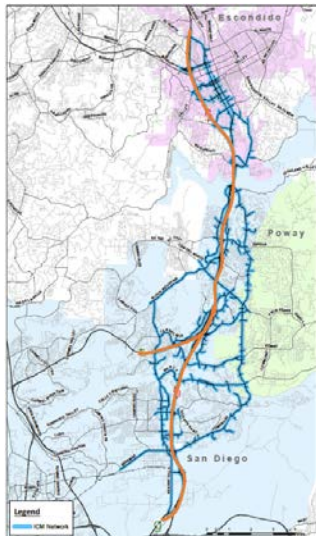# Analysis, Modeling, and Simulation (AMS) Testbed Development and Evaluation to Support Dynamic Mobility Applications (DMA) and Active Transportation and Demand Management (ATDM) Programs

Evaluation Summary for the San Diego Testbed

U.S. Department of Transportation

Produced by
Booz Allen Hamilton and TSS-Transport Simulation Systems for
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Intelligent Transportation System (ITS) Joint Program Office (JPO)

Notice

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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 summarizes the evaluations conducted on the San Diego Testbed.

To see the full results, see FHWA-JPO-16-389 (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). The report provides comprehensive documentation of the testbed development as well as the experimental results for the various traffic conditions included in the analysis.

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AMS Testbed Project Overview

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. In order 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 a number of technical risks associated with developing an AMS Testbed which can facilitate detailed evaluation of the DMA and ATDM concepts. Rather than a single Testbed, it is desirable to identify a portfolio of AMS Testbeds in order 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. At the conclusion of the initial selection process, six testbeds were selected to form a diversified portfolio to achieve rigorous DMA bundle and ATDM strategy evaluation. They are: (1) San Mateo, CA, (2) Pasadena, CA, (3) Dallas, TX, (4) Phoenix, AZ, (5) Chicago, IL and (6) San Diego, CA. Chicago and San Diego Testbeds were not a part of the original AMS Testbed selection process but were added later owing to their significance in covering some of the operational conditions and predictive methods that were not covered with the other four testbeds. Table 1 presents an overview of the Testbeds including their geographic details, description of the facility as well as the primary application/strategy type that is included in the Testbed.

Table 1. Overview of Testbeds

Testbed	Geographic Details	Facility Type	Applications / Strategies
San Mateo, CA	8.5-mile-long section of US 101 freeway and a parallel SR 82 arterial.	Freeway and Arterial	DMA only
Pasadena, CA	Covers an area of 11 square miles and includes two major freeways – I-210 and CA-134 along with arterials and collectors between these.	Freeways and arterial system.	DMA and ATDM
Dallas, TX	A corridor network comprised of a 21-mile-long section of US-75 freeway and associated frontage roads, transit lines, arterial streets etc.	Freeways/Arterials and Transit (Light-Rail and buses)	ATDM only
Phoenix, AZ	Covers the entire metropolitan region under Maricopa County including freeways, arterials, light rail lines etc.	Freeways/Arterials and Transit (Light-Rail and buses)	DMA and ATDM
Chicago, IL	Freeways and arterials in the downtown Chicago area including I-90, I-94, I-290.	Freeways/Arterials	DMA, ATDM and Weather-related strategies.
San Diego, CA	22 miles of I-15 freeway and associated arterial feeders covering San Diego, Poway and Escondido	Freeway and Arterial System	DMA and ATDM

The primary purpose of this report is to summarize the evaluation conducted on the **San Diego** Testbed. The full results are in the report titled San Diego Testbed Evaluation Report (FHWA-JPO-16-389). 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.

The San Diego testbed was also calibrated to four existing operational conditions. They are: (i) Southbound (AM) + Medium Demand + Medium Incident, (ii) Southbound (AM) + Medium Demand + High Incident, (iii) Northbound (PM) + Medium Demand + High Incident, and (iv) Northbound (PM) +Medium Demand + Medium Incident

The study addressed important research questions regarding the effectiveness of specific ATDM and DMA strategies under different operational conditions in a simulated testbed environment. The research questions fall under the following categories: (1) the application/strategy performance under varied operational conditions, (2) synergies and conflicts among applications, (3) impact of communication latency and errors on connected vehicle applications, and (4) impact of prediction on different ATDM strategies.

San Diego Testbed Overview

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 1.
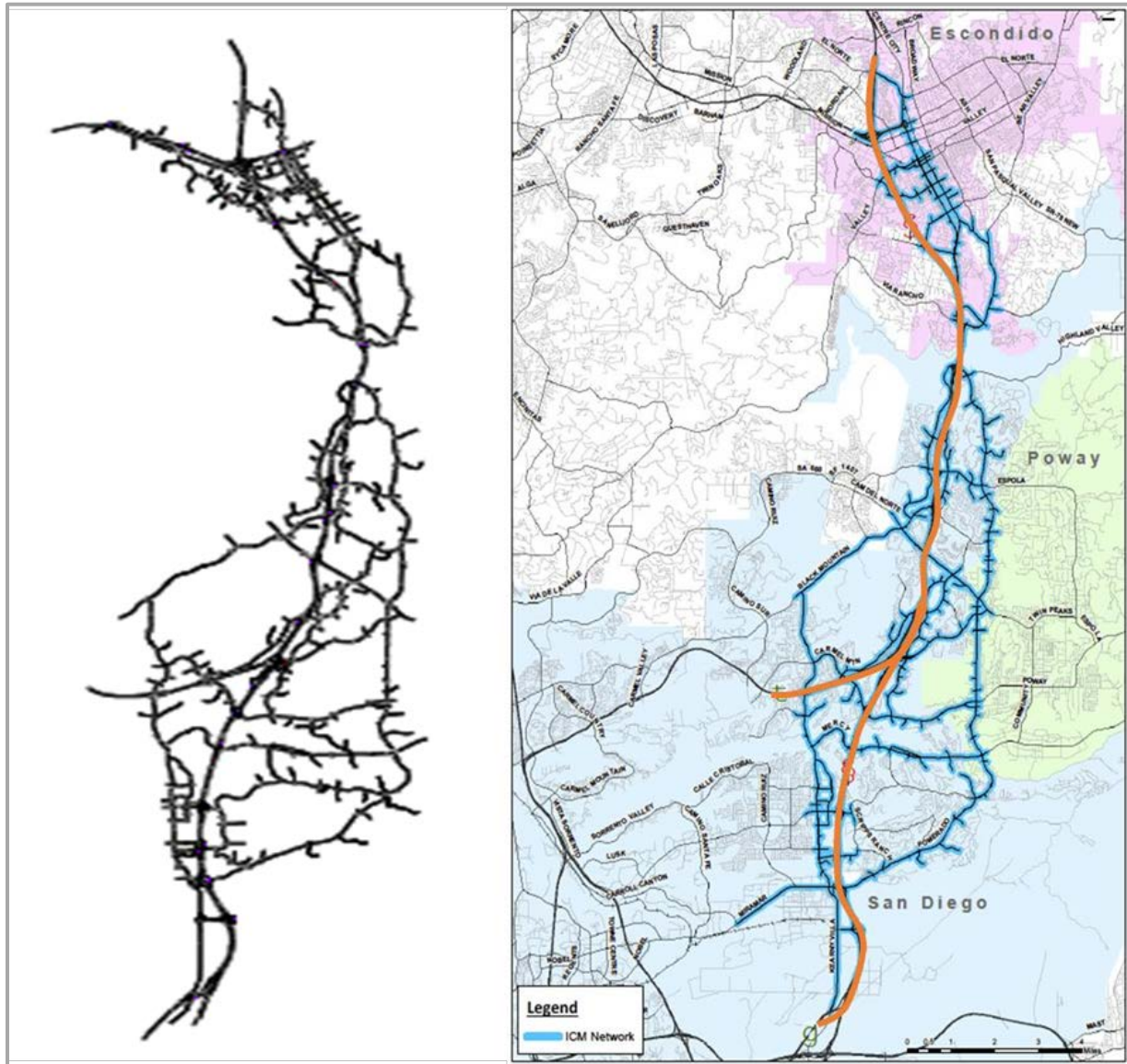

Figure 1: Map of the Extracted Network of San Diego

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.

The San Diego Testbed was developed based on the modularized structure for all AMS Testbeds as shown in Figure 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.

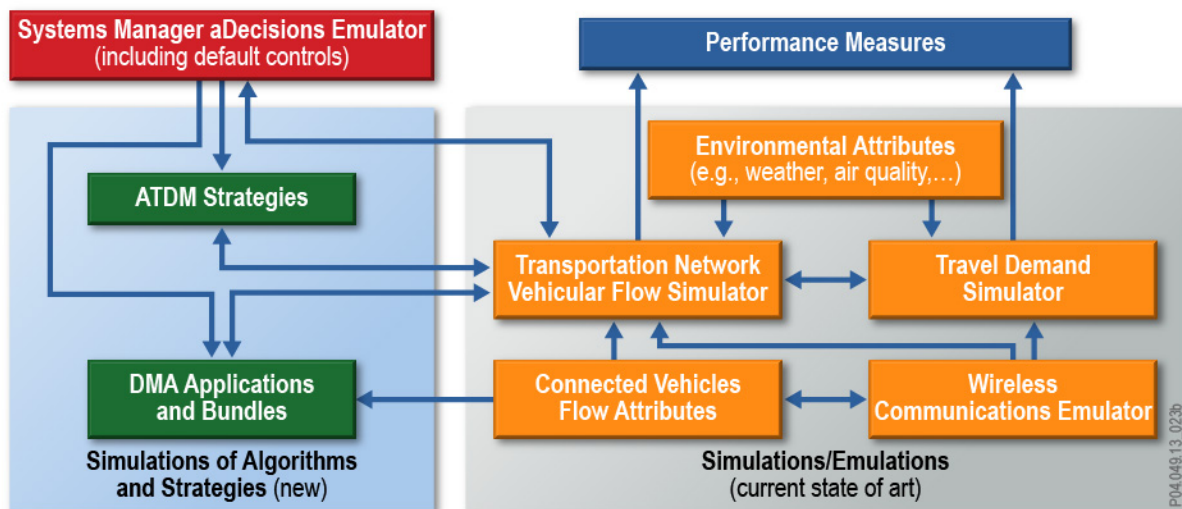**Figure 2: Generic Modeling Framework**

Figure 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.
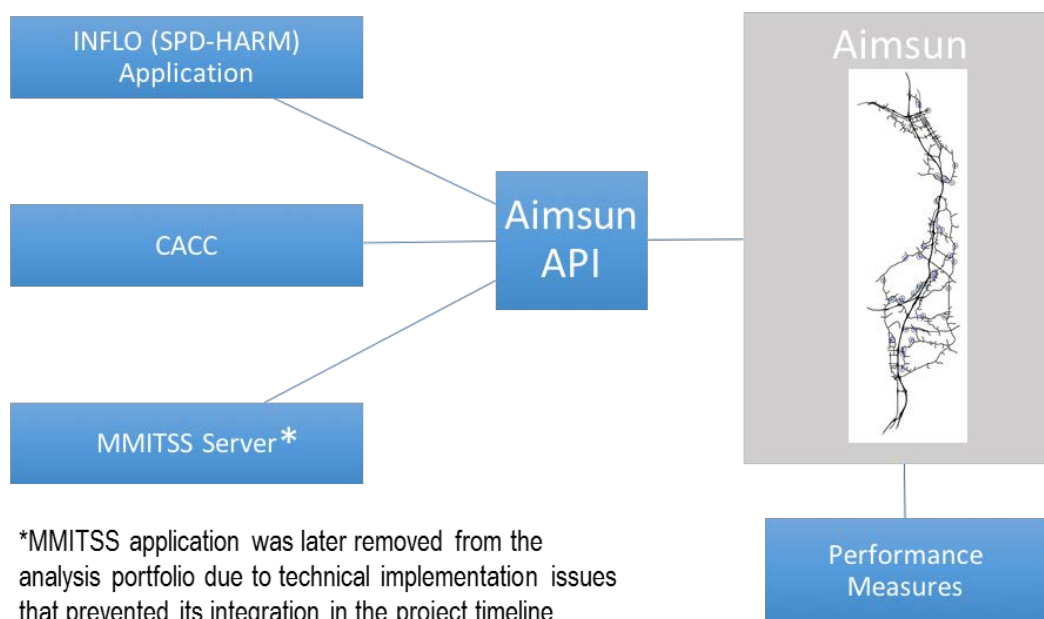
Figure 3: San Diego Testbed Modeling Framework

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 Figure 3.

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 FHWA-JPO-16-389[1].

Summary of 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

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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 Evaluation Report, USDOT Document FHWA-JPO-16-389.

analysis and the selection of operational conditions are presented in the "San Diego Testbed Analysis Plan" document (FHWA-JPO-16-375)[2].

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 2provides a description of these clusters.

Table 2: 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 2.

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)[3]. Table 3 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.

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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 Analysis Plan, USDOT Document FHWA-JPO-16-375, Accessed at: https://ntl.bts.gov/lib/61000/61100/61113/FHWA-JPO-16-375.pdf

[3] 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

Table 3: 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

DMA Applications and ATDM Strategies Modeled

The Dynamic Mobility Applications implemented and evaluated in this project are Speed Harmonization (SPD-HARM) and Cooperative Adaptive Cruise Control (CACC) within the INFLO bundle. 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 modeled similar to the USDOT Impact Assessment Project. The CACC algorithm is based on the report "Design and evaluation of an Integrated Full-Range Speed Assistant", prepared by TNO in 2007[4].

Additionally, six ATDM strategies were included in this evaluation. The three Active Traffic Management strategies implemented were Dynamic Lane Use, Dynamic Speed Limits and Dynamic Merge Control. The three Active Demand Management strategies implemented were Predictive Traveler Information, Dynamic HOV/Managed Lanes and Dynamic Routing.

For details on how these applications were incorporated in to the AMS San Diego model, readers are encouraged to refer to the full report FHWA-JPO-16-389[5]

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[4] 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
[5] 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 Evaluation Report, USDOT Document FHWA-JPO-16-389.

Summary of Findings and Conclusions

Using the San Diego Testbed, the project team modeled ATDM strategies and DMA applications for answering 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. For detailed evaluation results, readers are encouraged to refer to the full report FHWA-JPO-16-389

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 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. Dynamic Lane Use and Dynamic HOV/Managed Lanes alone would produce better traffic performance. 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 do not 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 does not 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.

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 does not 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:
  - o 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:
  - o Managing the transition (vehicle joining or leaving the platoon) is key to avoid instabilities.
  - o Managing the vehicle distribution across multiple lanes is key with multiple reserved lanes (higher penetration rates).
  - o Managing the length of the platoon is key with mixed traffic, to prevent blocking non-connected vehicles.
  - o 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.

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 does not seem to be sensitive to latency: at all penetration rates, even a latency of 3 seconds does not 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 rates, even 20% message loss does not 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 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 does not 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.

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.

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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