Finding the tipping point: a sensitivity analysis of network performance and environmental benefits of cooperative adaptive cruise control in freeway driving

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INTRODUCTION

Vehicle automation is expected to improve the ease and accessibility of personal vehicle travel; some predict this could induce travel, although connected and automated vehicle (CAV) driving systems such as cooperative adaptive cruise control (CACC) are expected to increase freeway capacity, improve fuel efficiency, and reduce tailpipe emissions. The US Department of Transportation developed the Automated Vehicle Benefits (AVB) framework to better predict the impacts of CAVs.

EVALUATION FRAMEWORK

This study builds upon earlier work for the AVB framework that proposed a three-layered modeling approach for evaluating CAV driving systems. It layers 1) the microscopic model for simulation of intelligent cruise control (MIXIC), 2) PTV Vissim for traffic microsimulations, and 3) the Motor Vehicle Emission Simulator (MOVES) at project scale. Despite tight model integration, this sequential approach is highly sensitive to parametric design and input data, as highlighted in Figure 1 below.

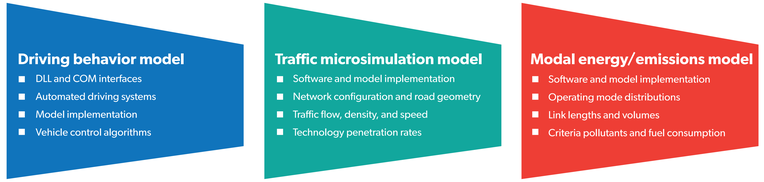

Figure 1. Conceptual diagram of modeling sensitivities for evaluating the traffic flow and environmental impacts of CAV applications

CASE STUDY

In a case study of a 4-mile freeway segment on Interstate 91 (I-91) near Springfield, Massachusetts, we compared passenger vehicles using CACC longitudinal control systems against baseline Wiedemann 99 car following using Massachusetts Department of Transportation measurements of traffic speeds and volumes. Table 1 below shows the key link-specific attributes of the I-91 Springfield freeway network.

Link ID	Length (mi)	Number of Lanes	Base Volume (veh/hr)	Average Speed (mph)
100	0.55	2	2612	57
101	0.19	2	2793	50
102	0.43	2	2335	59
103	1.88	3	3832	57
104	0.24	2	1084	61

Table 1. Freeway characteristics for each I-91 Springfield link, including length, number of lanes, traffic volume, and average speed

As more agencies and institutions show interest in studying the impacts of CAVs, it will become increasingly important to document modeling assumptions and formulate common scenarios.

U.S. Department of Transportation

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SENSITIVITY ANALYSIS

To test the operational and environmental sensitivities of the I-91 network, we varied traffic volumes and CACC technology penetrations. The following cases were considered:

- Four traffic volume cases: the base observed volumes (weekday morning peak period), multiplied by 1.0, 1.2, 1.4, and 1.6,
- Three CACC technology penetrations: 0% CACC (baseline), 50% CACC, and 100% CACC. In the 50% CACC scenario, CACC-equipped vehicles following non-equipped vehicles revert to adaptive cruise control (ACC) behavior, and
- Each volume-penetration pairing was run 5 times for 4500 seconds, with 900 seconds for warm up, and results reported for the final 3600 seconds.

ROAD GEOMETRY & DESIGN

Figure 2 shows the I-91 limited access network near Springfield, which includes five links (100-104) and six traffic entry points (1-6).

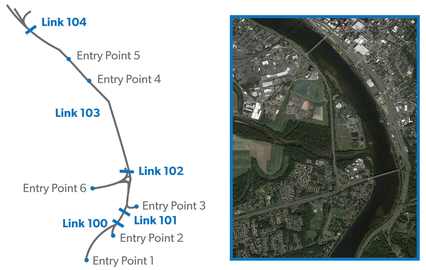

Figure 2. Sketch rendering (left) and aerial image (right) of the I-91 Springfield network with labelled links and entry points

Our findings below in Figure 3 confirm sensitivities to link geometry but also underscore sensitivities to traffic volumes and technology penetrations. Fuel savings for both the 50% and 100% CACC scenarios clearly peak in the 1.4x volume case.

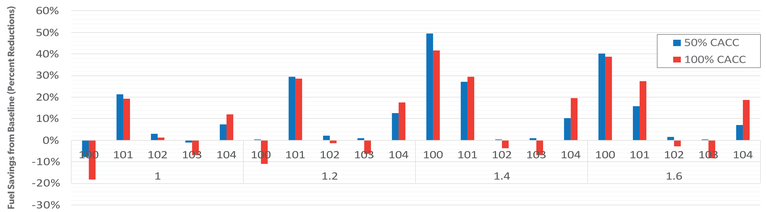

Figure 3. Modeled I-91 fuel savings normalized per vehicle from CACC driving to the baseline as volume increases by link

NETWORK PERFORMANCE

Traffic density was computed by dividing the flow over the average speed for each link. Figure 4 below shows the fundamental traffic flow diagrams for two links (100 and 103) on the I-91 Springfield network. Link 100 is a particular good illustration of the parabolic traffic flow-density curves and all scenarios have high goodness-of-fit values (R^2 is greater than 0.93) for second-order polynomial functions. Link 103—the longest I-91 link—also produces well-fitted functions, but the maximum flow rate is not visible.

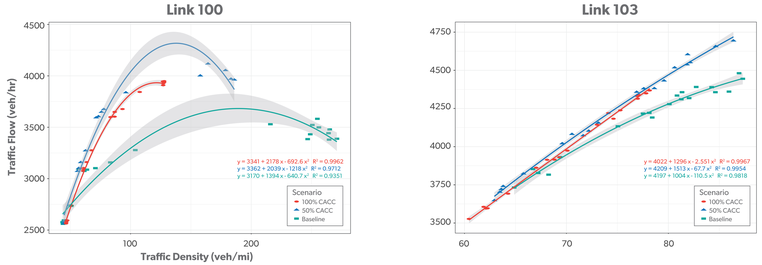

Figure 4. Traffic flow-density diagrams for Link 100 (left) and 103 (right) of the I-91 network under the baseline, 50% CACC, and 100% CACC scenarios with second-order polynomial fitted curves and 95% confidence bands

ENVIRONMENTAL BENEFITS

On a network level, increased I-91 volumes often led to per-vehicle fuel efficiency gains and fine particulate matter (PM2.5) emission reductions for the 50% and 100% CACC scenarios versus the baseline. Under certain conditions, the 50% CACC scenario outperformed the 100% CACC scenario due to higher speeds and tighter headways, as shown in Table 2 below.

Volume	Change in PM2.5		Change in Fuel Use	
	50% CACC	100% CACC	50% CACC	100% CACC
1.0	-14%	-7%	-1%	+4%
1.2	-20%	-11%	-5%	+1%
1.4	-21%	-16%	-16%	-11%
1.6	-21%	-17%	-12%	-9%

Table 2. I-91 network-level PM2.5 reductions and fuel savings per vehicle for 50% and 100% CACC scenarios against the baseline

Our results indicate high sensitivity to network design and road geometry and moderate sensitivity to traffic volumes and CACC penetrations. Further research with other networks and other CACC models can confirm the operational and environmental benefits found in this freeway study.

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FOR MORE INFORMATION

See our AVB Report (https://rosap.ntl.bts.gov/view/dot/34458), visit its.dot.gov or contact Andrew Eilbert (andrew.eilbert@dot.gov).

AVB Report

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