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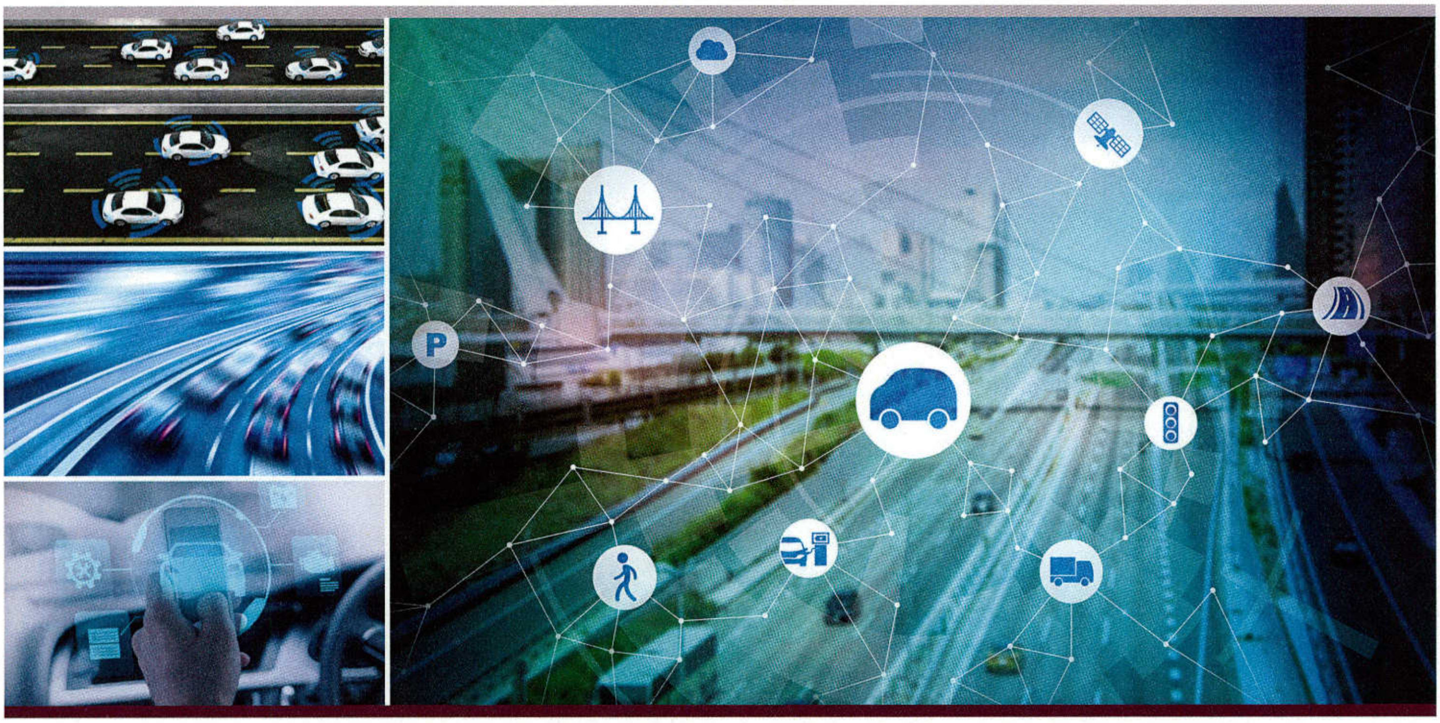

Revolutionizing Our Roadways

Modeling the Traffic Impacts from Automated and Connected Vehicles in a Complex, Congested Urban Setting

TRANSPORTATION
Policy Research CENTER

Revolutionizing Our Roadways

Modeling the Traffic Impacts from Automated and Connected Vehicles in a Complex, Congested Urban Setting

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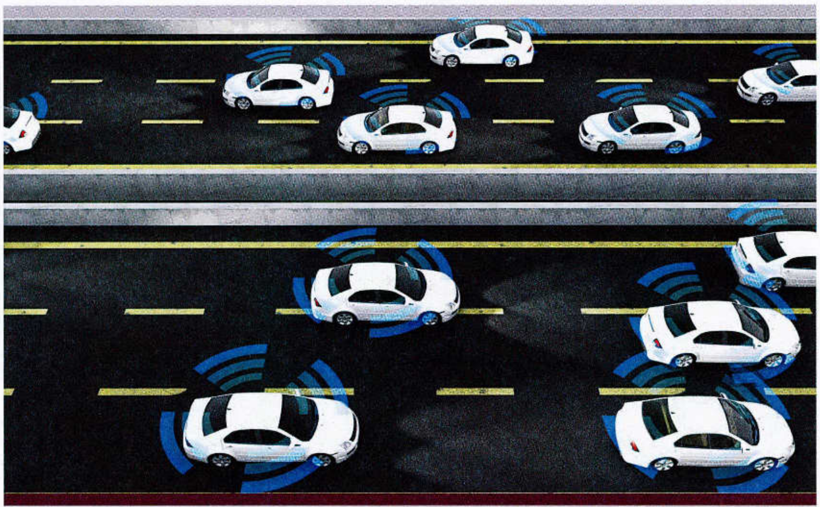
List of Acronyms

ACC	Adaptive Cruise Control
AV	Automated Vehicle
CACC	Cooperative Adaptive Cruise Control
CAMPO	Capital Area Metropolitan Planning Organization
CV	Connected Vehicle
D-HARM	Dynamic Speed Harmonization
DTA	Dynamic Traffic Assignment
DUE	Dynamic User Equilibrium
IDM	Intelligent Driver Model
INFLO	Intelligent Network Flow Optimization
km	Kilometers per Hour
mph	Miles per Hour
MRM	Multi-resolution Modeling
OD	Origin-Destination
Q-WARN	Queue Warning
TDM	Travel Demand Model
TTI	Texas A&M Transportation Institute
USDOT	U.S. Department of Transportation
V2I	Vehicle to Infrastructure
veh/hr/ln	Vehicles per Hour per Lane
VSL	Variable Speed Limit



Executive Summary

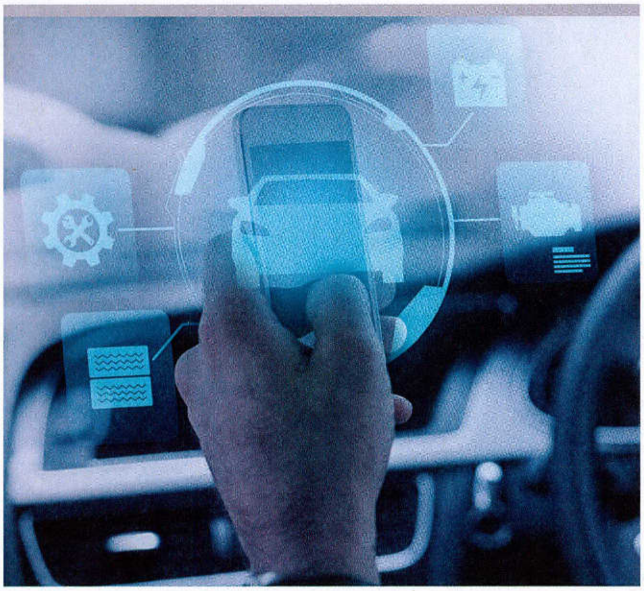
The idea of automated and connected vehicles revolutionizing our transportation system is tantalizing because the way people and goods currently move is both inefficient and unsafe. Many gallons of fuel and hours of time are wasted at idle in congested traffic, and tens of thousands of travelers die on America's roads each year. A revolution is needed, but will automated and connected vehicles prove to be the panacea many expect? Putting aside the question of safety, will automated and connected vehicles improve mobility and reduce congestion for the average commuter?

Determining the effect automated and connected vehicles could have on traffic flow would ideally require testing the vehicles themselves in a real-world environment. In the absence of large-scale, real-world testing, researchers at the Texas A&M Transportation Institute (TTI) used traffic modeling software to develop and test a vehicle mimicking the behaviors of several automated and connected vehicle applications in a congested and complex urban network. The vehicle design drew inspiration from several sources, including cooperative adaptive cruise control, queue warning, and speed harmonization. However, the cooperative adaptive cruise control algorithms used in the model may not align with expected implementations and conceptual models.

To verify that the custom vehicle behaved as expected, the team tested it against results from previous studies modeling similar technologies. The team was able to replicate these results, where a simplified single-lane network full of equipped vehicles roughly doubled the normal highway capacity (increasing from about 2,000 vehicles/hour/lane [veh/hr/ln] to nearly 4,000 veh/hr/ln). This result indicated that the custom-coded vehicle was functioning properly and could be tested in a more complex and realistic setting.

Many gallons of fuel and hours of time are wasted at idle in congested traffic, and tens of thousands of travelers die on America's roads each year.

For the setting, the researchers selected a 12-mi section of I-35 in Austin, running from Parmer Lane in north Austin to East Riverside Drive just south of downtown. The model was set in 2035, with road configuration and population levels reflecting expectations for the period. Data were derived from the Capitol Area Metropolitan Planning Organization (CAMPO) forecast, and road design was based on CAMPO's plans. Since it is not known when automated and connected vehicles will come to market or their adoption rate, the research team tested six different market penetrations of equipped vehicles—ranging from 0 to 100 percent—in 20 percent increments.



The team used a multi-resolution model (MRM) that combines aspects from three types of modeling: macroscopic, mesoscopic, and microscopic. This type of modeling requires more steps and is more time intensive, but the result more closely approximates real-world conditions in a few important ways. This process incorporates and integrates data from several different sources—such as local sociodemographic information—which results in a model populated with routes that more accurately reflect the number of trips Austinites might take, their length and destination, and how they travel (mode). The MRM also provides a more robust approach for analyzing large sections of freeway corridors (e.g., speeds and travel times) and the effects of CVs on the freeway.

More research is needed to determine whether these advanced vehicle technologies could improve mobility on heavily traveled corridors.

After running the models and performing the analyses, the team received some surprising findings: across all measures, performance decreased. The counterintuitive results could be partially due to the application design: harmonizing traffic flow on a congested and complex urban highway worsened bottlenecks by extending their impacts downstream.

It quickly became apparent that despite having access to advanced modeling techniques, modeling the effects of connected vehicle applications in a real-world setting is complex. Researchers have developed state-of-the-art tools to help address many of the shortfalls of previous approaches, but modeling human behavior in combination with vehicle automation is challenging. A significant outcome of the research is that the research team was able to leverage an existing regional transportation model and transform that well-curated, regionally accepted model into a tool for assessing automated and connected vehicle impacts. TTI researchers have demonstrated this modeling path in this report. With further research, this technique could be used to provide valuable insights into a future where the transportation system is transforming because of increased automation and connectivity.

More research is needed to determine whether these advanced vehicle technologies could improve mobility on heavily traveled corridors. The connected and automated vehicles of tomorrow may behave differently than the current model process suggests. As developments in the technologies occur, the team can reevaluate its results by integrating the new technologies into the model and testing the results to see how they compare to the original findings. As a part of this process, the team developed a list of research questions and issues (included as Appendix F) that cover four broad issue areas: general operation, cooperative adaptive cruise control, speed harmonization, and queue warning.

Introduction

Automated and connected vehicles (AV/CVs) are rapidly developing technologies that seem poised to disrupt the global transportation system. These technologies have the potential to minimize or entirely remove human error from driving, enabling precise driving at a skill level beyond that of humans. Improved reaction times, situational awareness, decision making, and driving task execution could result in fewer crashes, shorter inter-vehicular headways, and a more efficient travel environment. Inter-vehicle communications could enable smoothed traffic flow where vehicles collectively respond to disruptions, minimizing their deleterious effect.

These are all assumptions, however, based on technologies that—while near on the horizon—have not been empirically demonstrated and rigorously tested in realistic settings. AV/CVs are not yet fully developed or widely deployed. It is not known how humans will take to these new technologies or how they might change their behaviors as a result of use. Additionally, many of the anticipated societal benefits are premised on technologies that require wide-scale deployment in the vehicle fleet. It is uncertain how, when, or if these technologies will enter and distribute throughout the market.

Despite the many uncertainties, changes are coming, and the transportation community cannot afford to delay making decisions until perfect information is available. Transportation and city planners must make long-term plans for capital-intensive infrastructure investments despite the uncertainty. While models and analyses of the potential impacts of these technologies provide an imperfect vision of the future, the additional data they provide can aid decision makers by giving them better insight into the potential effects of AV/CVs under certain assumptions. Modeling efforts and the data they provide advance the state of knowledge surrounding the effects of AV/CVs and enable better-informed decision making.

Transportation and city planners must make long-term plans for capital-intensive infrastructure investments despite the uncertainty.

The research team sought to understand the potential effects of AV/CVs on congestion and mobility in a Texas context by modeling the traffic impacts of vehicles running a custom suite of mobility-focused AV/CV applications—inspired by cooperative adaptive cruise control (CACC), speed harmonization, and queue warning applications—at varying market penetrations on a 12-mi section of I-35 in Austin, running from south of Riverside Drive to Parmer Lane, at 2035 population levels. Researchers used a multi-resolution modeling (MRM) methodology that incorporated all levels, including macroscopic, mesoscopic, and microscopic models.

This modeling approach does not take into account or measure the effects that AV/CVs could have on nonrecurring congestion. In other words, crashes—and other nonrecurring events—create congestion by disrupting normal traffic flow. AV/CVs could potentially reduce these crashes, which could then reduce congestion (*1*). The current modeling approach does not consider these types of changes or their effects but instead focuses on the more common causes of congestion (i.e., recurring congestion from a mismatch between demand and supply for roads).

Literature Review

The researchers initially began the literature review with the intention of identifying and adopting a standardized AV/CV control profile to test the effect on traffic flow; however, the team was unsuccessful at identifying such a unified standard. There are multiple applications designed to address mobility, but due to the early phase of research, detailed standards or control specifications were unavailable.

Through the literature review, the research team identified three main applications that are designed to improve mobility and traffic flow: CACC, dynamic speed harmonization (D-HARM) (also known as variable speed limit [VSL]),[1] and queue warning (Q-WARN) (*1*).

A recent U.S. Department of Transportation (USDOT) report documenting progress on CV application research showed limited results in some key areas (*1*). USDOT completed prototype applications and demonstrations on both the VSL and Q-WARN applications although USDOT did not complete a CACC prototype or demonstrate it because "more research was required." A consortium of automotive industry stakeholders working with USDOT on CV issues (i.e., the Crash Avoidance Metrics Partnership) has, however, "assessed the feasibility" of developing a prototype CACC application and is reportedly developing a plan to prototype and "conduct a small-scale test of CACC." Details on the specifications or standards used on the proposed systems were unavailable.

There are multiple applications designed to address mobility, but due to the early phase of research, detailed standards or control specifications were unavailable.

The research team focused its efforts on identifying a commonly used general approach to modeling these vehicles and decided to adopt a custom solution using elements of the aforementioned AV/CV applications. Specifically, the team integrated components from CACC, VSL, and Q-WARN to develop a custom CV mobility solution. The custom CVs drew heavily from existing technologies, and the research team reviewed the literature to identify how researchers had previously approached modeling these systems.

The team found that a small but varied sample of studies modeling CACC vehicles had been published, but most used slight variations on setting, methods, software, vehicle behavior assumptions, and many other design aspects. A common approach in the literature was modeling advanced vehicle technologies under very specific and controlled circumstances, frequently as a straight, single-lane highway of distances less than 10 km. Schakel et al., for example, modeled CACC vehicles on a straight, 4-km, single-lane highway and found that CACC vehicles can improve traffic flow by dampening shockwaves,

[1] For consistency, the research team uses the more common acronym—VSL—throughout the remainder of the report.

but the authors did not diagnose the effect on vehicle throughput (*2*).

Davis analyzed a situation that can commonly cause traffic disruptions on a highway: an entrance ramp (*3*). The author proposed and modeled the effects of a cooperative merging system that allowed equipped vehicles to merge without reducing speed. The system essentially eliminated congestion at 50 percent penetration rates and improved throughput by 18 percent. The author noted, however, that in peak demand periods, only full implementation across the vehicle fleet would reduce congestion.

Kesting et al. proposed and simulated a modified CACC system with both vehicle-to-vehicle and vehicle-to-infrastructure (V2I) communications, which altered CACC driving characteristics to optimize vehicle speed and acceleration for traffic conditions (*4*). Under their modified adaptive cruise control (ACC) system, "Vehicles automatically adapt the ACC parameters to improve the traffic flow and road capacity and, thus, to decrease traffic congestion while retaining driving comfort." The authors simulated their system on a 13-km, three-lane stretch of the German Autobahn (A8 between Munich and Salzburg) during rush-hour conditions and found that even a small percent of equipped vehicles "improves the traffic flow quality and reduces the travel times" (*4*).

Under their modified adaptive cruise control system, "Vehicles automatically adapt the ACC parameters to improve the traffic flow and road capacity and, thus, to decrease traffic congestion while retaining driving comfort."

Shladover et al. simulated the vehicle throughput effects of a mixture of ACC, CACC, and here-I-am message-broadcasting vehicles on a straight, single-lane, 6.5-km freeway (*5*). Shladover et al. used time gap settings based on human participant selection rather than relying on an assumed or estimated gap, as the previously referenced microsimulations used. Consistent with previous studies, Shladover et al. found that a 100 percent penetration of CACC vehicles on a simple network would nearly double the throughput capacity from 2,000 vehicles per hour per lane (veh/hr/ln) to nearly 4,000 veh/hr/ln.

Treiber et al. developed an intelligent driver model (IDM), which is a time-continuous car following model for simulating freeway conditions. The IDM uses information about the current speed of the simulated vehicle and the distance to the vehicle in front, as well as the differences in speed of the two vehicles, to describe accelerations and decelerations (*6*). Kesting et al. developed an enhanced IDM that defines an upper limit of a safe acceleration in an ACC environment based on the assumption that the lead vehicle will not change its acceleration for the next few seconds of simulation (*7*). The enhanced IDM, however, was intended to describe traffic dynamics in one lane only. In lane-changing situations, the IDM can lead to unrealistic driver behavior when the actual gap is significantly lower than the desired gap (*7*).

Mahmassani et al. researched and developed a bundle of USDOT-identified high-priority transformative applications entitled Intelligent Network Flow Optimization (INFLO) that fully considers the impact of wireless connectivity on the surface transportation system, including queue warning, dynamic speed harmonization, and CACC (*8*). Queue warning is a dynamic display of warning signs to alert drivers that congestion is ahead and warn of impending queue backup so that drivers can brake safely, change lanes, or modify their route to reduce secondary collisions.

Mahmassani et al. also considered speed harmonization as part of the INFLO application, where speeds are dynamically adjusted in response to downstream congestion, incidents, weather, or road conditions in order to maximize traffic throughput and reduce crashes. In a CV environment, speed harmonization is governed by CVs traveling along the corridor where a lead vehicle sends messages back to trailing CVs. The CVs broadcast their respective speeds with the goal of harmonizing traffic flow and reducing the impending shockwaves caused by congestion in merge/weave areas, thus improving safety on the specific roadway segments (*8*).

The literature review revealed that there is a great amount of uncertainty in how AV/CVs will ultimately operate and affect traffic flow. This uncertainty seems to have translated to a variety of different approaches to model these advanced vehicles, each with slightly different assumptions about its operating characteristics. Because of this variation, the research team decided to develop a custom approach to modeling AV/CVs' effects on congestion but one that is inspired by the ideas underpinning various AV/CV mobility applications. The research team ultimately settled on studying the effects of a custom mobility solution inspired by speed harmonization, CACC, and queue warning. The design, implementation, and modeling results of the custom CVs used in this study are detailed in the following sections.

Modeling

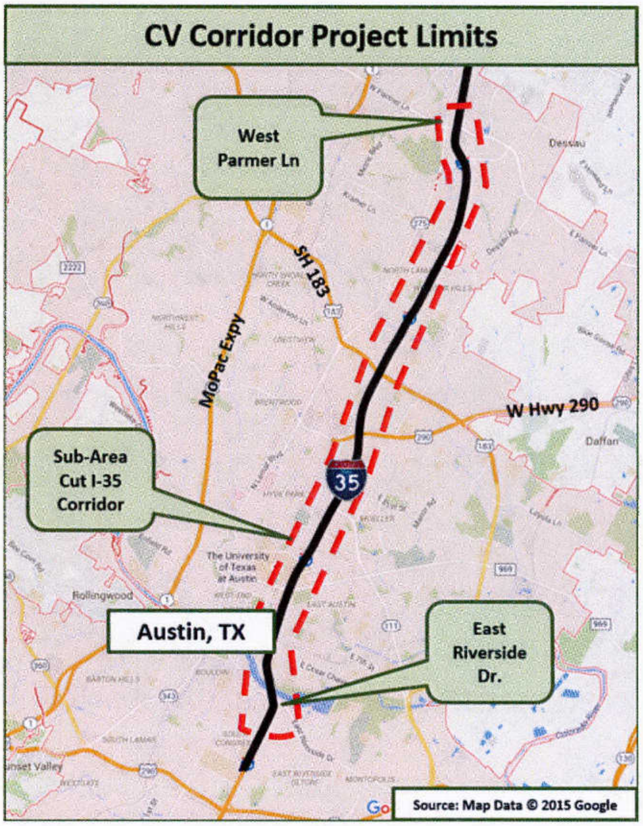
Modeling is a useful activity because it can help planners and other stakeholders make better-informed decisions about an uncertain future. Many of the previous efforts at simulating AV/CVs used simplistic networks, which help when establishing new tools and building a foundation of knowledge but provide limited external validity. Congestion commonly occurs in complex urban environments, complete with entrance and exit ramps, mixed traffic types, and many other complicated design elements. Therefore, modeling new technologies on simplified networks may provide strikingly different results than modeling on more complex networks. To address this gap, the research team simulated AV/CVs along a 12-mi stretch of I-35 in and around downtown Austin using demand values derived from population estimates for 2035.

Setting

The research team selected a core section of I-35 in downtown Austin, running from East Riverside Drive to West Parmer Lane, to model. This site was selected due to its preexisting congestion issues, significance as containing the state capitol, and large population area, as well as the presence of a major interstate with high international and domestic traffic volumes. In addition, the team was able to use a preexisting regional mesoscopic dynamic traffic assignment (DTA) model, originally derived from the Capital Area Metropolitan Planning Organization (CAMPO) five-county travel forecasting model, which saved development cost and time. The rationale for selecting the distance of 12 mi was that it provided sufficient length to accurately simulate real-world traffic conditions from congestion. Once in DTA format, researchers extracted and converted a sub-cut of the I-35 corridor and converted it to microscopic format. All routes and traffic volumes derived from the DTA model were truncated at the boundary layer of the project limits. After conversion, researchers calibrated the microscopic model, including speed profiles, vehicle compositions, and standard driving behavior parameters.

The rationale for selecting the distance of 12 mi was that it provided sufficient length to accurately simulate real-world traffic conditions from congestion.

The infrastructure modeled was not the same as the existing roadway. Instead, the research team designed the road to reflect the anticipated changes that local governmental agencies proposed—namely the addition of a bidirectional managed lane. One managed lane in each direction with various access points (slip ramps) into and out of the freeway main lanes was added to the regional DTA model. The modeled infrastructure was limited to freeway lanes, managed lanes, and ramps; frontage roads were not included. Figure 1 shows the project limits of the study area.

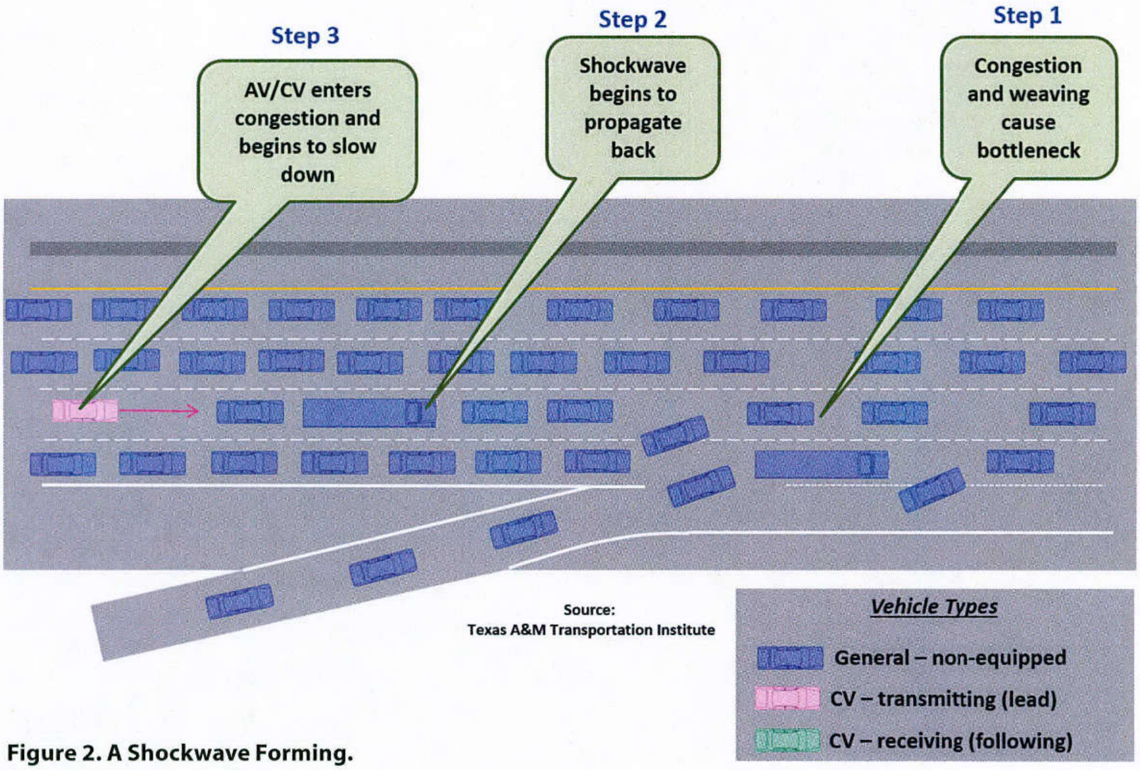


Source: Map Data © 2015 Google

Figure 1. Project Limits (I-35 Corridor).

Technology

The research team sought to understand the potential impacts from AV/CV technologies. The custom CVs designed for this study leveraged a few elements from existing AV/CV technology that enabled vehicles to maintain a set distance from a leading vehicle, up to a desired speed. The motivation for such a system is to increase vehicle throughput and smooth perturbations in the traffic flow, known as shockwaves, which are commonly caused by braking vehicles. Shockwaves can be seen in the cascading of brake lights upstream along a freeway and are most commonly caused by an increase in congestion, typically where vehicles are merging/weaving at on- and off-ramps, as shown in Figure 2.


Step 3
AV/CV enters congestion and begins to slow down
Step 2
Shockwave begins to propagate back
Step 1
Congestion and weaving cause bottleneck
Vehicle Types
General – non-equipped
CV – transmitting (lead)
CV – receiving (following)

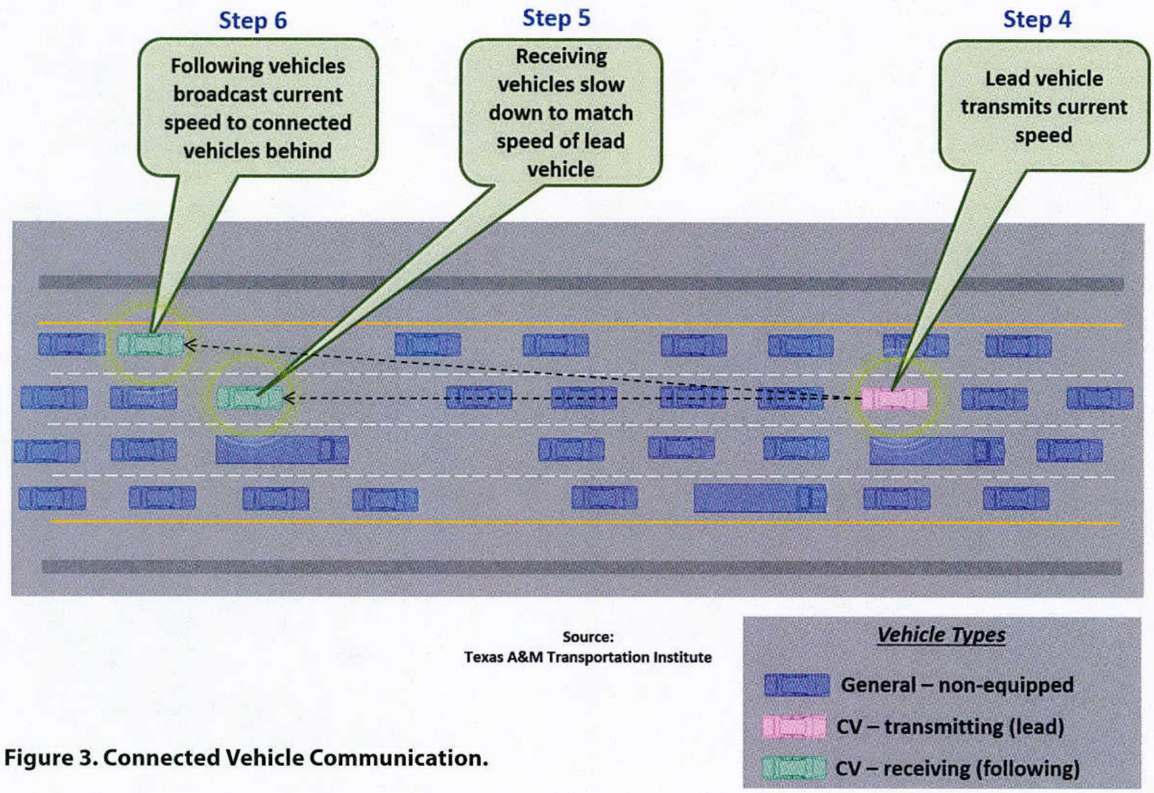
Source:
Texas A&M Transportation Institute

Figure 2. A Shockwave Forming.

The custom CVs behaved in the following way: When a lead vehicle hit congestion and slowed, it sent a message to trailing vehicles advising them to reduce their speed to match the speed of the lead vehicle. In turn, the following CVs broadcast their reduced speeds to other CVs traveling behind, and the subsequent messages propagated backwards, as shown in Figure 3. This warning functioned similarly to warnings in speed harmonization and queue warning applications, and was designed to reduce the speed differences between vehicles in the congested areas and those vehicles approaching the congestion. This warning also reduced shockwaves by enabling the trailing vehicles to adjust their speed to conditions ahead and eliminating the need to rapidly brake upon reaching congested traffic. However, translating these types of driver behaviors into a simulation model was challenging.

The model consisted of both commercial and private vehicles, sorted into two types: vehicles that were equipped as CVs and vehicles that were not equipped. Non-equipped vehicles in the model behaved in a manner consistent with normal human drivers, which is governed primarily by the traffic flow model, also known as the Wiedemann 99 car following model (*9*). The general premise of the Wiedemann model is the assumption that a vehicle can be in one of four driving modes:

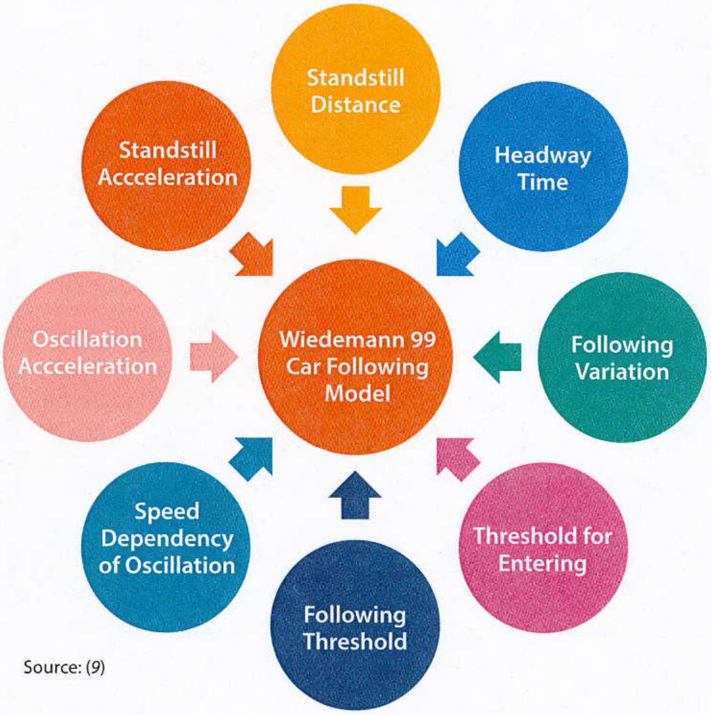
- *Free driving*—no influence on preceding vehicles is observable. In this mode, the driver seeks to reach and maintain a certain speed (i.e., individually desired speed).
- *Approaching*—the driver adapts his or her own speed to the lower speed of a preceding vehicle. While approaching, a driver decelerates so that the speed difference of the two vehicles is zero in the moment the driver reaches his or her desired safety distance (modified to 0.55 seconds for custom CVs and 0.99 seconds for non-equipped vehicles in this study).
- *Following*—the driver follows the preceding car without any conscious acceleration or deceleration. This mode keeps the same desired safety distance more or less, and the speed difference typically oscillates around zero.
- *Braking*—the driver applies medium to high deceleration rates if the distance falls below the desired safety distance. This can happen if the preceding car changes speeds abruptly or if a third car changes lanes in front of the observed driver.


Step 6
Following vehicles broadcast current speed to connected vehicles behind
Step 5
Receiving vehicles slow down to match speed of lead vehicle
Step 4
Lead vehicle transmits current speed
Vehicle Types
General – non-equipped
CV – transmitting (lead)
CV – receiving (following)

Source:
Texas A&M Transportation Institute

Figure 3. Connected Vehicle Communication.

The simulation model had several parameters (see Appendix A) associated with the Wiedemann 99 car following model. The safe following distance was the parameter that had the greatest influence on the saturation flow rate (e.g., vehicles per hour). The safe following distance is defined as the minimum distance a driver will keep while following another car. In cases where congestion levels are high, the safe following distance becomes the variable with the highest influence on capacity (*9*). The safety distance is comprised of the standstill distance (the desired distance between stopped vehicles) combined with the headway time (time drivers wish to keep when trailing another vehicle). Figure 4 outlines all the parameters used in the car following model.


Standstill Distance
Standstill Accceleration
Headway Time
Oscillation Accceleration
Wiedemann 99 Car Following Model
Following Variation
Speed Dependency of Oscillation
Threshold for Entering
Following Threshold

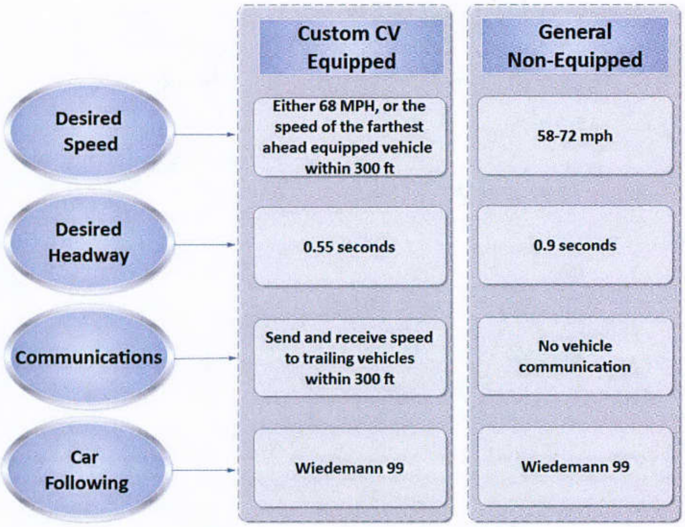
Source: (*9*)

Source: Planung Transport Verkehr AG

Figure 4. Wiedemann 99 Model Parameters.

The custom CVs mimicked the functionality of CV mobility applications by modifying several behaviors. Equipped vehicles communicated messages about their speed to other equipped following vehicles within 300 ft from the lead vehicle. If a custom CV did not detect a vehicle ahead, it traveled at 68 mph. Trailing custom CVs received messages from leading custom CVs that were farthest ahead but still within 300 ft. If a trailing CV received a message that CVs ahead had slowed below 68 mph, the trailing vehicle set its desired speed to match that of the leading vehicle. All custom CVs were set to maintain a gap of 0.55 seconds, which was consistent with what human drivers selected as a comfortable following distance in a previous study using CACC vehicles (*5*). Other travel behavior characteristics (like acceleration and deceleration) were governed by the Wiedemann 99 car following model.

For non-equipped vehicles, the speed profile for passenger cars and trucks was set to a distributed range of 58–72 mph to reflect the variability of traveling speeds of vehicles on a freeway setting. The desired headway was programmed to 0.9 seconds, which reflected larger spacing between vehicles. As with the equipped vehicles, acceleration/deceleration was administered by the Wiedemann 99 car following model. Non-equipped vehicles had no communication capabilities. The characteristics for equipped and non-equipped vehicles are described in Figure 5.



	Custom CV Equipped	General Non-Equipped
Desired Speed	Either 68 MPH, or the speed of the farthest ahead equipped vehicle within 300 ft	58-72 mph
Desired Headway	0.55 seconds	0.9 seconds
Communications	Send and receive speed to trailing vehicles within 300 ft	No vehicle communication
Car Following	Wiedemann 99	Wiedemann 99

Figure 5. Vehicle Behavior Characteristics.

Methodology

Proof of Concept

Before beginning the resource- and time-intensive process of running the fully loaded model on a complex urban network, the researchers first needed to ensure that the vehicle profiles functioned as expected. To determine if the custom CVs were properly calibrated, the researchers benchmarked the vehicles (with the associated AV/CV parameters) against the results from previous models using similar circumstances to see if their results could be replicated. In this case, the researchers tested against previous studies that found CACC vehicles could nearly double freeway capacity from around the normal 2,000 veh/hr/ln in a controlled and simplistic network to nearly 4,000 veh/hr/ln (*5*).

The test model replicated the setup from the literature consisting of a one-lane, 1-mi segment without any on- or off-ramps (i.e., no disruptions to traffic flow). The scenario tested the modified driver parameters plus the custom CV algorithm. Various market penetrations were simulated to determine the total volume over one hour. Results show that with increasing market penetration rates, total volume increases incrementally, with 100 percent market penetration reaching nearly 4,000 veh/hr/ln, as shown in Figure 6. These results suggest that under a simplified test network without external disruptions to traffic flow, the custom CV approach with modified driving behaviors (i.e., reduced gap) nearly doubled capacity. This finding indicates that the custom approach may be an effective re-creation of similar CV mobility applications, which received similar results in a similar test environment. Researchers then extrapolated all model parameters and input them into a large congested network that replicated 2035 congestion conditions using an integrated modeling approach.

Market Penetration of Equipped Vehicles	Total Through Volume (veh/mi/ln)
Base	2,424
20%	2,287
40%	2,276
60%	3,192
80%	3,585
100%	3,952

Figure 6. Test Network Simulation Results.

Model Conversion (Macro-Meso)

The research team used an integrated MRM approach to develop the I-35 corridor in Austin. The MRM process uses a combination of macroscopic, mesoscopic, and microscopic modeling platforms to derive the final analysis. The first stage of the MRM process is to convert the macroscopic planning model to a simulation-based mesoscopic model. The premise for using a mesoscopic model over traditional planning models (i.e., macroscopic) is that metropolitan planning organizations typically use DTA models. DTA is a time-dependent methodology that incorporates a time component into the routing assignment[2] in the model. Planning models do not use a time component and therefore only give an average of the total volume traveling on a freeway corridor. DTA models include this time component so that it is possible to replicate real-world conditions of traffic congestion, including peak-hour queuing,[3] bottleneck locations, and accidents. In addition, DTA models are capacity constrained, meaning if a route becomes too congested, vehicles will switch to take alternate routes—which more closely approximates how motorists often behave in the real world. Traditional macroscopic planning models do not have capacity constraints, so they unrealistically model sections of roadway where there is more volume than physical capacity (known as the volume-to-capacity ratio).

Once the model was in mesoscopic format, the team calibrated it to reflect 2035 conditions. Traffic signals were coded into the simulation model (macro-models do not use traffic signals but instead use an algorithm[4] to replicate delays at intersections) and were adjusted using timing plans provided by the City of Austin. Further calibration included the adjustment of the traffic flow model, which is used to dictate the flow of vehicles in the network. Traffic flow models were modified for both freeways and arterials at a regional level. Calibration was performed on the travel demand model (TDM), which is the official model of CAMPO. Calibration included origin-destination matrix estimation for the trip tables. However, once in DTA format, researchers did not further calibrate the demand tables or adjust origin-destination (OD) pairs at the micro-level. Figure 7 depicts the MRM modeling process.

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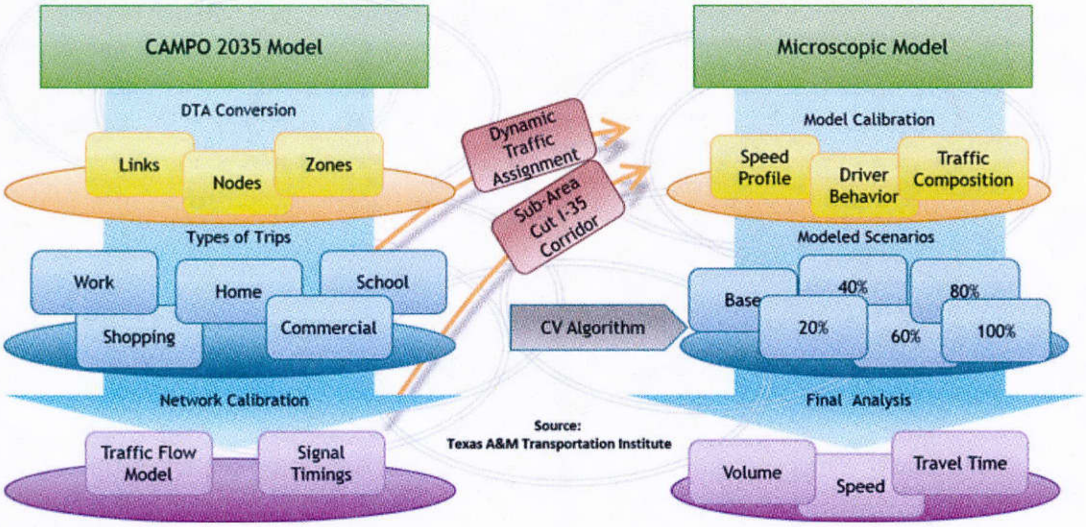
[2] Routing assignment allocates trips between origin and destination.

[3] Queuing refers to a line of vehicles waiting to enter a segment of roadway because there is more demand than capacity for the location.

[4] The volume-delay function is used to account for delay at signalized intersections.


CAMPO 2035 Model
DTA Conversion
Links
Nodes
Zones
Types of Trips
Work
Home
School
Shopping
Commercial
Network Calibration
Traffic Flow Model
Signal Timings
Dynamic Traffic Assignment
Sub-Area Cut I-35 Corridor
CV Algorithm
Microscopic Model
Model Calibration
Speed Profile
Driver Behavior
Traffic Composition
Modeled Scenarios
Base
40%
80%
20%
60%
100%
Final Analysis
Volume
Speed
Travel Time

Source:
Texas A&M Transportation Institute

Figure 7. Multi-resolution Modeling Process.

Dynamic Traffic Assignment

The objective function in a mesoscopic model, termed dynamic user equilibrium (DUE), is based on the idea of individual drivers choosing their routes through the network according to their generalized travel cost experienced during a trip. A generalized cost includes both travel time and any monetary costs (e.g., tolls) or any other costs linked to a trip. In other words, the model tries to replicate human behavior by determining the time-dependent shortest path to the destination while considering the tolls associated with the trip and routes vehicles accordingly. However, as congestion builds, some routes become more attractive while others become less attractive. Therefore, the model employs an iterative algorithmic procedure to establish DUE conditions where vehicles try different routes to find the most suitable one. At any given point and after multiple iterations, travelers learn and adapt to the transportation network conditions—much like real-world conditions where commuters try different options to their destination until they ultimately find the quickest while taking toll costs into consideration.

Researchers used a relative gap measure as a means to determine when the model had stabilized to DUE conditions. The relative gap used the aggregated change in overall travel time between OD pairs and compared that change to the previous iteration (see Appendix E). A stable solution was reached when the relative gap reached a point where there was minimal variation in aggregated travel times between iterations.

Model Conversion (Meso-Micro)

Once the research team calibrated the model using the process described, the team pared back the model from the entire Austin area to a smaller section of I-35 located in the core of the city. The team trimmed the model of any vestigial links, nodes, and zones to reduce it to the needed size (i.e., sub-area). Any vehicular paths or flows originating or terminating outside the I-35 core were also removed. The sub-area of the I-35 corridor was composed of freeway main lanes, ramps, and express lanes.[5]

Researchers used a relative gap measure as a means to determine when the model had stabilized to DUE conditions.

Once the sub-area process was completed, the DTA model was converted to a microscopic counterpart using a meso-micro conversion tool.[6] The tool converted all links, nodes, and, most importantly, time-dependent paths and flows within the bounded area. Once the model was in microscopic format, the researchers performed additional cleanup and calibration (e.g., geometry) before running scenarios for analysis.

Microscopic Model Development

Next, the research team developed the simulation. A speed profile was derived based on data obtained from previous forecasting studies (*10*). The speed distribution ranged from 58 mph to 72 mph (see Appendix B) distributed between a mix of both autos and trucks (see Appendix C). The roadway system model was composed of general-purpose freeway lanes and ramps, plus express lanes running parallel. The research team included the express lanes although vehicle behavior was not modified to simulate pricing or high-occupancy vehicle–style

[5] The 2035 CAMPO-adopted plan has proposed express lanes running parallel to the main lanes.

[6] This tool is the DynusT-VISSIM Converter developed by the Texas A&M Transportation Institute and the University of Arizona.

restrictions because those routes were already defined in the DTA model. There were also no restrictions on the use of the express lanes as dedicated AV/CV lanes although future modeling efforts could consider this option.

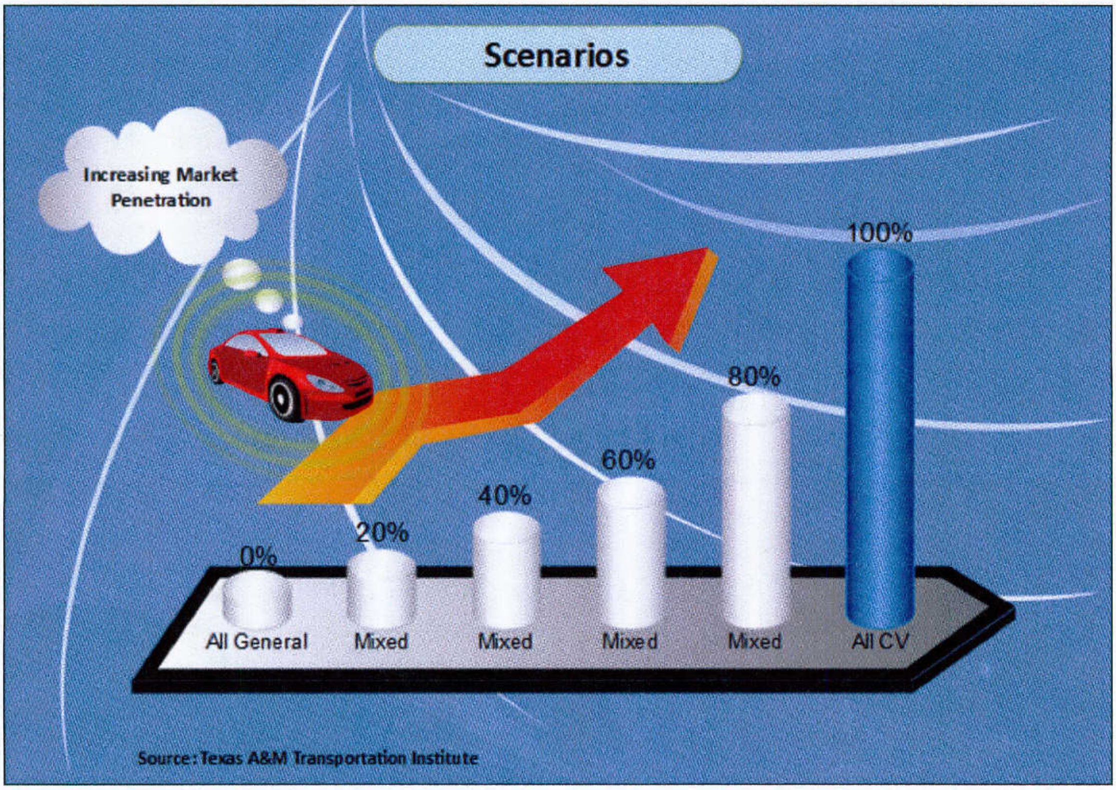
The simulation model was developed as a bidirectional model, so both northbound and southbound flows were analyzed. Additional adjustments were made to replicate planned geometric conditions of the I-35 corridor, consistent with the current CAMPO plans (e.g., upper and lower decks). The model was simulated for 5,400 seconds (1.5 hours), with the first half hour used to load the network with vehicles and the remaining hour used as the analysis period. Since researchers used an afternoon peak period with 2035 demand levels, all subsequent micro-models were run under saturation conditions.

Modeled Scenarios

Because it is not known how quickly AV/CV technologies will disperse throughout the vehicle fleet, the research team modeled a variety of market penetrations. The research team tested six different market penetrations of the custom CVs—0 percent, 20 percent, 40 percent, 60 percent, 80 percent, and 100 percent—as shown in Figure 8. Market penetration rates were distributed evenly between the weighted car and truck percentages.

Conclusions, Findings, and Future Work

Findings from the simulation-based modeling in this study showed counterintuitive results compared to the consensus results of previous studies modeling CACC. The literature review suggests that with increasing market penetration rates, the number of total vehicles that can be pushed through a corridor doubles to 4,000 veh/hr/ln (*5*). However, many of the previous studies reviewed either considered a control test environment where models had only one lane on a 1-mi segment without any on- or off-ramps or included an analysis that was performed with mathematical calculations. When the custom CVs were used on a 12-mi replicated real-world network, with multiple vehicle classes and on- and off-ramps (where disruptions to traffic flow tend



Source: Texas A&M Transportation Institute

Figure 8. AV/CV Market Penetration Scenarios.

to occur), simulation results were quite different. On a heavily congested network, the effects of the custom CV application were detrimental to the performance of the freeway in terms of mobility—speeds and total volumes were reduced, while total travel times increased.

Safety

From a safety perspective, speed harmonization and queue warning will likely create a safer freeway environment by reducing the amount of rear-end collisions when there is high market penetration. Previous research has shown that speed harmonization results in lower accident rates in part because the variable speed limits decrease the likelihood of severe congestion (i.e., bottlenecks) by increasing the stability of traffic flow (*11*). However, it is uncertain whether safety will be compromised in mid-level market penetrations due to extensive lane changing occurring when non-equipped vehicles try to pass slower CVs.

It is also unclear how custom CVs might affect traffic flow on congested freeway segments. The custom CV application improves safety by harmonizing traffic flow and warning drivers of stopped traffic ahead, but this benefit has trade-offs that society must consider. The simulation in this study found that increasing traffic harmonization and warning drivers of upcoming traffic also exacerbated existing bottlenecks by extending their geographical impact into traffic farther upstream.

Mobility

Results showed that with increased market penetration rates, the performance of the transportation system suffered from a mobility perspective. The custom CVs sent messages back through traffic informing other CVs of the slowed traffic ahead, and the vehicles responded to the message by slowing their speed and, in turn, advising other CVs behind them to slow as well. This message propagation exacerbated the delay for trailing vehicles in the network. Non-equipped vehicles responded logically to the slowing traffic around them by trying to pass the slowing CVs. This aggressive behavior in turn caused more friction on the roadway due to the increased lane changing. The custom CVs also contributed to traffic slowdowns by forming small blockades across all travel lanes, preventing non-equipped vehicles from passing, reducing speeds for all trailing vehicles, and creating further congestion and delay, as shown in Figure 9. Further research is needed

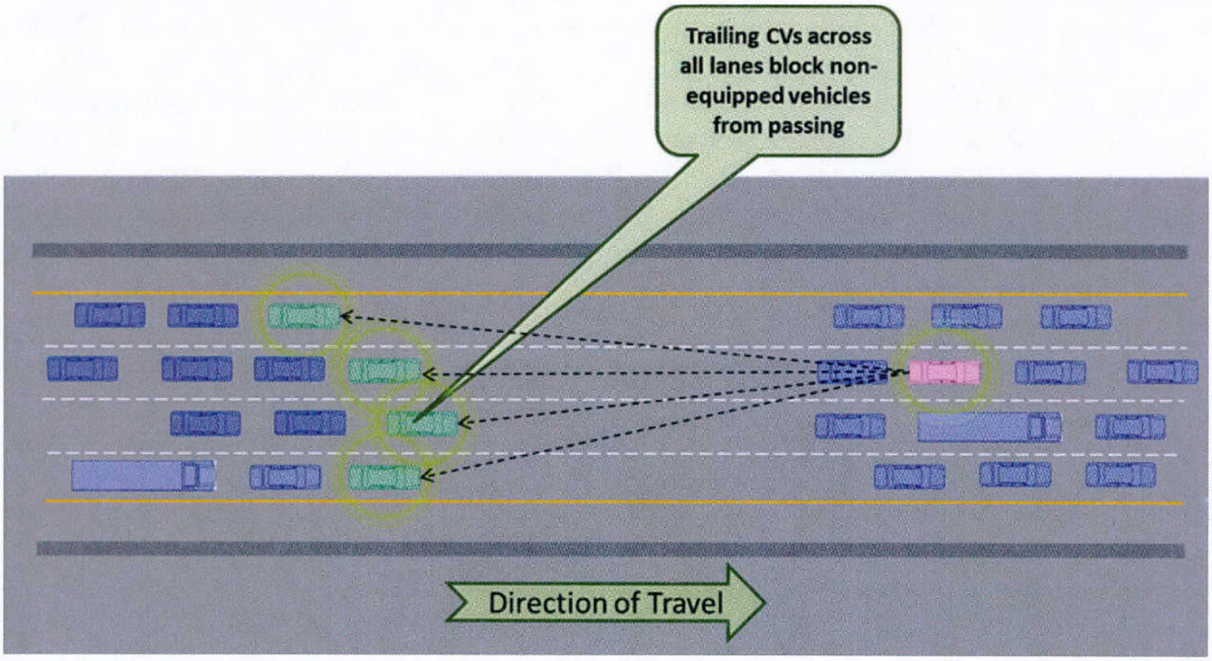

Trailing CVs across all lanes block non-equipped vehicles from passing
Direction of Travel

Figure 9. Example of Lane Blockage from Equipped Vehicles.

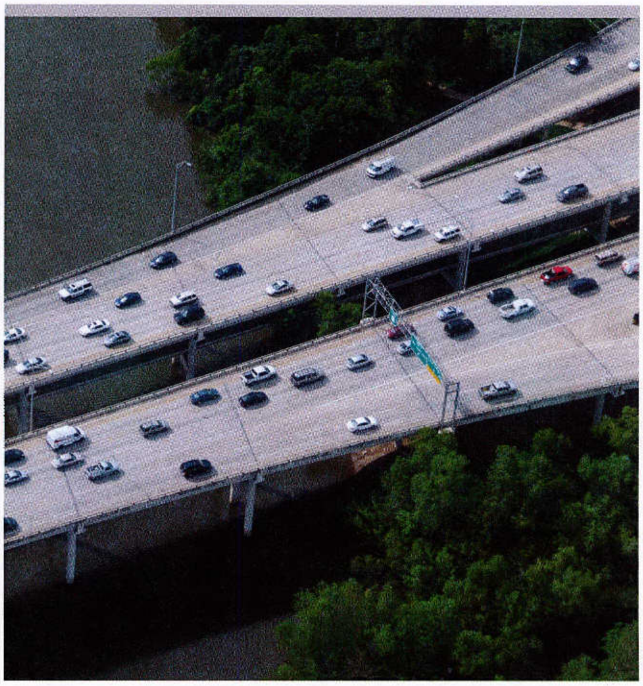
to understand the implications of modified acceleration/deceleration parameters in the context of CACC, lower congestion levels, and longer simulation periods, as well as the implications of using a dedicated CV lane.

> **Non-equipped vehicles responded logically to the slowing traffic around them by trying to pass the slowing CVs. This aggressive behavior in turn caused more friction on the roadway due to the increased lane changing.**

Barriers, Issues, and Areas for Further Research

Once researchers embarked on this project, it quickly became apparent that replicating this type of application in a real-world setting would present a variety of challenges—including developing a model, replicating CV behavioral characteristics and communication parameters, and considering the sheer size of the modeled network. The MRM process in itself is still at the early stages of being adopted by the research community due to the level of effort and modeling skillset needed. The MRM process requires expertise in both transportation planning and traffic operations, as well as thorough knowledge of both TDMs (macroscopic) and simulation-based models (mesoscopic and microscopic). In addition, all three model resolutions were developed in different software platforms (TransCAD, DynusT, and VISSIM), thus further complicating the transfer process from one model resolution to another.

Once the MRM process had been achieved, researchers needed to develop the custom CV algorithm and subsequent driver behavior characteristics for testing. The model for I-35 in Austin was developed in both the northbound and southbound directions. One of the largest hurdles to clear was determining which vehicles should act on received messages; for instance, researchers found it challenging to keep the custom CVs from acting on broadcast messages that were not intended for them (e.g., messages sent from vehicles traveling in the opposite direction).



In comparison to most models, microscopic models developed using the MRM process tend to have a larger file size and greater complexity, and as a result, they require much greater processing power and time. When it ran for 5,400 seconds, the I-35 Austin microscopic model generated over 85,000 vehicles for the 12-mi stretch of freeway. Simulating such a large number of vehicles puts a tremendous burden on computer processors. The research team had to rely on a limited supply of computers with sufficient amounts of memory (32 GB RAM) and computing power; thus, the run time to simulate 5,400 seconds of CV simulation took approximately eight days to complete. This lengthy period was due to the tremendous number of calculations performed at each time step (processing each vehicle sending and receiving messages every 0.1 seconds). Researchers are investigating whether the long run times were a result of inadequate computing power or other technical issues.

A detailed list of issues, questions, and other areas of uncertainty the researchers identified throughout the research process is included in Appendix F.

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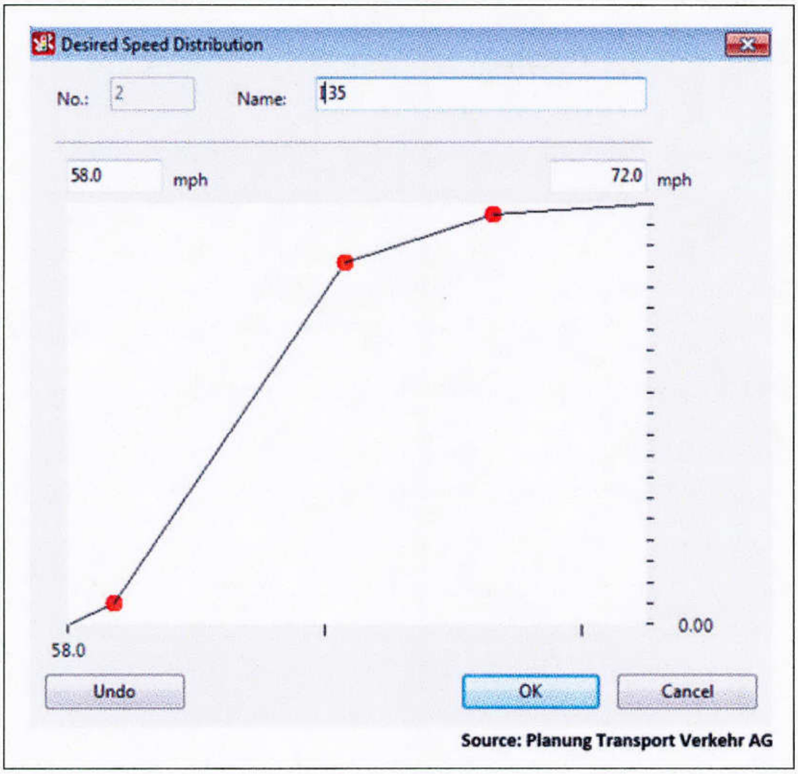
Appendix A—Wiedemann 99 Model Parameters

Standstill Distance	Desired distance between stopped cars.
Headway Time	Time drivers want to keep when trailing another vehicle. The higher the value, the more cautious the driver is.
Following Variation	Restricts how much more distance than the desired safety distance a driver allows before he or she intentionally moves closer to the car in front.
Threshold for Entering (Following)	Defines how many seconds before reaching the safety distance the driver starts to decelerate.
Following Thresholds (Negative and Positive)	Controls the speed differences when vehicles are in a following state.
Speed Dependency of Oscillation	Influence of distance on speed oscillation while in the following process.
Oscillation Acceleration	Actual acceleration during the oscillation process.
Standstill Acceleration	Desired acceleration from a standstill position.

Appendix B—Speed Profile



No.: 2
Name: 135

58.0 mph
72.0 mph

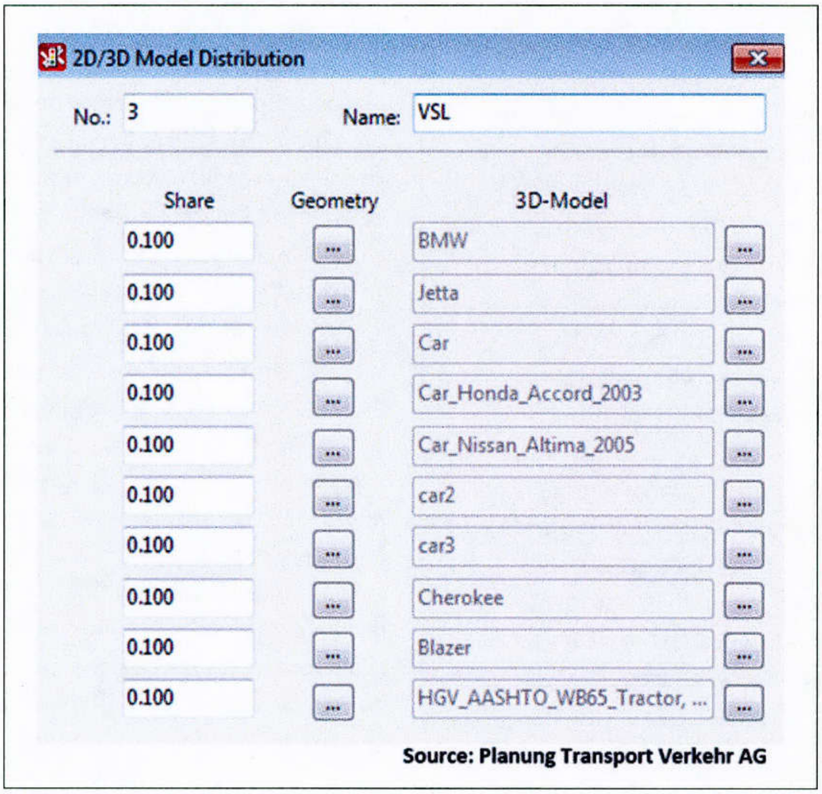
Source: Planung Transport Verkehr AG

Source: (*1*)

Reference

1. Planung Transport Verkehr AG. *VISSIM 5.30-05 User Manual*. Karlsruhe, Germany, 2011.

Appendix C—Vehicle Composition



No.: 3

Name: VSL

Share	Geometry	3D-Model
0.100	...	BMW
0.100	...	Jetta
0.100	...	Car
0.100	...	Car_Honda_Accord_2003
0.100	...	Car_Nissan_Altima_2005
0.100	...	car2
0.100	...	car3
0.100	...	Cherokee
0.100	...	Blazer
0.100	...	HGV_AASHTO_WB65_Tractor, ...

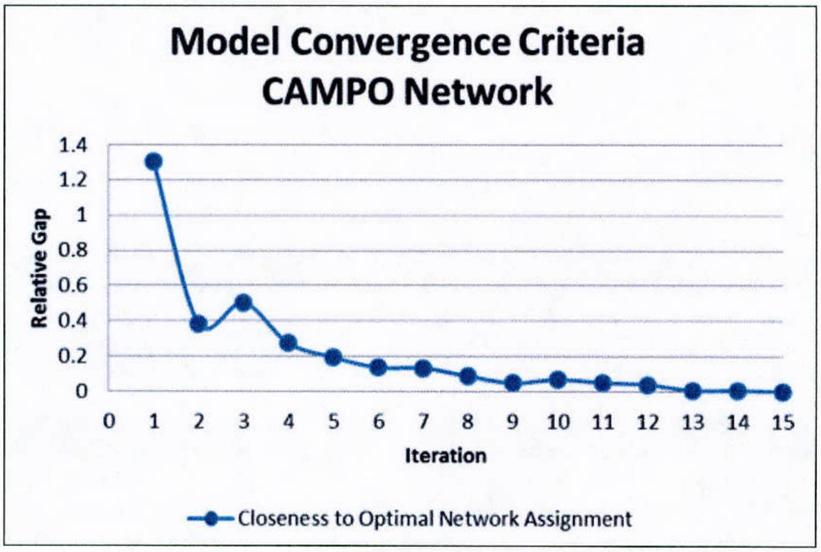
Source: Planung Transport Verkehr AG

Source: (*1*)

Reference

1. Planung Transport Verkehr AG. *VISSIM 5.30-05 User Manual*. Karlsruhe, Germany, 2011.

Appendix D—Convergence Criteria



Appendix E—Analysis of Results

Total Volume

The essential part of mobility from a CV perspective involved analyzing performance measures along the I-35 corridor, including total volume, speed, and travel time. Results from the simulation models seemed to follow a general pattern: as market penetration rates increased, the total volume that traveled the entire 12-mi corridor decreased. For example, when 40 percent of the vehicles were equipped, total through volume in the southbound direction decreased 57 percent, while a 100 percent penetration reduced traffic throughput by 65 percent.

In the northbound direction, the percent difference in through volume was substantially less due to the number of vehicles traveling in the opposite direction (i.e., southbound direction regularly experienced more congestion than northbound). A 40 percent penetration rate of equipped vehicles only reduced through volumes in the northbound direction by about 12 percent, while a 100 percent penetration rate resulted in a flow decrease of 59 percent. This discrepancy may indicate that a similar decrease in throughput may be less pronounced at lower traffic volumes although the differential was reduced at higher penetration rates. Further study is needed to test this hypothesis, however. Table 1 highlights the total volume comparison and percent difference between the base models (0 percent market penetration rate) in both directions of travel for the simulated one-hour period.

Average Speed

The average speed across all modeled scenarios showed a similar pattern. As the market penetration increased, the average speed of all vehicles decreased incrementally in a non-linear fashion. The average speed of the base model was 31 mph, while a 40 percent market penetration reduced the average speed to 20 mph. At 100 percent market penetration, the average speed of all vehicles dropped in half to approximately 15 mph. This result suggests that as the market penetration rate increases, more vehicles follow a uniform speed, which in turn decreases the total average speed. Model observations showed that as the market penetrations increased, so did the amount of lane changing. Non-equipped vehicles were still traveling at the predefined speed range (58–72 mph) and were inclined to pass the CVs. This caused friction on the freeway as more and more vehicles tried to pass the slower CVs broadcasting and receiving messages. This in turn propagated backwards as more vehicles entered the freeway segment, thus reducing the overall average speed. Figure 10 outlines the average speed for the various market penetrations.

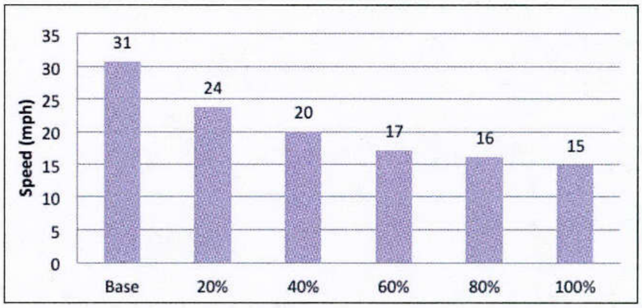


Figure 10. Average Speed—All Vehicles.

Table 1. Total Through Volume Comparison.

Northbound	Base	20%	40%	60%	80%	100%
Total Through Volume I-35 Main Lanes	1,015	1,022	893	693	640	419
Percent Difference		1%	−12%	−32%	−37%	−59%

Southbound	Base	20%	40%	60%	80%	100%
Total Through Volume I-35 Main Lanes	2,595	1,570	1,127	1,026	947	921
Percent Difference		−39%	−57%	−60%	−64%	−65%

Travel Time

Travel time was another performance measure that was calculated for the 12-mi corridor. The average travel time, calculated for the entire simulation period, increased by five minutes when the market penetration increased to 40 percent in the northbound direction. With full market penetration, the travel time increased to over 33 minutes. In the southbound direction, average travel times increased from approximately 30 minutes to 46 minutes with 40 percent market penetration, while 100 percent penetration saw travel times increase to 48 minutes. Increases in travel times indicate that as higher market penetrations are simulated, operational performance decreases due to the speed harmonization taking place (i.e., everyone reducing and traveling at a uniform speed). Figures 11 and 12 display the travel time results.

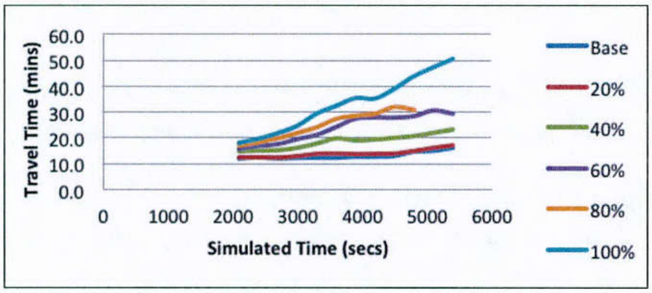


Figure 11. Travel Time I-35 Main Lanes (Northbound).

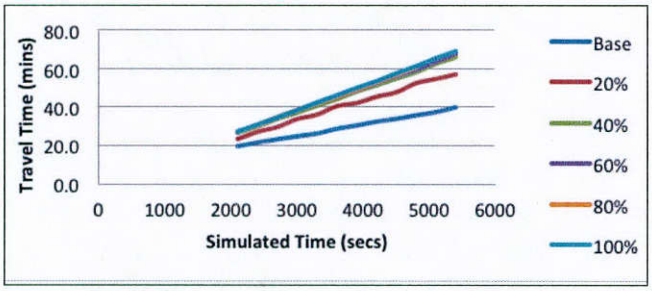


Figure 12. Travel Time I-35 Main Lanes (Southbound).

Total Through Volume Comparison

Figures 13 through 16 display the results for the total through volume comparison on the main lanes and managed lanes.

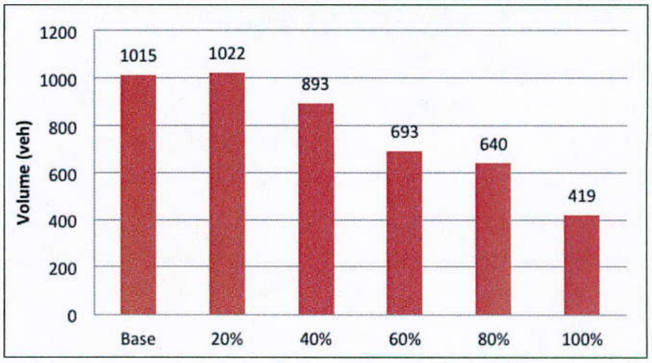


Figure 13. Total Through Volume I-35 Main Lanes (Northbound).

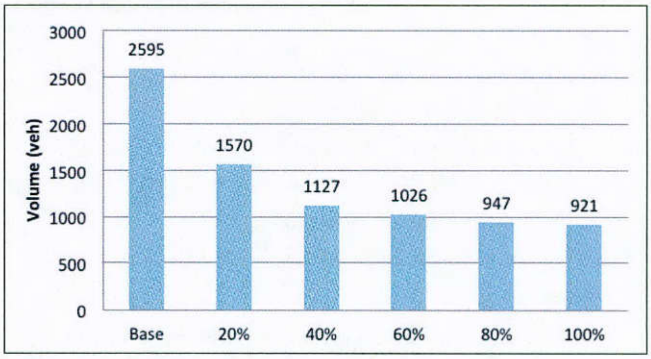


Figure 14. Total Through Volume I-35 Main Lanes (Southbound).

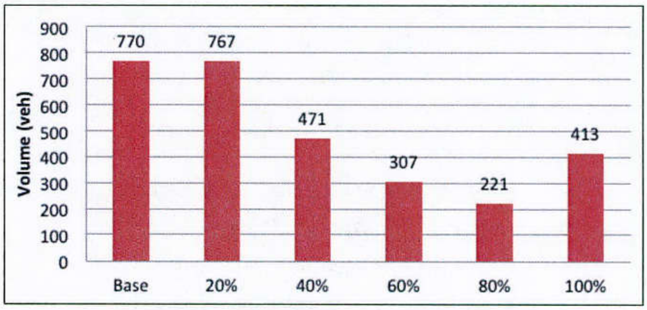


Figure 15. Total Through Volume I-35 Managed Lanes (Northbound).

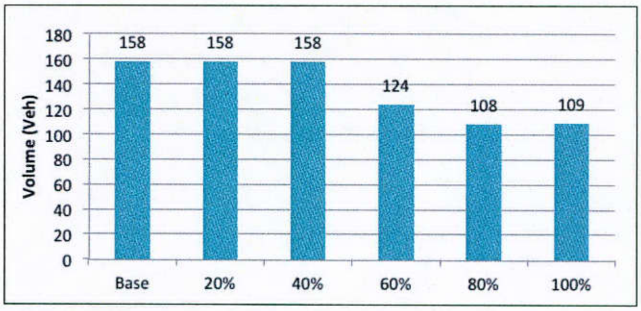


Figure 16. Total Through Volume I-35 Managed Lanes (Southbound).

Appendix F—Questions, Issues, and Uncertainties

This appendix is provided as a resource for future research purposes. Throughout the project, the research team came across a variety of questions and issues related to the development and implementation of a CV model. At the request of the research sponsor, many of these questions and issues are documented here.

Operational Issues and Questions

Operational issues encountered include the following:

- There is a lack of standardized control algorithms for CV applications.
- There do not appear to be standardized operational rules for mobility applications.

Operational questions for future consideration include:

- Do different vehicle makes behave differently when using the same mobility application?
  - How would behavioral differences affect network performance?
- Do vehicles need to behave uniformly for optimal traffic performance?
  - If so, how do we ensure interoperability in behavior, etc.?
- Do mobility applications take control of the vehicle, or is that up to the individual vehicle or motorist's discretion?
- What is an expected operational range of dedicated short-range communication radios? Several distances are listed in the literature, ranging from 20 m to 400 m, but it is unclear what range should be assumed for operational purposes.
- Should there be limitations on the communication of certain message types?
- Will there be perfect wireless communication in a CV environment and no communication delays?
  - Will the network ever be congested, and how would this affect performance?

CACC Questions

CACC questions include the following:

- What are the operational rules for CACC?
- What are the rules surrounding how platoons of vehicles form and function?
- Does CACC take place in general-purpose or dedicated lanes only?
- How much distance should CACC vehicles leave?
- Will CACC at shortened distances require V2I as well?
- What role does V2I play?
- How quickly do vehicles accelerate/decelerate under CACC?
  - Is there uniform acceleration for all vehicles?
  - How do differing acceleration rates affect throughput?
- How do different makes and models affect CACC or mobility applications?
- Are there minimum or maximum speeds for CACC to occur?
- Are there geographic or other road design constraints to platooning?
  - Can they be used on both urban and rural roads?
- Does adverse weather affect platooning and headway distances?
- Do incident locations cause platoons to disengage?
- Can an entire platoon change lanes? Simultaneously?

Speed Harmonization Questions

Speed harmonization questions include the following:

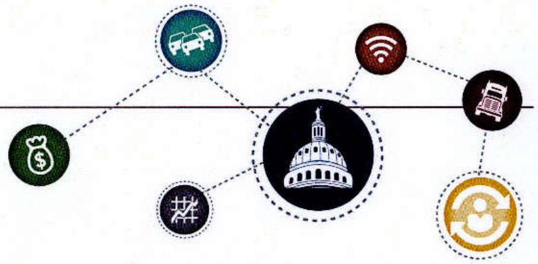
- Should there be limitations on communication of certain message types?
- Do different lanes have different speeds?
- Do vehicles in different lanes act on messages?
- Are there different algorithms based on prevailing road/weather conditions?
- Does topology play a role in speed limit (e.g., mountainous locations)?
- Can speeds be harmonized based on historical data (e.g., typical bottleneck locations)?
- Does the spacing or distance between ramps and access points affect speed harmonization?
- Does vehicle composition play a role? Do more trucks mean vehicles follow a more conservative algorithm?
- How does D-HARM react in heavily congested conditions?
- What happens when there is a non-equipped vehicle traveling between two consecutive CVs?
  - Do they change lanes?

- Should speed harmonization be deployed in conjunction with Q-WARN?
- What are the recommended speed reduction increments? How low can the speed limit go?
- At what level of congestion onset are the applications enacted?
- Are user classes (i.e., trucks) restricted, or are certain classes restricted to certain lanes?

Queue Warning Questions

Queue warning questions include the following:

- Which vehicles are subject to the messages being sent by leading vehicles? Do only vehicles in the same lane receive and respond to the message?
- What is the reaction time needed?
- What is the first reaction step of a Q-WARN vehicle? Does it try to change lanes before slowing down, while slowing down, or after slowing down?
- In Q-WARN, how far back should vehicles start to slow to match speed?
- Do cars and trucks receive the message at the same time? Do they each respond at the same rate?
- Should Q-WARN be deployed in conjunction with D-HARM?

Texas A&M
Transportation
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