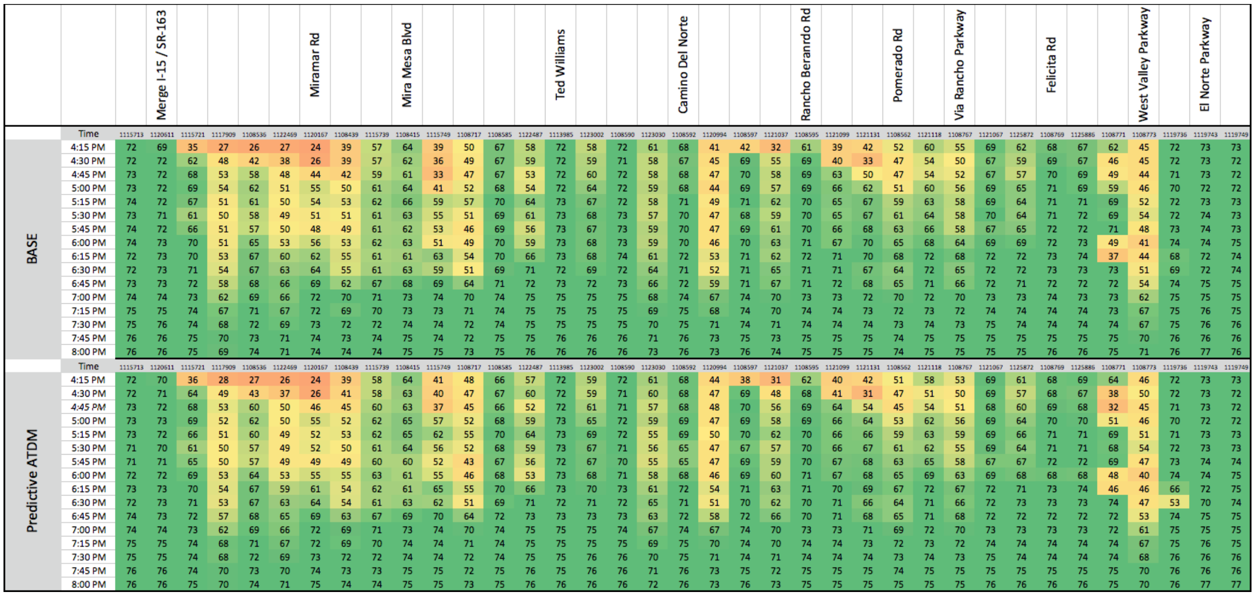


Figure 11-6: Performance measures with Predictive Traveler Information compared with the baseline case and with the activation of individual ATDM strategies under Operational Condition 3

11.2.1.4 Operational condition 4 (PM4)

An analysis of the speed contour on I-15 in the southbound direction shows that the Predictive Traveler Information produces no significant difference in terms of congestion (Figure 11-7).



			Merge I-15 / SR-163					Miramar Rd			Mira Mesa Blvd					Ted Williams				Camino Del Norte				Rancho Berarndo Rd			Pomerado Rd		Via Rancho Parkway			Felicita Rd			West Valley Parkway		El Norte Parkway	
	Time	1115713	1120611	1115721	1117909	1108536	1122469	1120167	1108439	1115739	1108415	1115749	1108717	1108585	1122487	1113985	1123002	1108590	1123030	1108592	1120994	1108597	1121037	1108595	1121099	1121131	1108562	1121118	1108767	1121067	1125872	1108769	1125886	1108771	1108773	1119736	1119743	1119749
BASE	4:15 PM	72	69	35	27	26	27	24	39	57	64	39	50	67	58	72	58	72	61	68	41	42	32	61	39	42	52	60	55	69	62	68	67	62	45	72	73	73
	4:30 PM	72	72	62	48	42	38	26	39	57	62	36	49	67	59	72	59	71	58	67	45	69	55	69	40	33	47	54	50	67	59	69	67	46	45	72	73	72
	4:45 PM	73	72	68	53	58	48	44	42	59	61	33	47	67	53	72	60	72	58	68	47	70	58	69	63	50	47	54	52	67	57	70	69	49	44	71	73	72
	5:00 PM	73	72	69	54	62	51	55	50	61	64	41	52	68	54	72	64	72	59	68	44	69	57	69	66	62	51	60	56	69	65	71	69	59	46	70	72	72
	5:15 PM	74	72	67	51	61	50	54	53	62	66	59	57	70	64	73	67	72	58	71	49	71	62	70	65	67	59	63	58	69	64	71	71	69	52	72	73	73
	5:30 PM	73	71	61	50	58	49	51	51	61	63	55	51	69	61	73	68	73	57	70	47	68	59	70	65	67	61	64	58	70	64	71	72	69	54	72	74	73
	5:45 PM	74	72	66	51	57	50	48	49	61	62	53	46	69	56	73	67	73	59	70	47	69	61	70	66	68	63	66	58	67	65	72	72	71	48	73	74	73
	6:00 PM	74	73	70	51	65	53	56	53	62	63	51	49	70	59	73	68	73	59	70	46	70	63	71	67	70	65	68	64	69	69	72	73	49	41	74	74	75
	6:15 PM	72	73	70	53	67	60	62	55	61	61	63	54	70	66	73	68	74	61	72	53	71	62	72	71	70	68	72	68	72	72	73	74	37	44	68	72	74
	6:30 PM	72	73	71	54	67	63	64	55	61	63	59	51	69	71	72	69	72	64	71	52	71	65	71	71	67	64	72	65	72	72	73	73	73	51	69	72	74
	6:45 PM	73	73	72	58	68	66	69	62	67	68	69	64	71	72	73	72	73	66	72	59	71	67	71	72	68	65	71	66	72	71	72	72	72	54	74	75	75
	7:00 PM	74	74	73	62	69	66	72	70	71	73	74	70	74	75	75	75	75	68	74	67	74	70	73	73	72	70	72	70	73	73	74	73	73	62	75	75	75
	7:15 PM	75	75	74	67	71	67	72	69	70	73	73	71	74	75	75	75	75	69	75	68	74	70	74	74	73	72	73	72	74	74	74	74	73	67	75	76	75
	7:30 PM	75	76	74	68	72	69	73	72	72	74	74	72	74	75	75	75	75	70	75	71	74	71	74	74	74	73	74	73	75	74	74	74	74	67	75	76	76
	7:45 PM	76	76	75	70	73	71	74	73	74	75	74	72	75	75	76	76	76	71	76	73	75	73	75	75	75	74	75	75	75	75	75	75	75	70	76	76	76
	8:00 PM	76	76	75	69	74	71	74	74	74	75	75	73	75	76	76	76	76	73	76	73	76	74	75	75	75	74	75	75	75	75	76	76	75	71	76	77	76
	Time	1115713	1120611	1115721	1117909	1108536	1122469	1120167	1108439	1115739	1108415	1115749	1108717	1108585	1122487	1113985	1123002	1108590	1123030	1108592	1120994	1108597	1121037	1108595	1121099	1121131	1108562	1121118	1108767	1121067	1125872	1108769	1125886	1108771	1108773	1119736	1119743	1119749
Predictive ATDM	4:15 PM	72	70	36	28	27	26	24	39	58	64	41	48	66	57	72	59	72	61	68	44	38	31	62	40	42	51	58	53	69	61	68	69	64	46	72	73	73
	4:30 PM	72	71	64	49	43	37	26	41	58	63	40	47	67	60	72	59	71	60	68	47	69	48	68	41	31	47	51	50	69	57	68	67	38	50	72	73	72
	4:45 PM	73	72	68	53	60	50	46	45	60	63	37	45	66	52	72	61	71	57	68	48	70	56	69	64	54	45	54	51	68	60	69	68	32	45	71	73	72
	5:00 PM	73	73	69	52	62	50	55	52	62	65	57	52	68	59	73	65	72	59	69	47	69	58	69	66	64	53	62	56	69	64	70	70	51	46	70	72	72
	5:15 PM	73	72	66	51	60	49	52	53	62	65	62	55	70	64	73	69	72	55	69	50	70	62	70	66	66	59	63	59	69	66	71	71	69	51	71	73	73
	5:30 PM	71	70	61	50	57	49	52	50	61	64	56	52	68	59	73	67	71	56	65	47	67	57	70	66	67	61	62	55	69	64	71	71	68	54	72	73	73
	5:45 PM	71	71	65	50	57	49	49	49	60	60	52	43	67	56	72	67	70	55	65	47	69	59	70	67	68	63	65	58	67	67	72	72	69	47	73	74	74
	6:00 PM	72	72	69	53	64	53	55	55	63	61	55	46	68	53	73	68	71	58	68	46	69	60	71	67	68	65	69	63	69	68	68	68	48	40	74	74	75
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	6:30 PM	72	73	71	53	67	63	64	54	61	63	62	51	69	71	72	71	72	65	71	51	70	62	70	71	66	64	71	66	72	73	73	73	74	47	53	70	74
	6:45 PM	74	73	72	57	68	65	69	63	67	69	70	64	72	73	73	73	73	63	72	58	72	66	70	71	68	65	71	68	72	72	72	72	72	53	74	75	75
	7:00 PM	74	74	73	62	69	66	72	69	71	73	74	70	74	75	75	75	74	67	74	67	74	70	73	73	71	69	72	70	73	73	73	73	72	61	75	75	75
	7:15 PM	75	75	74	68	71	67	72	69	70	74	74	71	74	75	75	75	75	69	75	70	74	70	74	74	73	72	73	72	74	74	74	74	74	67	75	76	75
	7:30 PM	75	75	74	68	72	69	73	72	72	74	74	72	74	75	75	76	76	70	75	71	74	71	74	74	74	73	74	73	75	74	74	74	74	68	76	76	76
	7:45 PM	76	76	74	70	73	70	74	73	73	75	75	72	75	76	75	76	76	71	76	73	75	72	75	75	75	74	75	75	75	75	75	75	75	70	76	76	76
	8:00 PM	76	76	75	70	74	71	75	74	74	75	75	73	75	76	76	76	76	72	76	73	76	73	75	75	75	75	75	75	76	76	76	76	75	70	76	77	77

Figure 11-7: Speed contour with Predictive Traveler Information compared with the baseline case under Operational Condition 4

If we compare network-wide traffic performance measures with Predictive Traveler Information with the baseline condition (Table 11-4 and Figure 11-8), we can notice that the difference is not significant. This is because this operational condition is characterized by almost no congestion, therefore most of the time no ATDM strategies are activated. If we compare with the activation of individual ATDM strategies, we can notice a slight improvement, which can be interpreted as follows: when there is no significant and sustained congestion, a constant and scheduled activation of an ATDM strategy may be ineffective or even counterproductive; the prediction allows a constant monitoring of the traffic condition to determine whether and when it each strategy should be activated.

Table 11-4: Performance measures with Predictive Traveler Information compared with the baseline case and with the activation of individual ATDM strategies under Operational Condition 4

Network Statistics	Base	Predictive ATDM	Difference	Dyn Lane Use + Dyn Managed lanes	Difference	Dynamic Speed Limit	Difference
Vehicle Miles Traveled (mi)	2,302,897	2,302,802	0.0%	2,301,997	0.0%	2,302,937	0.0%
Total Travel Time (h)	57,547	57,467	-0.1%	57,589	0.1%	58,476	1.6%
Passenger Hourly Travel Time (h)	75,856	75,809	-0.1%	75,918	0.1%	76,910	1.4%
VMT/VHT (mi/h)	40.02	40.07	0.1%	39.97	-0.1%	39.38	-1.6%

Figure 11-8: Performance measures with Predictive Traveler Information compared with the baseline case and with the activation of individual ATDM strategies under Operational Condition 4

11.2.1.5 Comparison between operational conditions

If we look at the results of operational conditions with more severe incidents and sustained congestion, we see that the predictions continuously activate ATDM strategies that increase the throughput, and the result in terms of traffic performance is similar to the constant activation of those strategies; if we look at the results of operational conditions with less congestion, we see that the predictions most of the time do not activate any ATDM strategies, and the result in terms of traffic performance is better than the constant activation of those strategies.

The conclusion is that on the corridor in which the evaluation was performed, predictions did not seem to increase the effectiveness of the ATDM strategies that were tested; however, predictions proved to be valuable to determine whether and when those strategies should be activated, rather than relying on a fixed schedule or on a trigger that reacts to the congestion when it is already formed.

11.3 Summary of Results

On the corridor in which the evaluation was performed, predictions did not seem to increase the effectiveness of the ATDM strategies that were tested, but they proved to be valuable to determine whether and when those strategies should be activated, rather than relying on a fixed schedule or on a trigger that reacts to the congestion when it is already formed.

Chapter 12. Deployment Readiness and Policy

This chapter deals with the impact of penetration rate on the effectiveness of DMA applications, bundles of applications and combinations of applications that specifically target connected vehicles, and with their effect on non-connected vehicles.

12.1 Research Questions

The following research questions are answered using this analysis:

1. At what levels of market penetration of connected vehicle technology do the DMA bundles (collectively or independently) become effective?
2. What are the impacts of future deployments of the DMA bundles in the near, mid, and long term (varying market penetration, RSE deployment density, and other connected vehicle assumptions)?
3. What are the benefits to participants versus non-participants?

To answer these questions, the following hypotheses were made:

1. As market penetration increases, the applications will perform better, but it is anticipated that 50 percent market penetration will provide most of the benefits, beyond which the increase in benefits will taper off.
2. Bundles that influence tactical driver decision-making and depend on emerging localized low-latency messaging concepts, e.g., MMITSS, Q-WARN and SPD-HARM, will yield measureable localized benefits under near-term deployment assumptions, but limited system-level impacts until market penetration of connected vehicle technology reaches bundle-specific thresholds.
3. Applications such as MMITSS will yield more benefits for participants whereas applications such as INFLO will benefit both participants and non-participants.

12.2 Analysis Approach

These questions can be answered by comparing the results with different penetration rates of the simulations run to evaluate DMA applications in isolation under different operational conditions (Chapter 9), and of the simulations run to assess synergies and conflicts of DMA applications (Chapter 8).

12.2.1 SPD-HARM

SPD-HARM starts showing benefits in terms of shockwave reduction at lower penetration rates, especially if there is enough congestion: under congested conditions the density is high enough to make the control of the speed of a subset of the vehicles affect the driving speed of all the vehicles around. It is therefore expected that this application will produce an increase of safety during peak hours already with 25% penetration rate; the benefit will be more significant as the penetration rate increases, and with 90% penetration rate it will be perceived also under non-congested conditions.

SPD-HARM benefits both participant and non-participants, if the penetration rate is high enough (at least 50%) and there is congestion: under these conditions, even if just a portion of the vehicles receives the messages and adapt its speed, the rest of traffic is also forced to adapt to their speed, and therefore the shockwave reduction benefits all vehicles.

12.2.2 CACC

CACC generally requires higher penetration rates to show its effectiveness; as for SPD-HARM, the higher the congestion, the lower the penetration rate that starts showing benefits.

An interesting phenomenon that could be noticed in the simulations[19] is that with lanes used by CACC and non-connected vehicles at the same time, penetration rates around 50% are critical and may actually produce worse overall traffic performance compared to lower or higher penetration rates: at the lowest penetration rates CACC vehicles are a minority and form shorter platoons, hence they don’t get to the point of producing an obstacle for lane changing of non-connected vehicles; at the highest penetration rates CACC vehicles are the majority of the traffic, so even if their platoons may make lane-changing for non-connected vehicles more challenging, the latter are a minority and cannot impact the overall traffic performance; however, around 50% penetration rate CACC vehicles already form platoons that are long enough to obstacle lane changing of non-connected vehicles, and there are enough non-connected vehicles that are impacted and have to reduce the speed looking for a suitable gap, which causes areas of congestion close to on and off-ramps and to weaving areas.

This phenomenon is even more evident if SPD-HARM and CACC are activated concurrently, because the speed control, which affects only connected vehicles, increases the desire for non-connected vehicles, which are not affected by SPD-HARM, to overtake connected vehicles, thus producing more lane-changing.

CACC mostly benefits participants, which can keep shorter headways, and hence experience less congestion thanks to the increase of throughput, and higher safety, thanks to the anticipatory effect of speed reduction through the platoon.

Indirect benefits for non-participants may be expected, as the increase of throughput and thus reduction of congestion implies a better travel speed for all vehicles, but are more difficult to assess, as the increase of throughput in a corridor may attract additional traffic.

The lane utilization policy for CACC platoons proved to have an impact on the benefits produced by this application. For example, can they use any of the available lanes or should they be forced to stay on a subset of them? Should non-connected vehicles be allowed to use these lanes or should they be exclusively dedicated to CACC platoons? On one hand, pushing CACC vehicles to a subset of the lanes promotes the formation of platoons, but on the other hand, long platoons may be an obstacle for non-connected vehicles to maneuver. Based on the results of the simulations, it is expected that reserving a subset of the lanes for CACC vehicles is beneficial at lower penetration rates, while at 50% penetration rate and above, allowing CACC vehicles to use any of the lanes allows the creation of shorter and more distributed platoons that cause less of an obstacle for non-connected vehicles.

Another critical aspect that has been highlighted by the simulations is that with mixed connected and non-connected traffic and without an explicit rule to promote lane-changing cooperation, at penetration rates around 50% the CACC platoons may making lane-changing and overtaking more difficult for non-connected vehicles, thus causing detrimental effects on the overall traffic performance.

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[19] It is worth noting that what has been evaluated is not CACC technology in general, but a specific CACC algorithm.

12.3 Summary of Results

All applications targeting connected vehicles produce higher benefits as the penetration rate increases; the more congested the traffic condition, the lower the penetration rate that starts showing some benefit.

SPD-HARM starts being effective in terms of shockwave reduction at 25% penetration rate, especially when the traffic is dense, while CACC requires penetration rates higher than 50% to have a positive impact on the traffic performance. At the same time, the 50% penetration rate for CACC proved to be the most critical, as with an even mixture of connected and non-connected vehicles, lane changing problems caused by compact CACC platoons on non-connected vehicles will expectedly increase the congestion around on and off-ramps and weavings.

SPD-HARM benefits both participant and non-participants. If the penetration rate is high enough and there is congestion: under these conditions, even if just a portion of the vehicles receives the messages and adapt its speed, then the rest of the traffic is also forced to adapt to their speed, and therefore the shockwave reduction benefits all vehicles.

CACC mostly benefits participants, which can keep shorter headways, and hence experience less congestion thanks to the increase of throughput, and higher safety, thanks to the anticipatory effect of speed reduction through the platoon. Indirect benefits for non-participants may be expected, as the increase of throughput and thus reduction of congestion implies a better travel speed for all vehicles, but are more difficult to assess, as the increase of throughput in a corridor may attract additional traffic.

It should be noted that 50% penetration rate for CACC is expected to be the most delicate situation, especially in case CACC platoons are forced to use a subset of the lanes, but these lanes are open also to non-connected vehicles. In this situation, the formation of long platoons may cause an obstacle for lane-changing of non-connected vehicles, which are forced to reduce the speed to wait for a suitable gap, causing a disruption for all traffic.

Chapter 13. Conclusions

This report evaluates ATDM strategies and DMA applications for specific research questions on the topics of synergies and conflicts, operational conditions with most benefits, communication latency and errors, prediction and active management, deployment readiness and policy. This chapter summarizes the major findings made in this research.

13.1 Synergies and Conflicts

Combinations of DMA applications, combinations of ATDM strategies, and combinations of DMA applications and ATDM strategies were evaluated under one operational condition to find synergies and conflicts. For this purpose, the performance measures obtained in the simulations were compared both with the baseline case, in which no DMA applications nor ATDM strategies are active, and with the results of the scenarios in which an individual DMA application or ATDM strategy is active. In all these evaluations, for DMA application that are based on connected vehicles perfect communication was assumed.

Synergy between SPD-HARM and CACC appeared to be minimal: at all penetration rates the effect of SPD-HARM seems to prevail over CACC, even though the vehicles engaged by CACC are not affected by SPD-HARM messages, and in fact it seems to neutralize the benefit in terms of traffic performance that CACC produces when deployed alone.

At low penetration rates the results show some synergy in terms of shockwave reduction; however, at high penetration rates the shockwave reduction is similar to that produced by SPD-HARM alone, and at 50% penetration rate the two DMA applications seem to produce a clear conflict, with lower traffic performance than each application alone, and less shockwave reduction than SPD-HARM alone. The explanation is that at 50% penetration rate CACC platoons are long enough to constitute an impediment for lane-changing of non-connected vehicles, and the addition of SPD-HARM introduces an heterogeneity in the desired speed of different vehicles that makes the attempts of overtaking more probable, and thus exacerbates the lane-changing issue.

Dynamic Lane Use, Dynamic HOV/Managed Lanes and Dynamic Speed Limits don’t show neither a significant conflict nor a significant synergy. The increase of congestion at the entrances and exits of the HOV lanes due to the increase of demand triggered by Dynamic Lane Use, Dynamic HOV/Managed Lanes is sensed by Dynamic Speed Limits, which extends the congestion over a larger space and longer time in order to avoid abrupt speed changes. This increase of safety is obtained at the expense of throughput and travel time. Dynamic Lane Use and Dynamic HOV/Managed Lanes alone would produce better traffic performance, at the expense of safety. Dynamic Speed Limits alone would produce an increase of safety, but with a more pronounced reduction of throughput. The combined effect of having an increase of safety with less reduction of throughput can be interpreted as a good compromise, which can be considered a synergy.

Dynamic Merge Control and Dynamic HOV/Managed Lanes show a synergy: Dynamic HOV/Managed Lanes compensate the slightly negative effect in terms of traffic performance caused by Dynamic Merge Control, which facilitates the entrance from SR-78, at the expense of penalizing traffic coming from the northern boundary of the I-15 corridor in the southbound direction. In other words, the decision to activate Dynamic Merge Control or not should be dictated purely by the need to reduce queueing on the ramp coming from SR-78 rather than by overall traffic performance benefits, and if Dynamic Merge Control is activated, Dynamic HOV/Managed Lanes would compensate its slightly negative impact on throughput.

Dynamic Merge Control, Dynamic HOV/Managed Lanes and Dynamic Routing show also a synergy: Dynamic HOV/Managed Lanes and Dynamic Routing compensate the slightly negative effect in terms of traffic performance caused by Dynamic Merge Control, which facilitates the entrance from SR-78, at the expense of penalizing traffic coming from the northern boundary of the I-15 corridor in the southbound direction. Again, the decision to activate Dynamic Merge Control or not should be dictated purely by the need to reduce queueing on the ramp coming from SR-78 rather than by overall traffic performance benefits, and if Dynamic Merge Control is activated, Dynamic HOV/Managed Lanes and Dynamic Routing would compensate its slightly negative impact on throughput.

SPD-HARM and Dynamic Merge Control show also a synergy: the benefit in terms of SPD-HARM alone in terms of shockwave reduction are not affected by Dynamic Merge Control, and the throughput reduction caused by Dynamic Merge Control is compensated by SPD-HARM. Again, the decision to activate Dynamic Merge Control or not should be dictated purely by the need to reduce queueing on the ramp coming from SR-78 rather than by overall traffic performance benefits, and if Dynamic Merge Control is activated, SPD-HARM would compensate its slightly negative impact on throughput.

SPD-HARM and Dynamic Speed Limits show a synergy in terms of safety improvement: with low penetration rates of connected vehicles, the number of vehicles affected by SPD-HARM is reduced, and the activation of an ATDM strategy that targets non-connected vehicles allows producing a higher shockwave reduction. As the penetration rate of connected vehicles approaches 90%, the contribution of Dynamic Speed Limits gets less significant, though still positive.

SPD-HARM and Predictive Traveler Information don’t show good synergy: with low penetration rates of connected vehicles, the shockwave reduction is limited, and the increase of throughput reduced compared to SPD-HARM alone; as the penetration rate of connected vehicles approaches 90%, the gain in terms of shockwave reduction doesn’t increase as quickly as with SPD-HARM alone, but the travel time increases significantly more. The explanation is that predictions are made without taking into account what speeds SPD-HARM will suggest, and SPD-HARM operates without knowing what rerouting has been triggered by predictive travel time information. It is therefore expected that a tighter integration between these two ATDM strategy and DMA application, with some interchange of information, would solve the conflict identified in this analysis.

13.2 Operational Conditions with Most Benefit

Each DMA application and ATDM strategy was evaluated in isolation under four different operational condition. The performance measures obtained in the simulations was compared with the baseline case, in which no DMA applications nor ATDM strategies are active. In all the evaluations of DMA applications, which are based on connected vehicles, perfect communication was assumed. The benefits of DMA applications and ATDM strategies appeared to depend on the congestion level.

SPD-HARM generally doesn’t produce significant benefits in terms of traffic performance, but an undeniable benefit in terms of increase of safety. Its effectiveness is more evident in congested situations, when it can be appreciated already at lower penetration rates, while when the congestion is low, high penetration rates are required to produce a reduction of shockwaves. The benefit in terms of safety comes at the cost of a slight increase of travel time under all operational conditions.

CACC is more effective in congested situations, where it can produce a significant increase of throughput and reduction of travel time, even at lower penetration rates. When congestion is low, at 50% penetration rate even a slight reduction of traffic performance can be observed, because CACC platoons may cause an obstacle for non-connected vehicle that want to change lane.

The analysis of the simulations with CACC suggest also the following observations:

- Most CACC algorithms available today only deal with car-following in a single lane and with an already formed platoon:
  - Care should be taken in selecting the parameters of the CACC algorithm (for example, the gain coefficients of the controller logic, the target headway, the update frequency), as only some combinations produce a stable car-following regime.
- To produce tangible benefits in real-world conditions, CACC algorithms should deal also with other aspects of vehicle movement:
  - Managing the transition (vehicle joining or leaving the platoon) is key to avoid instabilities.
  - Managing the vehicle distribution across multiple lanes is key with multiple reserved lanes (higher penetration rates).
  - Managing the length of the platoon is key with mixed traffic, to prevent blocking non-connected vehicles.
  - Managing the lane changing is key to allow connected vehicles to take the exit they need to take and to prevent blocking non-connected vehicles.

Dynamic Lane Use and Dynamic HOV/Managed Lanes are effective only in congested situations. Additionally, the location of incidents and bottlenecks may reduce the effectiveness of this ATDM strategy, because if the congestion caused by them affects the access points to the HOV lanes, vehicles have difficulty in reaching the additional lane that allows bypassing the bottlenecks.

Dynamic Speed Limits reduce the speed change between consecutive road segments, at the expense of reducing the overall speed along the corridor. With little congestion, the impact in terms of increase of delay is negligible, while as congestion increases the increase of delay increases, too, and is coupled with a slight decrease of throughput.

Dynamic Merge Control facilitates the entrance from SR-78, at the expense of penalizing traffic coming from the northern boundary of the I-15 corridor in the southbound direction. When the I-15 traffic is lower than that entering from SR-78, this strategy has a positive overall impact on the corridor, because it reduces conflicts at the merge.

Predictive Traveler Information with Dynamic Routing is more effective with higher demand and with more severe incidents. The benefit is evident if we focus on the I-15 corridor, while if we adopt a network-wide perspective, we can notice that in some operational condition the positive impact on the speed along the I-15 corridor is in fact counterbalanced by an overall slight increase of travel time because or rerouting along the arterials.

13.3 Communication Latency and Errors

The impact of latency and message loss on SPD-HARM was evaluated under one operational condition. Two values of latency (1 and 3 seconds) and two values of message loss (10% and 20%) were tested. The results obtained were compared with those produced under perfect communication conditions to assess the impact of these communication issues.

SPD-HARM doesn’t seem to be sensitive to latency: at all penetration rates, even a latency of 3 seconds doesn’t alter the performance of this DMA application. However, it is sensitive to packet loss at lower penetration rates of connected vehicles: at the highest penetration rate even 20% message loss doesn’t alter the performance of this DMA application because the number of vehicles receiving SPD-HARM message is high; at 25% penetration rate instead the effect of just a 10% message loss can already be perceived, while at 50% penetration rate only 20% message loss can impact the shockwave reduction.

13.4 Prediction and Active Management

To assess the benefit of prediction for DMA applications, SPD-HARM and Predictive Traveler Information were run concurrently, though as two independent applications with no interchange of information between them, under one operational condition.

As a result, with low penetration rates of connected vehicles, the shockwave reduction is limited, and the increase of throughput reduced compared to SPD-HARM alone. As the penetration rate of connected vehicles approaches 90%, the gain in terms of shockwave reduction doesn’t increase as quickly as with SPD-HARM alone, but the travel time increases significantly more. It can be concluded that a tighter integration between Predictive Traveler Information and DMA application, with some interchange of information, would produce significantly better results, by allowing the prediction of shockwaves and the dissemination of anticipatory speed harmonization messages, rather than reactive.

To assess the benefit of prediction for ATDM strategies, a Predictive Traveler Information framework with response plans based on the activation of ATDM strategies in an anticipatory rather than reactive fashion was simulated under four operational conditions. Predictions do not increase the effectiveness of ATDM strategies, but they can be valuable to determine whether and when those strategies should be activated, rather than relying on a fixed schedule or on a trigger that reacts to the congestion when it is already formed.

13.5 Deployment Readiness and Policy

The simulations to evaluate the impact of DMA applications in isolation under four operational conditions and the simulations run to assess synergies and conflicts of DMA applications were run with three penetration rates (25%, 50% and 90%). All applications targeting connected vehicles produce higher benefits as the penetration rate increases; the more congested is the traffic condition, the lower is the penetration rate that starts showing some benefit. SPD-HARM start being effective in terms of shockwave reduction already at 25% penetration rate, especially when the traffic is dense, while CACC requires penetration rates higher than 50% to have a positive impact on the traffic performance. At the same time, the 50% penetration rate for CACC proved to be the most critical, as with an even mixture of connected and non-connected vehicles lane changing problems caused by compact CACC platoons on non-connected vehicles will expectedly increase the congestion around on and off-ramps and weavings.

13.6 Policy

SPD-HARM benefits both participant and non-participants, if the penetration rate is high enough and there is congestion: under these conditions, even if just a portion of the vehicles receives the messages and adapt its speed, the rest of traffic is also forced to adapt to their speed, and therefore the shockwave reduction benefits all vehicles. CACC mostly benefits participants, which can keep shorter headways, and hence experience less congestion thanks to the increase of throughput, and higher safety, thanks to the anticipatory effect of speed reduction through the platoon. Indirect benefits for non-participants may be expected, as the increase of throughput and thus reduction of congestion implies a better travel speed for all vehicles, but are more difficult to assess, as the increase of throughput in a corridor may attract additional traffic. It should be noted that 50% penetration rate for CACC is expected to be the most delicate situation, especially in case CACC platoons are forced to use a subset of the lanes, but these lanes are open also to non-connected vehicles. In this situation, the formation of long platoons may cause an obstacle for lane-changing of non-connected vehicles, which are forced to reduce the speed to wait for a suitable gap, causing a disruption for all traffic.

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