Dedicating Freeway Lanes for Connected and Automated Vehicle for Priority or Exclusive Use

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Abstract

Connected and Automated Vehicles (CAVs) use the data provided over the wireless communication links to and from the vehicles to support driving automation systems at any of the SAE Levels (1 to 5). Connected and Automated Vehicle (CAV) technologies are fast expanding in the transportation and automotive markets and are envisioned to bring tremendous operational, safety, environmental and institutional impact. At sizable market penetration rates (defined as the percentage of vehicles on the roadways that are equipped with CAV technologies), CAV technologies are envisioned to achieve mobility, safety, and environmental benefits for our transportation systems. By dedicating a freeway lane could facilitate the adoption of CAV technologies among vehicle owners. This paper uses a simulation based approach to assess the operational and safety impacts of the Corporative Adaptive Cruise Control (CACC) and Dynamic Speed Harmonization (DSH) applications on a dedicated lane. The maximum vehicle throughput on a dedicated lane occurs at 45% CACC market penetration with a carrying capacity of approximately 3300 vehicles per hour per lane. The highest network throughput occurs at 35% CACC market penetration. The DSH application shows a reduction in traffic shockwave at 25% market penetration. The DSH plus CACC application combination shows a synergic safety effect at 25% market penetration by further dispersing the shockwaves.

KEYWORDS: Corporative Adaptive Cruise Control, Dynamic Speed Harmonization, High Occupancy Vehicle

Introduction

Connected and automated vehicles (CAVs) are fast expanding in the automobile and transportation industry and are expected to become a significant share of the market in the next decade. Agencies are preparing themselves for this disruptive change, which can bring safety, mobility, and operational benefits. This paper objective is to assess the operational and safety impacts of CAVs on freeway facilities. One policy catalyst to facilitate a greater market penetration of CAVs is thought to be dedicating lanes for priority or exclusive CAV use as an initial incentive to encourage CAV ownership.

Background

Connected vehicles (CV) are vehicles that use wireless communication technologies to communicate with other cars on the road (vehicle-to-vehicle [V2V]), roadside infrastructure (vehicle-to-infrastructure [V2I]), and the "Cloud". This technology can be used to not only improve vehicle safety, but also to improve vehicle efficiency and commute times [1]. Dedicated Short Range Communication is expected to be one of the leading communication technology to be used in a CV environment [2].

In the classical sense, connected vehicles may offer little or no automated control, but focus on enhancing driver awareness through advance warnings that are received by the in-vehicle communication equipment. The CVs may transmit a wide range of messages containing a wide variety of information about the condition of the vehicle and about higher-level applications of interest to the driver and/or passengers. The most elementary (and likely to be legally required) message that is broadcasted by the in-vehicle device (or on-board equipment), known as the Basic Safety Message (BSM) [3], contains information about a vehicle's speed, position, size, heading, acceleration, and other representative elements [4]. When other vehicles receive this information, applications can use this information to provide warnings, alerts, and advisories. For example, drivers could receive notifications and alerts of dangerous situations, such as someone about to run a red light as they are nearing an intersection or an oncoming car, out of sight

beyond a curve, swerving into their lane to avoid an object on the road. Infrastructure-based devices, known as Road Side Equipment, also receive this information and broadcast messages such as MapData, Signal Phase and Timing (SPaT) etc., which can be received by in-vehicle devices to continuously monitor the infrastructure based warnings and alerts.

Automated vehicles, on the other hand, are those in which some portions of the dynamic driving task occur without direct driver inputs to control the steering, acceleration, and braking. Highly automated driving systems are designed so that the driver is not expected to constantly monitor the roadway while operating in the automated driving mode [5]. According to the SAE, vehicle automation can fall under five different levels of automation, defined as Level 1 through Level 5.

One of the highly-researched examples of Connected and Automated Vehicle (CAV) technologies is the Cooperative Adaptive Cruise Control (CACC) system, which uses a combination of sensors and vehicle-to-vehicle and infrastructure-to-vehicle communication to enable vehicles to automatically adjust their speed to the preceding vehicle in the same lane [6]. Given the level of research and development activity associated with CACC systems, the research team will be using CACC as the evaluation model for conducting CAV research in this project. The team will also utilize Dynamic Speed Harmonization (DSH), which aims at dynamically adjusting the speeds of equipped vehicles on a freeway, in response to downstream congestion, to improve throughput and reduce shockwaves and the associated possibility of secondary crashes [7].

Research Objective and Approach

Cooperative Adaptive Cruise Control Model

The CACC is a Connected and Automated vehicle application which uses a combination of sensors and vehicle-to-vehicle communication to enable vehicles to automatically adjust their speed to the preceding vehicles in the same lane. CACC vehicles utilize connectivity and a range of sensors to increase situational awareness and utilize automated methods of acceleration and deceleration which are more accurate than human control. CACC vehicles dynamically and automatically coordinate cruise control speeds within groups of vehicles to significantly increase traffic throughput (Figure 1). By tightly coordinating vehicle movements, headways among vehicles can be significantly reduced, resulting in a higher vehicle density, and the coordination also produces a smoothing of traffic flow, or an improvement in traffic flow stability. A CACC string is defined as a group of CACC vehicles that use connectivity and automated longitudinal control to act as a platoon of vehicles with very short headways.

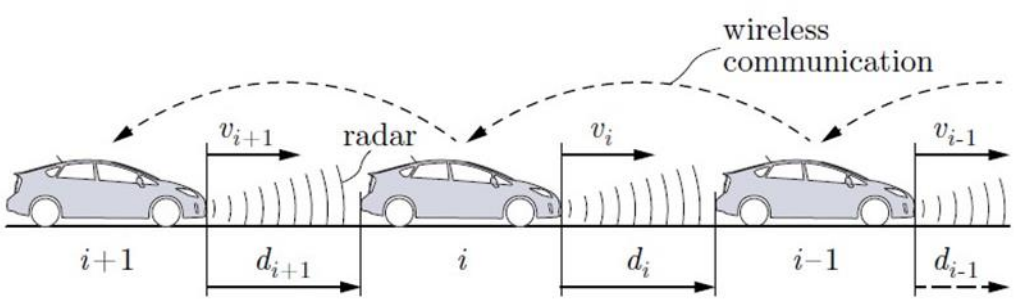

Figure 1: Illustration of CACC application for Connected and Automated Vehicles [CAAT, 2016]

The selected model logic used for the simulation analysis was originally developed in 2014 and then enhanced in 2016 is based on TNO's work that utilizes a modified Intelligent Driver Model (IDM) to achieve the target CACC objectives and benefits. The model was later enhanced to add lane-change logic and was used in conducting an evaluation of the impact of a CACC dedicated lane on traffic flow using a 13-mile long freeway segment of I-66 in Northern Virginia as the simulation test-bed. The primary goal of their research was to examine the system-wide impacts of early-deployment CACC dedicated lane strategies on roadway performance based on a variety of external factors such as

overall demand, market penetration of the equipped vehicles, dedicated lane use strategy and CACC operational parameters such as inter-vehicle headway, critical gap for leading and following vehicles and critical speed differential for leading and following vehicles.

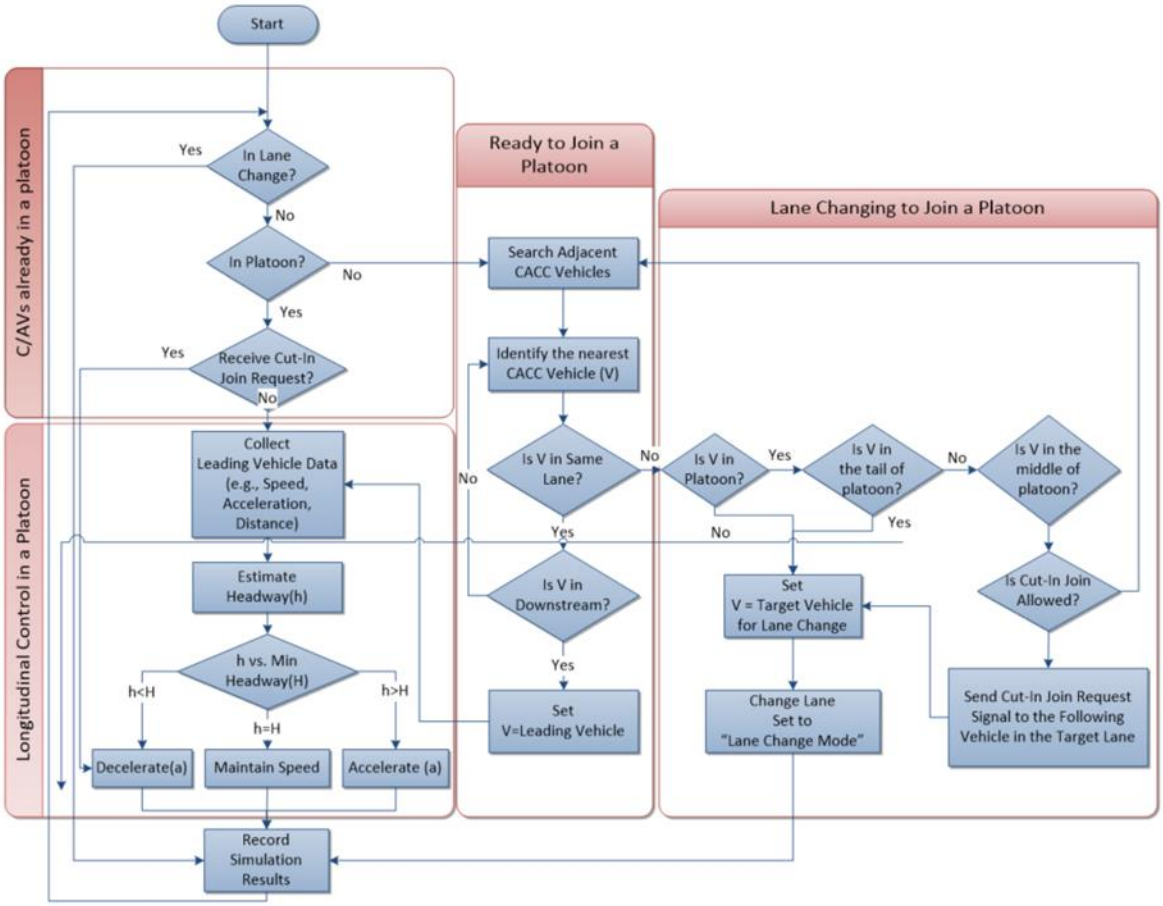

Figure 2: CACC Driver Behavior Logic used in Lee et al. (2016)

The model used three types of car-following behavior for the analysis: 1) VISSIM's default car-following model (i.e., psycho-physical car-following) for non-CACC driver; 2) the IDM for ACC driver to represent the leader vehicle of a CACC platoon; and 3) a customized IDM to deal with CACC longitudinal maneuver. Both ACC and CACC models are based on the collision-free IDM and were implemented using VISSIM's driver behavior API. Figure 1 shows the driver behavior of vehicles that are already using CACC vehicle following control and how their lateral and longitudinal control is governed. It also shows the behavior of vehicles when they are joining a CACC string.

Dynamic Speed Harmonization Model

DSH is another CAV application that is mature in terms of prototype development and field testing, that can be implemented in a freeway dedicated lane environment. While several algorithms exist, the general objective of the application is to harmonize the speeds of vehicles upstream on a freeway to minimize shockwaves and potentially improve mobility of the system by detecting congestion or queues downstream. This process is demonstrated in Figure 3, where once the Traffic Management Center (TMC) identifies congestion in a freeway segment, the speed harmonization application will compute speed recommendations for upstream freeway segments to enhance the throughput and avoid sudden deceleration and braking (thereby reducing shockwaves and probability of secondary collisions). In a connected environment, the vehicles use V2I communication to inform their traffic states to a

management center, which in turn selects the optimum speeds for vehicles to travel in the upstream sections and uses I2V communication to provide this information back to the vehicles.

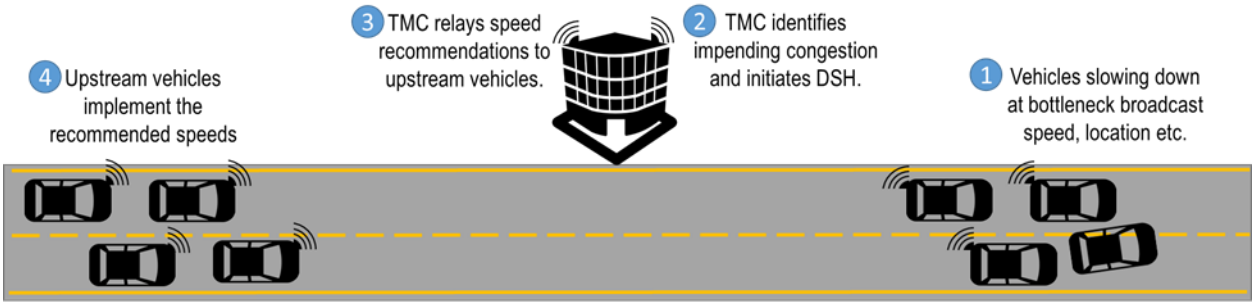

Figure 3: Process Flow of Dynamic Speed Harmonization

In the development of the simulation model, speed measurement stations at 0.5-mile spacing and map vehicle locations to 0.5-mile resolution were used. The speed recommendations were updated every 15 seconds and provided to the equipped vehicles as a desired speed distribution. A minimum speed recommendation of 25 miles per hour was maintained and the application was only initialized if a congested condition is detected on the dedicated lane. A DSH module which uses VISSIM's Component Object Model (COM) capability was developed to extract inputs to the application, compute the speed recommendations, and output the recommendations as desired speed distributions for vehicles at different distances from the congested area. The overall implementation logic is provided in Figure 4.

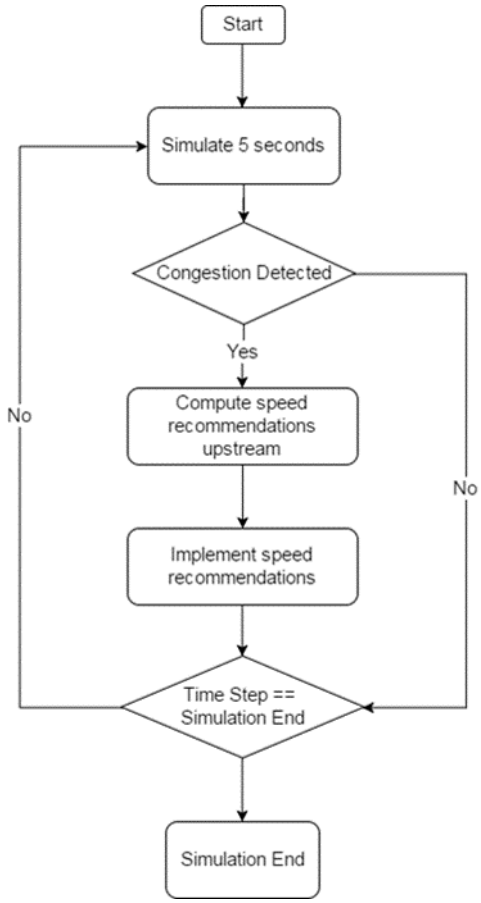

Figure 4: DSH Algorithm Implementation

Simulation Testbed

The test site selected is Interstate Highway 66 (I-66) in Northern Virginia as the case study site. The I-66 corridor is an east-west corridor taking traffic from the suburbs of Northern Virginia to Washington DC. The test site represents the segment of I-66 between the I-495 interchange to SR-234 interchange, spanning approximately 13-miles as shown in Figure 4. The corridor has an AADT of 150,000 to 160,000 and one peak-hour peak-direction HOV 2+ lane, in addition to two to three general purpose lanes and a peak-hour peak-direction shoulder lane. The freeway corridor has a posted speed limit of 55 mph. This suburban test site includes six interchanges and two dedicated on-and-off ramps for the HOV lane separate from general purpose lanes. The average distance between interchanges is approximately 1.2 miles, yielding 0.6 miles and 2 miles of minimum and maximum interchange spacing, respectively.

Figure 5: I-66 Case Study Site

The I-66 managed lanes are single-lane time-of-day HOV-2 lanes in both eastbound and westbound directions in the left-most lanes. User-type restrictions along the existing HOV-2 allow for all vehicle classes with 2 or more vehicle occupancy requirements. The existing managed HOV-2 lanes operate on a time-of-day basis with restrictions applying during morning and evening peak periods on weekdays. There is no physical barrier separating the managed HOV-2 lanes from the mixed-use lanes. Currently, only double solid white lane markings are used for lane separation and to indicate no lane changing or access. Access points between the dedicated HOV-2 lanes and mixed-use lanes are only permissible along dashed lane striping.

The I-66 also has hard shoulder running lanes on the right-most lanes in both directions, which operate from 5:30AM to 11:00AM in the east bound direction and from 2:00PM to 8:00PM in the west bound direction. Lane utilization is indicated via variable message sign (VMS) showing a green arrow for permitted use and a red-cross keeping the drivers away until they are close to an exit.

Analysis Results and Conclusions

Operational Impacts of CACC Market Penetration

When assessing CACC application, it was found that at lower market penetration, sharing lanes with HOVs will prevent oversaturation of GPLs. Hence, for 10 percent market penetration, we considered shared lane use, whereas for higher market penetrations only CAVs were allowed on the dedicated lanes. Figure 6 shows comparison of vehicle throughputs at different levels of market penetration for the I-66 case study site. The primary axis data shown by the left-hand vertical scale demonstrates the percentage difference in throughput when compared to the base case and the secondary axis shown by the right-hand vertical scale shows the baseline throughput.

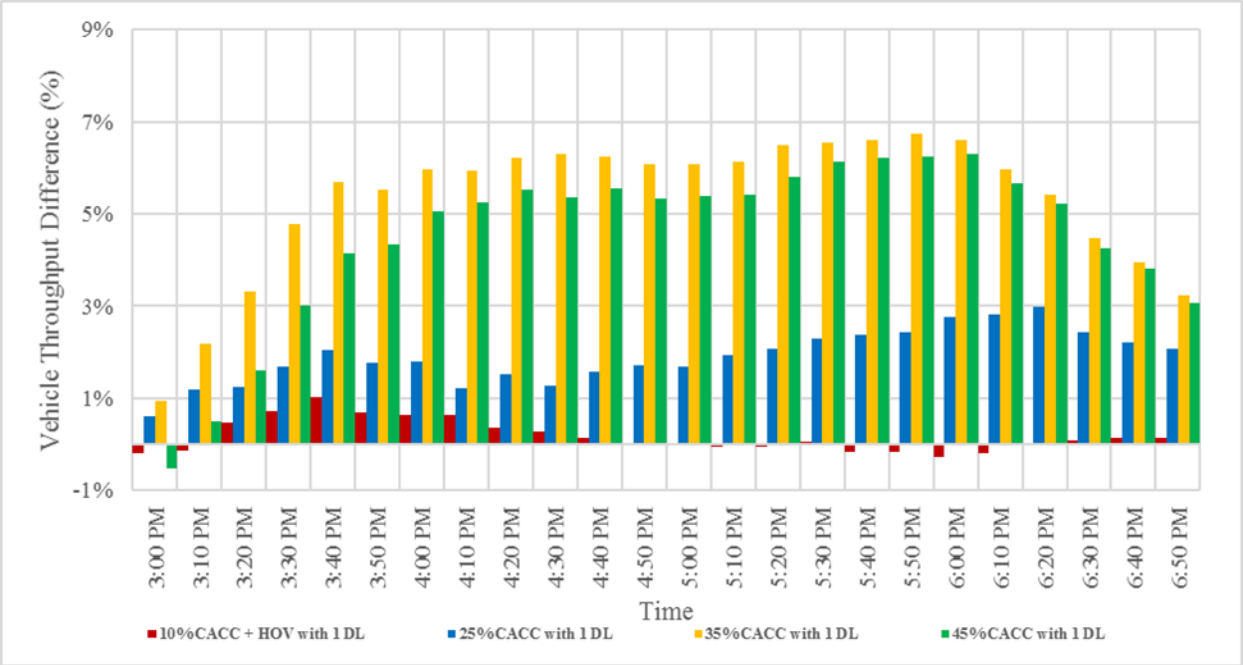

Figure 6: Impact of Market Penetration on CACC Dedicated Lanes

As shown, all the cases showed improvement in throughput, and the improvement increases till 35 percent market penetration, beyond which the improvement reduces. This is because of the significant volume imbalance that happens at higher market penetration. There are 3 GPLs and 1 DL in the I-66 case study site. At 25% market penetration, this amounts to an equitable distribution of demand. At 35% market penetration, the demand distribution becomes for DL vs GPL 35%:22% and at 45% market penetration, it becomes 45%:18%. It should, however, be noted that even at higher market penetration, the lane dedication was allowing higher throughput on dedicated lanes.

Figure 7 shows a comparison of maximum dedicated lane throughput that was achieved through CACC implementation at different levels of market penetration. As shown, at 10% market penetration, sharing dedicated lanes with HOV can improve the throughput by up to 21 percent, whereas not sharing with HOVs can decrease the throughput by almost 60 percent (primarily because only fewer vehicles are allowed on the DLs). When not shared with HOVs, CACC dedicated lane throughput increases as market penetration goes up. At 25 percent, there is a marginal reduction in throughput, whereas at 35 and 45 percent, the throughput increases by up to 32 and 60 percent respectively.

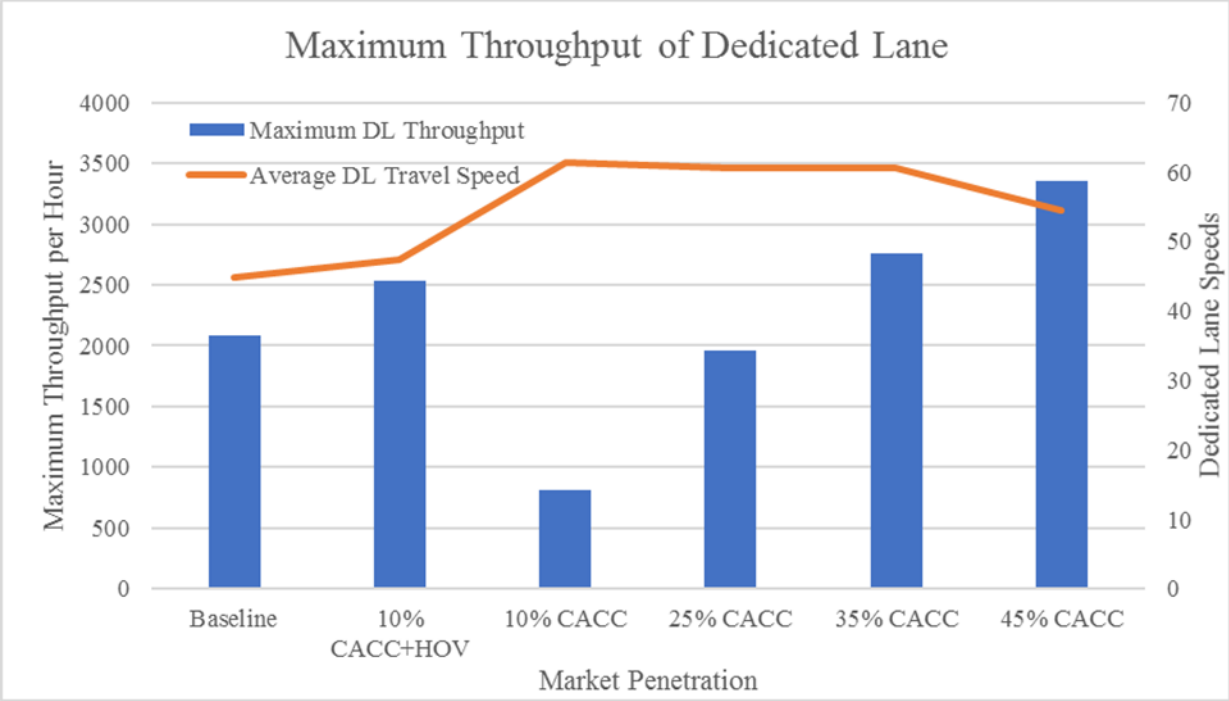

Figure 7: Maximum Throughput of Dedicated Lanes

Figure 7 also shows the average travel speeds on the dedicated lane under each condition. As shown, the travel speeds are much higher when there is exclusive lane access to CACC vehicles, even when the throughput is higher. The average travel speeds reduce to 54 miles per hour, when the CAV market penetration increases to 45 percent and they still have exclusive dedicated lane access.

Safety Impact of CACC and DSH Combination

The safety benefits of combining CACC with the DSH application was also assessed by analyzing the reduction in the probability of shockwaves. Figure 7 shows a comparison of speed contours when DSH is implemented at 25 percent market penetration on an exclusive dedicated lane.

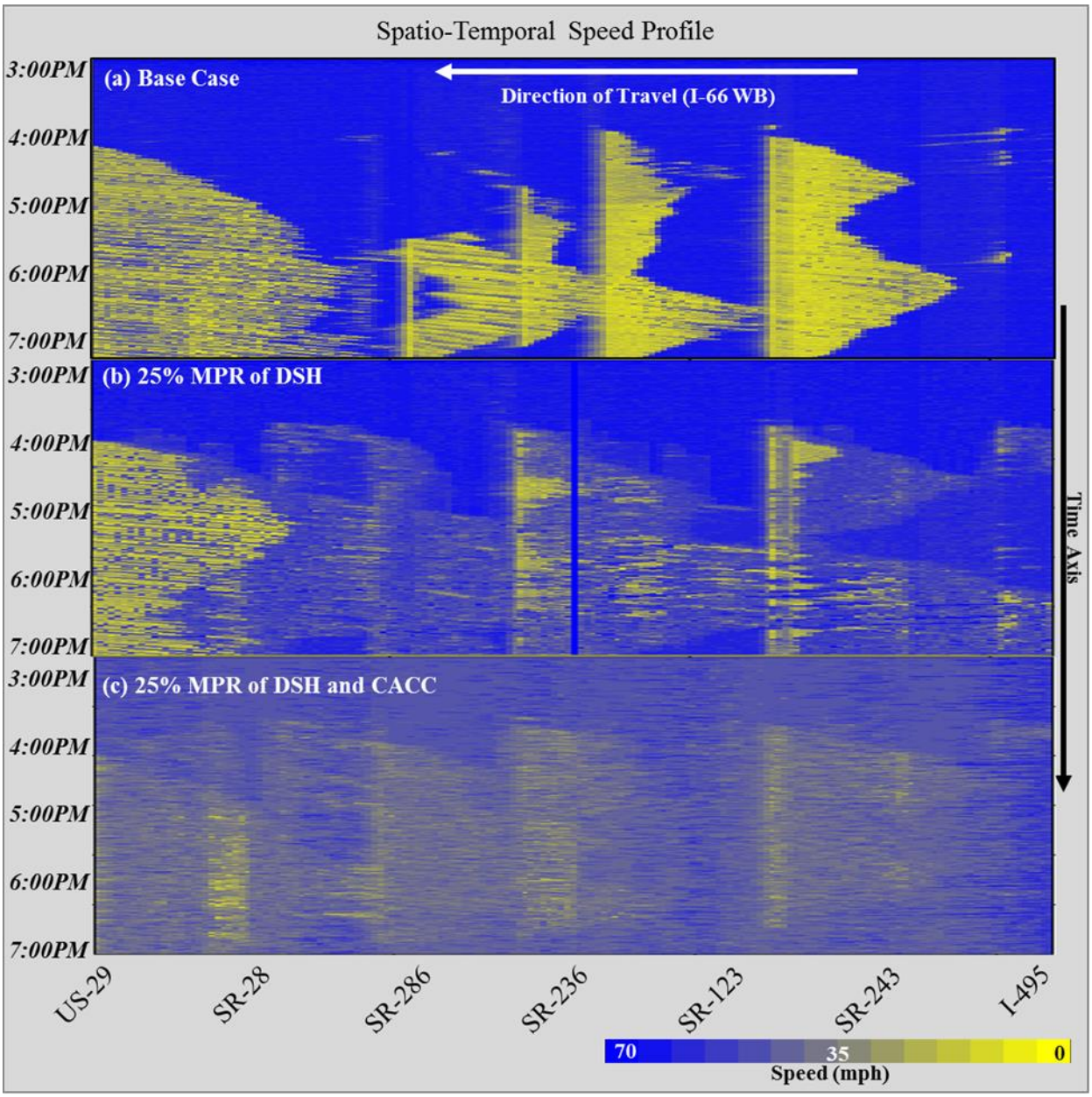

Figure 8: Speed Contours for I-66 WB Direction When DSH is Combined with CACC

When compared to the base-case, DSH application reduced the shockwaves by dispersing concentrations of slow-downs on the network, as shown in the spatio-temporal speed contours shown above. Additionally, when CACC was also implemented, there were virtually no more slow-downs in the network and there were significant improvements in environmental savings as well. For example, the DSH-only case (b) increased the fuel consumption by nearly 20% over the base-case, whereas the combination of DSH and CACC (case (c)) reduced the fuel consumption by over 16% over the base-case.

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