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Kittelson & Associates
North Central Texas Council of Governments

AV2.1 SCENARIO EVALUATION REPORT

AV2.1: Conduct a Planning Process to help the North Texas Region Prepare for Automated Vehicles and Related Technologies

September 23, 2022

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EXECUTIVE SUMMARY

One of the greatest uncertainties in transportation planning today is private sector market forces and what will emerge as the sustainable price points, if any, of automation transportation and other emerging transportation technologies.

Currently, planners do not have enough data to assign probabilities to potential future scenarios, so proactively identifying a diverse suite of potential future scenarios to assess potential needs provides a framework that agencies can use to start the planning process and adapt agilely as more information emerges from external market forces.

Scenario Development

A major assumption used for this research is that vehicles are both connected and automated. Hence, we specify connected and automated vehicles (CAVs) throughout. The ability for vehicles to communicate with other vehicles and with roadside infrastructure like traffic signals is fundamental to the assumptions of capacity improvements, following distance assumptions related to platooning, and intersection operations efficiencies. Automated vehicles tested today do not benefit from this connectivity. As a result, they are more conservative than most human drivers. They follow at longer distances and waiting for larger gaps between approaching vehicles. That conservative behavior could *decrease* capacity, rather than increase it.

The Scenario Development Report explains how we developed seven potential future transportation automation scenarios for the region, and how we selected three of these scenarios for further modeling evaluation under the AV2.1 project:

> **CAV Impact on Roadway Network Performance.** This scenario assumes that vehicles that are both connected and automated will enhance roadway network capacity and reduce the value of time for drivers.
>
> **CAV Impact on Intersection Performance.** This scenario assumes that connected vehicle-to-infrastructure technology will improve intersection capacity and reduce intersection delays.
>
> **CAV Impact on Population and Employment Distributions.** This scenario assumes that automated vehicles will cause travelers to make longer trips due to the decreases in their travel delay and the value of time for drivers. It will capture possible growth opportunity scenarios due to CAVs. Each city or county can use these scenarios to define what it considers desired or undesired growth patterns for their area and to develop policies to incentivize their desired growth pattern.

Scenario Evaluation

The NCTCOG Modeling Group selected a modeling platform developed by the University of Texas Austin in conjunction with NCTCOG staff (the UTAV-TAFT model) for the AV2.1 project team to use to evaluate future technology scenarios.

This Scenario Evaluation Report summarizes the modeling methodology, assumptions, and results. For each scenario, we tested a range of CAV fleet penetration rates (0%, 25%, 50%, and 100%). Model input assumptions include AV fleet penetration rate, link capacity improvement, AV value of time reduction, increased speed, increased non-freeway saturation flow rate, lower signal control delay, and demographic data for population and employment redistributions.

This is the first study to apply the new capacity adjustment factors for connected and automated vehicles from the *Highway Capacity Manual* 7th Edition[1] to a regional travel demand model.

Key Findings

CAVs alone will not solve the region's future congestion problems. Additional travel demand management and capacity increasing strategies are needed to meet current and future transportation needs.

The model results followed predicted patterns. Generally, under any capacity improvement scenario:

- Vehicle Miles Traveled (VMT) *increases*
- Vehicle Hours Traveled (VHT) *decreases*
- Average Daily Speed *increases*
- Daily Delay *decreases*

Change in VMT, VHT, Average Daily Speed, and Daily Delay varies between different roadway functional classes and by time period (morning peak (AM), evening peak (PM), off peak (OP)).

Scenario 1: CAV Roadway Performance has the most impact on the overall system performance compared to *Scenario 2: CV Intersection* and *Scenario 3: CAV Demographic Distribution*. Scenario 1 accounts for an increase in the roadway capacities across all functional classes based on different CAV penetration rates. The incremental changes in the network performance under Scenario 2 and then Scenario 3 are smaller than the change recorded for Scenario 1.

When roadway capacity increases, travelers will drive longer due to faster speeds on the network. Hence, the adoption of CAVs could significantly increase the VMT in the region. If population and employment are redistributed (spread out along major corridors instead of centered in central business districts), this increase in the VMT is expected be about 30% to 40% less because jobs are relocated closer to households. Even this reduced VMT impact is still higher than the VMT recorded for the base scenario.

Eventually, CAV technologies could reduce the need for significant typical capital improvements and result in a potential shift of investments from adding concrete to adding technology. The technology considerably reduces the congestion in a hypothetical no-build scenario in the target year.

These conclusions were based on a set of model runs performed under specific assumptions regarding each of the modeling steps of a four-step travel demand model. Considering that no large deployments of CAVs yet exist in the world, these results should be used as a general guideline on how the regional traffic patterns and network performance could change during and after the integration of CAVs into the traffic stream. North Central Texas needs to continuously monitor its transportation system as CAVs are deployed and integrated into the system to improve

[1] National Academies of Sciences, Engineering, and Medicine. 2022. *Highway Capacity Manual 7th Edition: A Guide for Multimodal Mobility Analysis*. Washington, DC: The National Academies Press. https://doi.org/10.17226/26432.

our understanding of the incremental effects of CAVs on system operations and safety performance.

Connected vehicle communications have been researched and discussed for over 30 years across the transportation industry. Yet, widespread deployment has not happened. A fundamental assumption of this research is that CAVs can communicate with other vehicles (so that vehicles can follow closely behind another or better judge gaps between approaching vehicles) and that CAVs can communicate with infrastructure (like knowing if a signal is red or green, or knowing if there is an incident on the road ahead). The small number of automated vehicles currently being tested do not have the benefit of this communication. As a result, automated vehicles tested today are much more conservative than an aggressive human driver. If automated vehicle performance continues to be this conservative, it will *decrease* capacity, rather than increase it.

The methods of communication are changing, and the adoption rates are still low. To prepare for future modeling research, municipalities should continue to upgrade infrastructure (like signal controllers) so it can communicate with vehicles when needed. NCTCOG and municipalities should monitor the vehicle-to-vehicle communication trends to learn if the capacity assumptions reflect real-world impacts.

Future Research Needs

This analysis was an initial effort to understand the potential impacts of CAV adoption in the North Central Texas region. The assumptions should be reviewed and updated as more information becomes available about the real-world impacts of CAVs. Below is a list of additional actions and analysis to consider.

The analysis could be extended to consider other transportation automation scenarios, including automated trucks, teleworking, and automated vehicle ride-hailing services. Some of these scenarios, such as the automated vehicle ride-hailing services, would require significant modifications to the regional model, which is beyond the scope of this study.

Agencies should collect and monitor model performance measures from real-world deployments to determine if our assumptions should be revised in future modeling efforts.

The region needs a data repository for the different transportation automation pilot studies conducted in the DFW region. This data repository is essential for calibrating and validating models that can accurately predict the transportation system's performance under adopting these technologies.

The regional model enables quantifying the performance of the entire region and benchmarking it against other capital improvement projects. However, there is a need to model these scenarios at the city or county level using higher-resolution modeling platforms capable of capturing CAV traffic flow characteristics, especially those related to car-following behavior and data-sharing at connected intersections.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

1 INTRODUCTION

The fast evolution of transportation automation technologies in the North Central Texas region required a thorough planning effort to ensure adequate policy development and infrastructure investment that maximize these technologies' overall benefits. The effort entails (1) identifying leading technologies that address the region's transportation challenges, (2) predicting near and long-term operational scenarios in which these technologies will be deployed, and (3) developing adequate modeling and analysis platforms that can be used to quantify the transportation system performance and to evaluate the benefits of these technologies.

The North Central Texas Council of Governments (NCTCOG) is preparing for emerging transportation technologies through a three-phase Automated Vehicle 2.0 (AV2.0) program. The first phase of the AV2.0 program is AV2.1: Conduct a Planning Process to Help the North Texas Region Prepare for Automated Transportation & Related Technologies.

This report represents the second in a series of deliverables documenting future transportation automation scenarios' modeling and evaluation efforts. Seven potential transportation automation scenarios were initially identified and developed as possible futures for the North Central Texas region. However, the project budget combined with the amount of extra model development work required for some of the scenarios, allowed for only three scenarios to be further developed and modeled for evaluation. For a detailed description of the process of determining these scenarios, the reader is encouraged to reference the Scenario Development Report[2]. A summary is provided in Section 2 of this report.

As described hereafter, the three scenarios considered for modeling and analysis are:

1. **CAV Impact on Roadway Network Performance.** This scenario assumes vehicles that are both connected and automated will enhance network capacity and reduce the value of time for drivers.
2. **CAV Impact on Intersection Performance.** This scenario assumes that connected vehicle-to-infrastructure technology will improve intersection capacity and reduce intersection delays.
3. **CAV Impact on Population and Employment Distributions.** This scenario assumes that automated vehicles will cause travelers to make longer trips due to the decreases in their travel delay and the value of time for drivers. It will capture possible growth opportunity scenarios due to CAVs. Each city or county can use these scenarios to define what it considers desired or undesired growth patterns for their area and to develop policies to incentivize their desired growth pattern.

This research assumed that vehicles will be both connected and automated. That is why we specify connected and automated vehicles (CAVs) throughout. The connectivity with other vehicles and with roadside infrastructure like traffic signals is fundamental to the assumptions of capacity improvements and intersection operations efficiencies. However, there is not a clear path forward to widely expand vehicle connectivity. NCTCOG and municipalities should monitor

[2] NCTCOG, 2022, *AV2.1 Scenario Development Final Report*.

the vehicle-to-vehicle communication trends to learn if the future capacity assumptions reflect real-world impacts.

These three scenarios describe the anticipated evolution of transportation automation technologies and their impact on the performance of the regional transportation system.

- First, as CAVs demonstrate their superiority over regular vehicles concerning cost, safety, and convenience, more households are expected to adopt them gradually. As the CAV penetration rate increases in the region, one can anticipate an improvement in the overall network capacity as CAVs could be traveling at higher speeds and shorter headways.
- Second, municipalities are expected to invest in upgrading their signalized intersection, taking advantage of the connected intersection technology. The technology will enable vehicles and the signal controller to share data to increase the intersection capacity and minimize vehicle delays.
- Third, because of the anticipated improvement in the overall performance of the transportation system and the elimination of the driving inconvenience, households and businesses are expected to move to the region's peripheral zones to take advantage of the reduced real estate cost in these zones. The relocation of households and businesses will result in a new OD demand pattern in the region.

The AV2.1 Team coordinated with the NCTCOG Modeling Team to determine which modeling platforms are suitable to model the three selected transportation automation scenarios. The NCTCOG Modeling Group recommended a modeling platform developed by the University of Texas Austin in conjunction with the NCTCOG staff (the AV-TAFT model) for the AV2.1 Team. The AV-TAFT regional model platform enables evaluating the different scenarios at the regional level and benchmarking them against other planned capital investment projects.

The project team conducted a preliminary review of the AV-TAFT model. The AV-TAFT model considers more emerging technologies than the NCTCOG's existing TAFT model and has the functionality to simulate the effects of some CAV technology scenarios. The NCTCOG's TAFT model does not include that functionality in any modeling stages. The project team developed a slightly modified version of AV-TAFT (CMAV-TAFT), which provides the capabilities required for modeling the AV2.1 scenarios. To distinguish between the modified AV-TAFT developed by the project team and the original AV-TAFT model, the rest of the document uses UTAV-TAFT to refer to the original platform and CMAV-TAFT to refer to the platform used to model the AV2.1 scenarios.

More than 25 model runs (experiments) were designed to evaluate these three scenarios. These experiments examined the effect of several experimental factors (or model input variables and parameters) describing the possible changes in the traffic flow characteristics, travelers' behavior, the intersection control logic, and the overall demand pattern resulting from the anticipated population and employment redistribution in the region. These experiments considered the year 2045 as the target year, assuming different CAV penetration rates of 0%, 25%, 50% and 100%. All scenarios are benchmarked against a base scenario representing the 2045 target year with no CAVs.

Several performance measures were collected to evaluate these scenarios, including vehicle miles traveled (VMT), vehicle hours traveled (VHT), average speed, and delay both at the daily and time-of-day levels. In addition, traffic volume change maps and travel time contour maps were generated to understand the regional travel pattern resulting from adopting the CAV technology.

This report is organized as follows. Section 2 describes the scenario selection process and defines the three main scenarios considered for modeling and evaluation. Section 3 provides an overview of NCTCOG's regional demand forecasting model (TAFT) and describes the main modifications to model the CAV technology (the CMAV-TAFT model). The experiments designed to model these scenarios using the CMAV-TAFT model are described in Section 4. Sections 5 through 10 summarize the results of the experiments. Concluding comments are given in Section 11.

2 TRANSPORTATION AUTOMATION SCENARIO DESCRIPTION

2.1 Scenario Selection Process

As mentioned above, the process for selecting the scenarios considered for modeling and analysis is described in detail in the AV2.1 Scenario Development Report. The process started with a comprehensive literature review of the most common transportation automation technologies and their real-world applications. The study also collected information on the estimated market growth for these technologies. The AV2.1 Team developed seven potential future transportation automation scenarios for the North Central Texas region:

- Connected-Automated Vehicle (CAV) Impact on Roadway Network Performance
- CAV Intersection Systems
- CAV Effect on Population and Employment Distributions
- Automated Shuttles for Improved First- and Last-Mile Travel
- CAV Technology Lane and Impact on Truck Routing
- Long-Distance, High-Speed Mass Transit Services
- Urban Air Mobility (UAM) Systems for People and Goods Movement

After consultation with the Project Advisory Committee and the NCTCOG travel demand modeling group, three transportation automation scenarios selected for further modeling evaluation under the AV2.1 project are:

1. **CAV Impact on Roadway Network Performance.** This scenario assumes that both connected and automated vehicles will enhance network capacity and reduce the value or time (VOT) for drivers.

2. **Connected Vehicle-Intersection Systems.** This scenario assumes connected vehicle-to-infrastructure (V2I) technology will improve intersection capacity and reduce delays.

3. **CAV Effect on Population and Employment Distributions.** This scenario assumes that connected-automated vehicles (CAVs) will cause travelers to make longer trips due to the decreases in travel delay, increased comfort in the CAV vehicles, and reduction of VOT. It will capture possible regional growth opportunity scenarios due to CAVs. Each city or county can use these scenarios to define different growth patterns for their area and develop policies to incentivize their desired growth pattern.

The order in which these three scenarios are listed replicates the expected roll-out of the technology adoption and its impacts. Households will gradually adopt CAVs, which will increase the number of CAVs on the roadway (or the *penetration rate*). This might happen personal vehicle ownership, or through fleets of automated vehicles that are shared or accessed through a subscription service. This research tested impacts of 0%, 25%, 50%, and 100% penetration rates.

As CAV penetration rate increases, roadway capacity is assumed to increase because CAVs can follow with less headway at high speeds compared to regular vehicles (Scenario 1). Next, municipalities will gradually invest in upgrading their intersection control equipment to more advanced technologies that enable the vehicle-to-infrastructure connection and data sharing

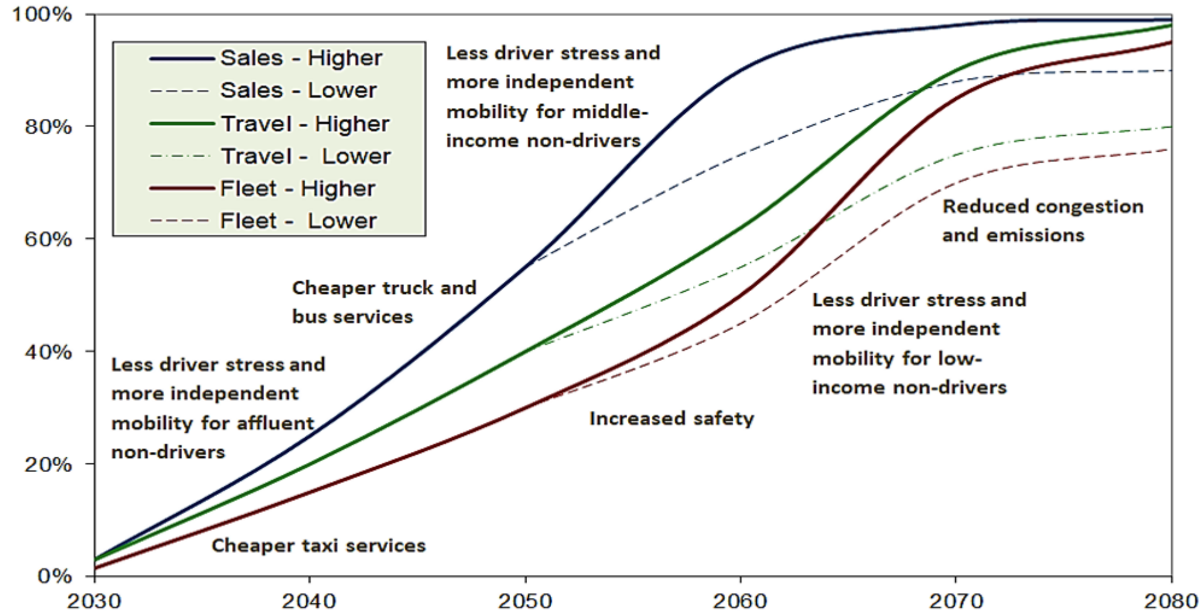
(Scenario 2). It is worth mentioning that most DFW intersections are currently capable of enabling vehicle-intersection connections and data sharing, ready for more vehicles to receive and act on this data. The innovative technology is assumed to minimize vehicle delays and enhance the intersections' throughput. The travel time improvement resulting from enhanced roadway capacity and delay reduction at intersections, along with the travel convenience using CAVs (i.e., elimination of driving stress and the better use of the in-vehicle travel time) will encourage households to revisit their residential and job locations. Households and businesses are likely to move to peripheral areas of the metropolitan area, taking advantage of cheaper real estate and rent in these areas, resulting in a redistribution of population and employment in the region (Scenario 3).

2.2 CAV Penetration

The market penetration rate of CAVs is the main factor driving how common CAVs will be on the road and their impact on the overall transportation system performance. It can also be viewed as the public's resistance to adopting CAVs. The literature reported several studies focusing on predicting AV penetration rates. Two general observations were reported in these studies. First, most of these studies are conducted by consulting firms, investment banks, and other private enterprises, most of which do not focus on the forecasting methods used in their reports. Studies performed by academic institutions are rare in the literature. Second, the range reported for these penetration rate variables in these studies varies considerably. One of the most cited works on AV penetration prediction is the work of Litman, 2022.[3]

As shown in Figure 1, Litman provided penetration rate predictions for Level 4 AVs (High Driving Automation) until year 2080. The predictions are given for vehicle fleet, new vehicle sales, and trips. For each case, rather than predicting one value for the penetration rate, Litman provided a pessimistic-optimistic range, which accounts for uncertainty in the pace of AV technology advancements and product cost, legislation changes, and infrastructure readiness. In year 2045 (the target year considered in this study), Litman predicts an AV fleet penetration rate close to 20%. Bansal and Kockelman (2017)[4] compile the main literature regarding the adoption of autonomous vehicles and provide their own estimates. Like Litman, they assumed different scenarios and provided a prediction of the AV penetration rate for each scenario. Like the work of Litman, these scenarios account for the external factors that affect travelers' decisions to adopt AVs. Based on Bansal and Kockelman (2017), the AV Level 3 penetration rate is estimated to range from 3% to 26% and Level 4 to range from 25% to 87% in 2045. This study tested impacts of 0%, 25%, 50%, and 100% CAV market penetrations for the 2045 planning year.

[3] Litman, T, Autonomous Vehicle Implementation Predictions Implications for Transport Planning, VTPI, May 2022.
[4] Bansal, P., & Kockelman, K. M. (2017). Forecasting Americans' long-term adoption of connected and autonomous vehicle technologies. *Transportation Research Part A: Policy and Practice*, 95, 49-63.



This analysis suggests that it will be at least 2045 before half of new vehicles are autonomous, and 2060 before half of the vehicle fleet is autonomous. Significantly faster deployment will require scrapping many otherwise functional vehicles that lack self-driving ability. Some benefits, such as reduced driver stress and independent mobility for affluent non-drivers, can occur when autonomous vehicles are relatively costly and rare. However, most benefits, such as independent mobility for moderate-income non-drivers and affordable taxi and micro-transit services, can only be significant if they become common and affordable, and some benefits, such as reduced congestion, will require dedicated lanes to allow platooning.

Figure 1. Projections of Level 4 AVs (Source: Litman, 2022)

2.3 Scenario 1: CAV Impact on Roadway Network Performance (Capacity)

The AV technology has considerable growth potential; the global autonomous vehicle market demand is estimated to grow from approximately 6.7 thousand units in 2020 to about 4.3 million units in 2030.[5] With this fast growth and the ongoing race among major technology companies and car manufacturers to build the first operational vehicle, there is an urgency among planning agencies to carefully evaluate the benefits and issues associated with the introduction of AV technologies on their roadway networks.

The transportation industry is still working to conceptualize AV operations in urban areas. However, there is agreement among transportation planners that AVs will have a significant impact on (1) the travelers' behavior and (2) the traffic flow efficiency. For example, AVs are expected to alter travelers' perception of long trips. As riders are not under the stress of driving and may be involved in more productive activities, they will be more willing to spend more time in their vehicles to access farther destinations. Thus, one can expect a notable increase in the average vehicle miles traveled resulting from this behavior change. In addition, as this technology advances, vehicles that are both connected and automated (CAVs) will allow vehicles to travel at higher speeds and with shorter headways, enable platoons with harmonized speed, and eliminate accidents due to drivers' errors. Thus, CAVs are expected to improve roadway capacity and non-recurring congestion situations.

2.4 Scenario 2: CAV Impact on Intersection Performance

The connected intersection technology aims to improve signalized intersections' performance by reducing vehicle delays and stops. It establishes communication between the vehicles and the intersection's signal controller to enable real-time data sharing (vehicle-to-intersection communications or V2I). The controller receives real-time data from the vehicles on their locations and speeds and uses it to adjust the green time allocation to the different phases optimally. Simultaneously, vehicles approaching the intersection receive information on the signal phasing and timing (SPaT) and recommendations to adjust their speeds to avoid unnecessary stops/delays at the intersection. The system is also conceptualized to provide movement assistance to vehicles while navigating an intersection. For instance, a vehicle could receive a warning that it is not safe to enter an intersection when there is a high probability of colliding with other vehicles. The V2I technology is expected to reduce total delays and stop opportunities at intersections.

The technology will reduce the delays at the intersections and enable a better distribution of the traffic along the different roadway facilities in the network. For example, with the anticipated reduction in the travel time along the arterials and increased capacity on the freeway facilities, there is no need for freeway traffic to divert to the arterial network to bypass the freeway congestion. This correction in facility usage can also translate into significant fuel consumption and emissions reduction. As for the impact on traffic safety, the National Highway Traffic Safety Administration estimates that movement assistance systems in connected intersections would

[5] Autonomous Vehicle Market Size, Share & Trends Analysis Report by Application (Transportation, Defense), By Region (North & South America, Europe, APAC, MEA), And Segment Forecasts, 2021 – 2030. https://www.grandviewresearch.com/industry-analysis/autonomous-vehicles-market

prevent between 413,000 and 592,000 crashes, save between 777 and 1,083 lives, and reduce 191,000 to 270,000 injuries in the US every year[6].

2.5 Scenario 3: CAV Impact on Population and Employment Distributions

The current practice in demographic forecasting relies on available historical data to establish a relationship between a zone's accessibility and amenities and the desire for future home or work locations to locate in those areas. In reality, the household's choice of home location is typically a complex function of household income, accessibility, number of workers in the household, work location(s), and school district rating. The introduction of autonomous modes in the mix of transportation options can change this paradigm and relax some constraints such as distance to work or entertainment/shopping venues from the home location selection process. This shift can result in more uniform population distribution and/or employment across the region.

As previously discussed, one of the important discussion topics among planners regarding the introduction of CAVs into the traffic mix is their potential impact on travelers' perception of travel distance due to the increased travel comfort, reduced driving stress, and decreased vehicle operating cost. The added comfort can also potentially result in more productive utilization of the in-vehicle time. These factors can change one's home location choice criteria and result in households deciding to live farther away from the center of activities where housing prices are more affordable, resulting in increased urban sprawl and an increase in total vehicle miles of travel.

2.6 Scenario Naming Convention

A set of experiments was designed to explore the impacts of the three main scenarios. A total of 29 experiments (or runs) were developed. Scenario S1 is modeled using 15 experiments, numbered S1R1 to S1R15. Scenario S2 is modeled using six experiments numbered S2R16 to S2R21. Scenario S3 is modeled using four experiments, S3R24, S3R27, S3R28, and S3R29. Tables 2 through 4 in Section 4 explain the naming convention and assumptions used for each experiment conducted.

[6] USDOT, Connected Vehicle Basics: What type of Connected Vehicle user are you? https://www.its.dot.gov/cv_basics/cv_basics_type.htm

3 MODELING PLATFORM

Several modeling frameworks are initially proposed to model these transportation automation scenarios, including microscopic traffic simulation models, the mesoscopic simulation-based dynamic traffic assignment models, and the regional travel demand model developed and maintained by NCTCOG. Considering the planning scope of this study and the ongoing effort to upgrade the DFW regional travel demand model (the TAFT model) to account for connected and autonomous vehicle technologies, there was an agreement to adopt the regional travel demand model in this study. The model expects to enable evaluating the proposed transportation automation scenarios at the regional and sub-regional levels and benchmarking the performance of the transportation system considering the region's other transportation improvement activities. Of course, other high-resolution simulation-based modeling frameworks could be adopted. However, they will require intensive effort for model development, calibration, and validation that are beyond the scope of this study. For completeness of this report, this section provides an overview of the TAFT model, how it simulates the CAV technologies as the AV-TAFT model, and how it is modified to account for autonomous vehicles as the CMAV-TAFT model.

3.1 The Regional Travel Demand Model (TAFT): An Overview

3.1.1. SPATIAL AND TEMPORAL MODEL SCOPE

The modeling area of TAFT includes the counties of Collin, Dallas, Denton, Ellis, Hill, Hood, Hunt, Johnson, Kaufman, Parker, Rockwall, Tarrant, and Wise. The model is used to model an entire average day divided into morning, afternoon, and off-peak periods (AM, PM, and OP periods).

The TAFT accepts the following input files: demographic data, roadway network including toll roads and HOV, transit supply system including rail and park-and-ride, and airport and external stations forecasts. The model produces traffic volumes and speeds on roadways and transit usage data on the transit system.

The modeling area is divided into travel analysis zones (TAZ). The transportation network is GIS-databased representing the actual roadway and rail links for the year of analysis. The transportation network file is a series of links connected through nodes representing railroad tracks, roads, and intersections. The model integrates four main modules (steps) that run sequentially with the possibility of iterating them, creating an iterative feedback process. These modules are Trip Generation (Step 1), Roadway Skim and Trip Distribution (Step 2), Mode Choice (Step 3), and Traffic Assignment (Step 4). The following subsections provide a brief description of these four steps.

3.1.2. TRIP GENERATION

The trip generation module converts demographic data into person trips productions and attractions for different trip purposes. The input demographic data for the trip generation module includes population, the number of households, median household income, the number of basic, retail, and service employments and special generator employments, the household income distribution, and the household size distribution for each TAZ. The underlying model for the trip generation module is a cross-classification model . The model gives a trip rate by purpose for each population segment. The segmentation is conducted based on socioeconomic characteristics. The outputs of the trip generation production and attraction person trips from and to each TAZ for fourteen trip purposes. The outputs are used in the trip distribution step along with roadway skims.

3.1.3. TRIP DISTRIBUTION

The Trip Distribution module determines the number of trips between each origin and destination (OD) TAZ in the study area. The model adopts a form of the gravity model for trip distribution. A gravity model estimates the number of trips between two zones (the origin and the destination). The trip distribution is affected by trip production in an origin TAZ, trip attraction in a destination TAZ, and the travel cost between the origin and destination TAZs. The parameters are calibrated for each trip purpose. The gravity model requires information on the friction factor, production/attraction totals, and the travel impedance matrix (or travel costs). The gravity model produces trip matrices where each cell in a matrix gives the number of trips between an origin-destination zone pair for one of the defined trip purposes.

3.1.4. MODAL SPLIT

The mode choice module determines the portion of trips that use different modes. The module is applied to the trip table produced by the trip distribution process. The main modes considered in the TAFT model are drive alone, shared-ride with two occupants (SR 2), shared-ride with three or more occupants (SR 3+), transit with walk access, and transit with drive access. Mode choice models are developed for different trip purposes. The output of the mode choice module are sets of person trip tables using the modes Drive Alone, SR 2, SR 3+, Transit Walk Access, and Transit Auto Access for the different trip purposes.

3.1.5. TRIP ASSIGNMENT

The last step in the 4-Step framework is the traffic assignment (or route assignment). The vehicular traffic is assigned to the network's different routes for the AM period, PM period, and OP periods. The transit demand is assigned in the peak and off-peak periods. The inputs for roadway traffic assignment are vehicle trip tables for the different periods. The model considers 10 vehicle classes. The model adopts a generalized cost method for multi-modal multi-class N-conjugate user-equilibrium (N = 5) roadway assignment. The generalized cost considers path choice by a combined measure of roadway operating cost, toll cost, and travel time. The model allows different vehicle classes to access different sets of roadway networks and different parameters for VOT.

3.1.6. THE FEEDBACK PROCESS

The primary purpose of the feedback process is to ensure that the link travel times resulted from the traffic assignment step are consistent with the travel time assumptions in the trip distribution and model choice stages. In this process the travel time skim matrices are fed-back in the trip distribution step and the modeling process repeats unless the inputs to the modeling process are close to the outputs of the traffic assignment stage.

3.2 Modification for Transportation Automation Scenario Modeling

The Center for Transportation Research (CTR) at The University of Texas at Austin conducted a research study sponsored by NCTCOG to develop an upgraded version of the NCTCOG's regional model (the TAFT model) that enables modeling CAV traffic called AV-TAFT[7] . As mentioned earlier, this latest version, AV-TAFT, is adopted in this study and slightly modified to develop the CMAV-TAFT for the purposes of this study. The following subsections describe the main considerations for modifying the UT AV-TAFT model to further upgrade its CAV modeling capabilities for the purposes of this study (resulting in the CMAV-TAFT model).

3.2.1. ROADWAY CAPACITY MODIFICATIONS

The change proposed here focuses on modeling how the AV traffic impacts the capacity of the roadway links. The UTAV-TAFT model estimates the amount of roadway capacity consumed by each AV while on a trip. The approach adopted in this version modifies the passenger car equivalent (PCE) factors for AVs as a function of AV penetration rate in the traffic composition and the prevailing traffic speed. The model assumes that AVs have smaller PCE factors than regular vehicles. The value of these factors increases with the AV penetration rate and reduces with the increase of the traveling speed. While this approach is valid, it differs from the latest procedure proposed in the recent version of the Highway Capacity Manual[8], which suggests directly increasing the roadway link capacity as a function of the AV penetration rate. Table 1 provides the proposed capacity improvement by the highway capacity manual for the different penetration rate values. The table shows that the roadway link capacity improves as the CAV penetration rate increases. For example, at a 20% penetration rate, the roadway link capacity improves by 2%. At a 100% penetration rate, the capacity improves by 33%.

Table 1. HCM Capacity Adjustment Factors for Basic Freeway and Diverge Segments (Source: HCM Exhibit 26-15).

The proportion of CAVs in Traffic Stream	Adjusted Segment Capacity		
	2,400 pc/h/ln	2,100 pc/h/ln	1,800 pc/h/ln
0	1.00	1.00	1.00
20	1.02	1.02	1.15
40	1.07	1.10	1.27
60	1.13	1.25	1.40
80	1.22	1.37	1.60
100	1.33	1.52	1.78

3.2.2. NON-FREEWAY FACILITY SATURATION FLOW RATE MODIFICATIONS

The link capacity factors were also applied to the saturation flow rates of the non-freeway links for calculating the intersection traffic control delays. Although the HCM proposes slightly higher values for increase in saturation flow rates, but due to the existing unknowns about the performance of CAVs and the V2I technology and to stay on the more conservative side, the study opted to apply the lower capacity factors.

[7] The AV-TAFT model was developed by The University of Texas at Austin Center for Transportation Research under the NCTCOG project Travel Modeling in an Era of Connected and Automated Transportation Systems: An Investigation in the Dallas-Fort Worth Area (2017-2021).

[8] National Academies of Sciences, Engineering, and Medicine. 2022. *Highway Capacity Manual 7th Edition: A Guide for Multimodal Mobility Analysis*. Washington, DC: The National Academies Press. https://doi.org/10.17226/26432.

3.2.3. TRAFFIC CONTROL DELAY MODIFICATIONS

The assumption is that the intersection delay will be reduced after the implementation of V2I technology. Therefore, a signal control delay reduction factor was added as an input to the network creation process and uniformly applied to all link functional classes and area types.

3.2.4. FREE FLOW SPEED MODIFICATIONS

The AV2.1 scenario modeling assumptions account for an increase in travel speeds under all volume to capacity (V/C) ratios across all link functional classifications when CAVs are in the traffic stream. Therefore, a free-flow speed adjustment factor was added as an input to the modeling process and applied during the network creation stage. The speed limit is assumed to be unchanged.

The model does not originally assume that travel speeds are typically faster than the posted speed limits in the off-peak period when V/C ratios are lower. The model sees only one speed limit for all time periods.

This research introduced a slight increase of up to 10% in speeds at 100% CAV penetration. This will assume that only in extremely low V/C ratios, the actual travel speeds can go above the currently specified speed limits. At high V/C ratios, the travel speeds will be below the posted speeds in most cases.

This research did not study a scenario in which the speed limits are reduced. The travel demand model cannot have different speed limit assumptions by core because it uses a single volume-delay function that only takes one free-flow speed value for all cores in the MMA assignment.

3.2.5. VALUE OF TIME (VOT) AND VEHICLE OPERATING COST MODIFICATIONS

As discussed in the previous sections, the general comfort associated to driving a CAV vehicle will result in a reduction of perceived VOT for the vehicle occupants. Therefore, we added an input in the modeling process to account for this reduction and applied in the traffic assignment stage. We assume uniform changes to VOT for all automated vehicle modes (including taxis and transportation network company or ridehailing vehicles) due to CAV penetration.

We added an additional adjustment input factor to the traffic assignment stage to account for the potential reduction in vehicle operating costs.

3.3 Measures of Performance

Several performance measures are used in this study to evaluate the transportation system performance for the three automation scenarios described above. These performance measures are defined as follows.

- **Vehicle Miles Traveled (VMT)** is calculated by multiplying the amount of traffic on a roadway segment by the length of the segment, then summing all the segments' VMT to obtain a total for the geographical area of concern. The VMT could be calculated for a period (e.g., AM peak, PM peak, and PM period) or the entire day.
- **Vehicle Hours Traveled (VHT)** is calculated by multiplying the amount of traffic on a roadway segment by the time spent traveling this segment, then summing all the

segments' VHT to obtain a total for the geographical area of concern. The VHT could be calculated for a period (e.g., AM peak, PM peak, and OP period) or the entire day.

- **Average Speed** is the average speed of all roadway links in the network during a period of interest. The speed of a roadway link is a function of its functional classification, traffic volume, capacity, and volume-delay function (VDF).
- **Total Travel Delay** is calculated as the difference between the travel time required to traverse a roadway segment under the prevailing traffic conditions and the travel time corresponding to the free flow traffic conditions, then summing all the segments' delays to obtain a total for the geographical area of concern. The total travel delay could be calculated for a period (e.g., AM peak period, PM peak period, and OP period) or the entire day.
- **Total Travel Time** is calculated for trips originated and destined to the DFW international airport from all points within the modeling area during the AM and PM peak periods. This measure was presented in the form of travel time contours to provide a simpler visual aid explaining the potential changes in the roadway network with the introduction of CAVs in the traffic composition.
- **Level-of-Service (LOS)** is calculated as a weighted average of link V/C ratios by length across all link functional classes and area types and in each of the time periods. The traditional LOS thresholds of 0.8 for LOS ABC, 0.9 for LOS D, 1.0 for LOS E and above 1.0 for LOS F was used in this analysis. It is worth mentioning that these thresholds might change in the future based on the driver driving experience as CAVs start integrating in the traffic streams.

4 SCENARIO SPECIFICATIONS AND EXPERIMENTAL DESIGN

4.1 Experimental Factors used to Model the Transportation Automation Scenarios

Based on the structure of the modeling platform, seven experimental factors (or model variables and input parameters) are identified to model the three transportation automation scenarios described above. This subsection defines these factors, their selection justification, and corresponding modeling assumptions.

- **Roadway Link Capacity:** The link capacity is a model input that defines the maximum hourly volume per lane a roadway link can accommodate (i.e., the link throughput) under the prevailing operational conditions. The capacity value varies across the different roadway classes, where freeways typically have the highest values, and access roads have the lowest values. As CAV platooning and shorter headways are expected to increase the link throughput, the new *Highway Capacity Manual 7th Edition*[9] suggests an increase in the roadway capacity proportional to the overall CAV penetration rate in the traffic composition. A capacity increase of 33% is estimated when all vehicles on the road are fully automated and connected (i.e., 100% CAV penetration rate). This percentage is reduced for lower CAV penetration rates.

- **Volume Delay Function (Congestion Delay):** The model defines a volume delay function (VDF) for the different roadway classes (freeway, major arterials, minor arterials, access roads, etc.). The VDF is a monotonically increasing function, which estimates the traffic speed on a roadway link as a function of that link's V/C ratio. The function is also specified to account for the low sensitivity of the speed to low V/C ratio (i.e., close to free-flow conditions). In this study, we build on the general assumption that increasing the CAV penetration in the traffic composition will result in higher speed due to reduced human error and improved traffic flow stability. In other words, we assume that CAV can travel at a higher speed for the same V/C ratio. Although the capability to modify the VDF variables was provided in the CMAV-TAFT user interface but soon it was realized that we cannot achieve the goal of uniformly increasing the travel speeds at the same rate for all V/C ratios by modifying the VDF. Therefore, the free low speed adjustment factor was added as an input. An improvement of 5% is assumed for a 100% CAV penetration rate, with appropriate interpolation for low penetration rates. Here, it is assumed that there is no change in the speed limit on any of the roadway links. In addition, all links in the network, regardless of the functional classification and area type, are assumed to have the same improvement in speed.

- **Link Saturation Flow Rate:** A saturation flow rate is defined for each roadway class. This rate is defined for links with signalized control at their downstream intersections and gives the maximum number of vehicles that can be accommodated by a lane of that link in one hour of green time. It is assumed that communications between the intersection control and CAV increase the saturation flow rate. The HCM recommends a 52% increase in

[9] National Academies of Sciences, Engineering, and Medicine. 2022. *Highway Capacity Manual 7th Edition: A Guide for Multimodal Mobility Analysis*. Washington, DC: The National Academies Press. https://doi.org/10.17226/26432.

saturation flow rate at a 100% CAV penetration rate. However, to be on the conservative side, we assume the improvement in the saturation flow rate ranges from 0% to 33%, like the capacity values. The saturation flow rate for a typical arterial road increases from 1,700 vehicles/lane per hour of green to a maximum of about 2,200 vehicles/lane per hour of green. We assume that all signalized intersections in the network, regardless of their functional classification and area type, have the same percentage increase in the saturation flow.

- **Volume Delay Function (Traffic Control Delay):** A delay function is specified for each link with signalized control at its downstream intersection. It estimates the delay amount experienced by the traffic as a function of the V/C and the amount of allocated green. As mentioned earlier, the increase of the CAV penetration rate in the traffic composition and the adoption of connected intersection technologies is expected to reduce vehicle delays. The technology enables intersection-vehicle communications and data sharing, which is expected to reduce the signal lost time (i.e., increase the effective green time) and improve signal coordination along arterials. To capture this delay reduction, we assume that the decrease in the delay at intersections ranges from 0% to 10% as a function of the overall CAV penetration rate. This reduction reflects eliminating the lost time at each cycle (e.g., 4 seconds out of 90 seconds cycle) and the better coordination among nearby intersections. This delay reduction is assumed to be additional to the effect of the saturation flow. Here, we assume that all signalized intersections in the network, regardless of their functional classification and area type, have the same delay reduction percentage.
- **Vehicle Operating Cost:** The average vehicle operating cost is a model input that defines the average operating cost for passenger cars per mile of travel. Building on the assumption that CAV will be more energy efficient (e.g., electric vehicles) and require less maintenance, these vehicles are assumed to have lower average operating cost than traditional combustion engine vehicles. To reflect the anticipated reduction in the CAV's operating cost in the model, we assume the average vehicle operating cost parameter will be reduced by a predefined percentage equal to 10% for all CAVs identified as part of the model's traffic demand. We also note that vehicle capital costs are not model inputs. The vehicle operating cost is used in the model to address the route selection between faster/longer freeway routes versus slower/shorter non-freeway routes. Once CAVs start rolling out to the masses, the NCTCOG modeling team can update the vehicle ownership model to better represent who buys or uses these CAVs.
- **Value of Time:** The traveler value of time (VOT) is another model input that defines the traveler's cost associated with the unproductive time wasted in travel. The value of VOT has a significant impact on the travelers' route choice behavior. As VOT increases, travelers will seek faster routes as any safe travel time could be used for other highly paying activities. As travelers are no longer involved in driving when using AVs as their mode of transportation, they are expected to better use their time by being involved in other activities (e.g., working, resting, entertaining, etc.). Thus, one might anticipate a change in travelers' behavior as they do not mind spending more time on the road (i.e., using longer routes) if they are involved in some productive activities. Capturing this anticipated change in the travelers' behavior could be achieved by reducing the VOT parameter for travelers using AVs. In this study, the VOT parameter in the traffic assignment module is uniformly decreased for the CAV demand matrices across all trip purposes. We assume a 35% reduction in VOT for all AVs. This percentage is equivalent to that of transit users ($9/hr.)

compared to the car VOT ($14/hr.), as was used in the previous version of the NCTCOG regional travel demand model (DFX). No change in truck VOT is considered in this analysis.

- **Origin-Destination (OD) Demand Table:** The OD demand table describes the demand pattern in the study area under consideration. As travelers depend on CAVs, they will be less sensitive to the inconvenience of long commutes. Thus, they will be willing to live away from their workplaces, taking advantage of affordable housing in the region's peripheral zones. Similarly, employers might move their offices to areas where larger spaces with less rent are available, often located in the region's peripheral areas. This analysis did not consider the opposite scenario in which travelers move to more dense areas as they are not concerned with driving in congested areas due to CAVs. Adjustments to the OD demand table are made in some of the scenarios to replicate changes in the travelers' residential and job locations associated with using CAVs as their primary transportation mode. These adjustments reflect the potential new population and employment distribution pattern in the region anticipated with demand growth and the CAV adoption. The trip demand table is generated while keeping the NCTCOG control totals constant.

4.2 Experiments for Scenario 1: CAV Impact on Roadway Network Performance (Capacity) Scenario

Fifteen experiments are designed to model Scenario 1, where the roadway capacity improves as CAV penetration increases. Four experimental factors are considered in this set of experiments: the roadway link capacity, the volume delay function, the vehicle operating cost, and the traveler's time value. The experiments help understand the effect of each of these factors on the overall network performance individually and collectively. Table 2 provides a summary of these experiments. The table provides the value assigned for each of these fifteen experiments for each experiment. For example, Experiment S1R10 assumes CAV penetration of 50%. At this penetration rate, a capacity improvement of 10% is considered for all roadway links in the network. The free flow speed parameter in the VDF is increased by 2.5%. A reduction of 35% in the travelers' value of time is considered. No change in the vehicle operating cost is considered for this experiment.

Table 2. Experiments Designed to Evaluate Scenario 1: Roadway Capacity Enhancement

Scenario 1: Roadway Capacity Enhancement Scenario					
Experiment	CAV Penetration Rate	Roadway Link Capacity Improvement	Roadway Link Speed Improvement	Reduction in Vehicle Operating Cost	Reduction in Traveler Value of Time
Base	0%	0%	0%	0%	0%
S1R1	25%	5%	0%	0%	0%
S1R2	50%	10%	0%	0%	0%
S1R3	100%	33%	0%	0%	0%
S1R4	25%	5%	0%	0%	35%
S1R5	50%	10%	0%	0%	35%
S1R6	100%	33%	0%	0%	35%
S1R7	25%	5%	1.25%	0%	0%
S1R8	50%	10%	2.50%	0%	0%

S1R9	100%	33%	5.00%	0%	0%
S1R10	25%	5%	1.25%	0%	35%
S1R11	50%	10%	2.50%	0%	35%
S1R12	100%	33%	5.00%	0%	35%
S1R13	25%	5%	0%	10%	0%
S1R14	50%	10%	0%	10%	0%
S1R15	100%	33%	0%	10%	0%

4.3 Experiments for Scenario 2: CAV Impact on Intersection Performance Scenario

Six additional experiments are designed to model the connected vehicle-intersection scenario. These experiments focus on evaluating how the connected vehicle-intersection technology improves the performance of the intersections and the effect on the overall network performance. Hence, in addition to the experimental factors considered for modeling scenario one (except for the vehicle operating cost), two experimental factors are considered for the experiments designed for modeling this scenario. These factors are the percentage improvement in the roadway links' saturation flow rate and the percentage reduction in the delays at the intersections. Table 3 provides a summary of the experiments designed for this scenario. The table lists these experiments and gives the value assigned for each experimental factor. For example, Experiment S2R20 models a scenario where CAVs represents 50% of the traffic composition. At this penetration rate, the roadway link capacity and the saturation flow rate for roadway links with signalized control are assumed to improve by 10%. In addition, the percentage increase in the free flow speed of the links' VDF is increased by 2.5%, and the control delay is reduced by 5%. Finally, the reduction in the travelers' VOT is 35%.

Table 3. Experiments Designed to Evaluate Scenario 2: CAV Impact on Intersection Performance

Scenario 2: CAV Impact on Intersection Performance Scenario						
Experiment	CAV Penetration Rate	Roadway Link Capacity Improvement	Roadway Link Speed Improvement Percentage	Roadway Link Saturation Flow Improvement	Reduction in Roadway Link Control Delay	Reduction in Traveler Value of Time
S2R16	25%	5%	1.25%	5%	2.5%	0%
S2R17	50%	10%	2.50%	10%	5.0%	0%
S2R18	100%	33%	5.0%	33%	10.0%	0%
S2R19	25%	5%	1.25%	5%	2.5%	35%
S2R20	50%	10%	2.50%	10%	5.0%	35%
S2R21	100%	33%	5.0%	33%	10.0%	35%

4.4 Experiments for Scenario 3: CAV Impact on Population and Employment Distributions Scenario

Four experiments are designed to model the population employment redistribution scenario. The main experimental factor introduced in this set of experiments is the OD demand table's underlying population and employment data. Two cases are considered for this factor. In the first case, the OD table is adjusted to reflect the joint redistribution of population, households, and employment. The second case is limited to only redistributing the population and households. More details on the procedure for adjusting the OD demand tables are given in Section 4.5.

A summary of these four experiments is given in Table 4. Experiments S3R24 and S3R28 extend S2R18 to consider the effect of two cases. S3R24 considers the POP/HH/EMP redistribution, while Experiment S3R28 considers the POP/HH redistribution only. These two experiments assume no change in the travelers' value of time. In addition, Experiments S3R27 and S3R29 extend S2R21 to consider the effect of two cases. S3R27 considers the POP/HH/EMP redistribution, while Experiment S3R29 considers the POP/HH redistribution only. These two experiments assume travelers' VOT is reduced by 35%.

For example, Experiment S3R27 models a scenario with a 100% CAV penetration rate. At this penetration rate, the roadway link capacity and the saturation flow rate for roadway links with signalized control are assumed to improve by 33%. In addition, the percentage increase in the free flow speed of the links' VDF is increased by 5%, and the control delay is reduced by 10%, respectively. The reduction in the travelers' VOT is set at 35%. In this experiment, the demand pattern is adjusted to reflect the joint redistribution of the population, households, and employment in the region.

Table 4. Experiments Designed to Model Scenario 3: CAV Impact on Population/Employment Distribution

Scenario 3: CAV Impact on Population/Employment Distribution							
Experiment	CAV Penetration Rate	Roadway Link Capacity Improvement	Roadway Link Speed Improvement Percentage	Roadway Link Saturation Flow Improvement	Roadway Link Reduction in Control Delay	Reduction in Traveler Value of Time	OD Demand Table
S3R24	100%	33%	5.0%	33%	10.0%	0%	Adjusted OD Table (POP/HH/EMP)
S3R27	100%	33%	5.0%	33%	10.0%	35%	Adjusted OD Table (POP/HH/EMP)
S3R28	100%	33%	5.0%	33%	10.0%	0	Adjusted OD Table (POP/HH)
S3R29	100%	33%	5.0%	33%	10.0%	35%	Adjusted OD Table (POP/HH)

4.5 Setting Up the Population and Employment Redistribution Scenario

A general hypothesis is that introduction of CAVs into the traffic mix can result in a shift in home and work location decision choices due to the travel comfort associated with this mode of travel. This shift can result in a more uniform growth across the region. Therefore, the team was tasked to model several uniform demographic growth scenarios and examine the network performance differences when compared against the original NCTCOG 2045 model assumptions. Two sets of demographic scenarios were developed. The S3R24/S3R27 scenarios assume universal growth in household (HH), population (POP) and employment (EMP) by sector, and S3R28/S3R29 scenarios factor in universal growth for HH and POP only. The demographic adjustment steps for S3R24 and S3R27 are listed below. The steps for S3R28 and S3R29 are similar but without adjustments to EMP data by sector.

- Identified TAZs with 0 values in HH, POP, Basic (BAS), Retail (RET) or Service (SER) employments in model years 2019 or 2045 and named them as set {TAZ0} where their corresponding 2045 NCTCOG demographic values were retained.
- Applied uniform growth rates to TAZs excluding the TAZs in set {TAZ0}. The growth factors from 2019 to 2045 for HH, POP, BAS, RET, and SER were calculated through dividing 2045 totals by 2019 totals and applied to all TAZS except for the TAZS in set {TAZ0}. The growth factors were then further adjusted to make sure that the NCTCOG 2045 control totals were matched.
- Applied a floor to the TAZ demographic data reductions. After Step 2, a check was carried out to evaluate how the uniform growth scenario differs from original NCTCOG 2045 demographic dataset. To prevent drastic changes in the demographic data, the maximum reduction in HH/POP/EMP was capped at 30%. If HH, POP, BAS, RET, or SER reduced more than 30%, they were named set {TAZDC} and their adjusted values were set at 70% of the original NCTCOG 2045 values.
- Balanced the control totals. After Step 3, HH, POP, BAS, RET, and SER had surpluses compared to the original 2045 NCTCOG totals. The surpluses were subtracted from the TAZs except from the ones in {TAZ0} and {TAZDC} zone sets based on their shares.
- Applied a ceiling on TAZ demographic data increases. Another round of modification was carried out to cap the TAZs that showed a higher than 30% growth compared to the original NCTCOG 2045 values. In this step, these TAZs were named set {TAZIC} and their growth was capped at 130% of their corresponding NCTCOG 2045 values.
- Balanced the control totals. After Step 5, HH/POP/EMP totals had deficits when compared to original NCTCOG 2045 totals. The deficits were added to the TAZs except for the ones in sets {TAZ0}, {TAZDC} and {TAZIC} based on their shares.

Figure 2 through Figure 4 depict the TAZs HH/POP/EMP differences between the modified scenario (S3R24/S3R27) and the original NCTCOG 2045 model. The red TAZS represent areas were the HH/POP/EMP were reduced when compared to the original NCTCOG 2045 demographic data. All four of the demographic scenario runs (S3R24, S3R27, S3R28, and S3R29) have shown decreases in regional VMT, VHT, delay and increase in average speeds compared to the NCTCOG CAV scenario with 100% penetration rate (S2R18) and original 2045 demographic dataset. The new scenarios reassign the HH, POP and EMP from the periphery of the four counties to either the rural area of the metroplex or the urban areas, and as a result, the network is less congested overall.

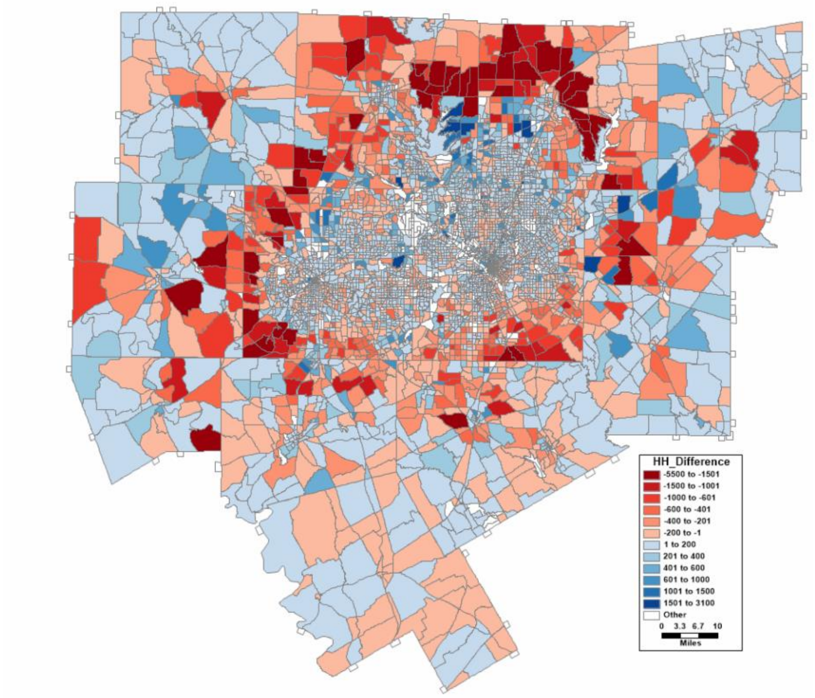


Figure 2. TAZ Household Difference Map Compared to Original 2045 NCTCOG Model

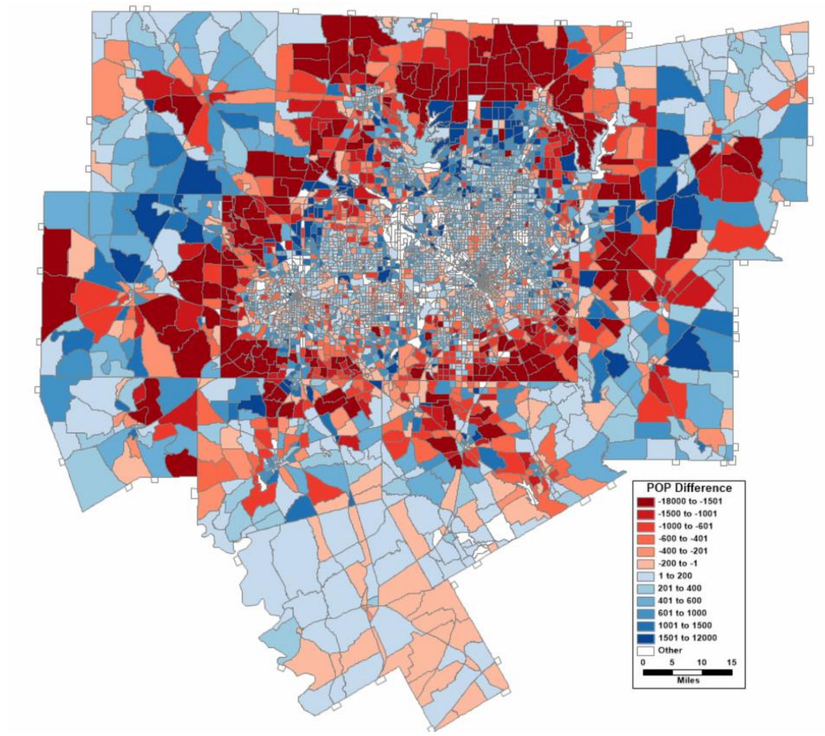


Figure 3. TAZ Population Difference Map Compared to Original 2045 NCTCOG Model

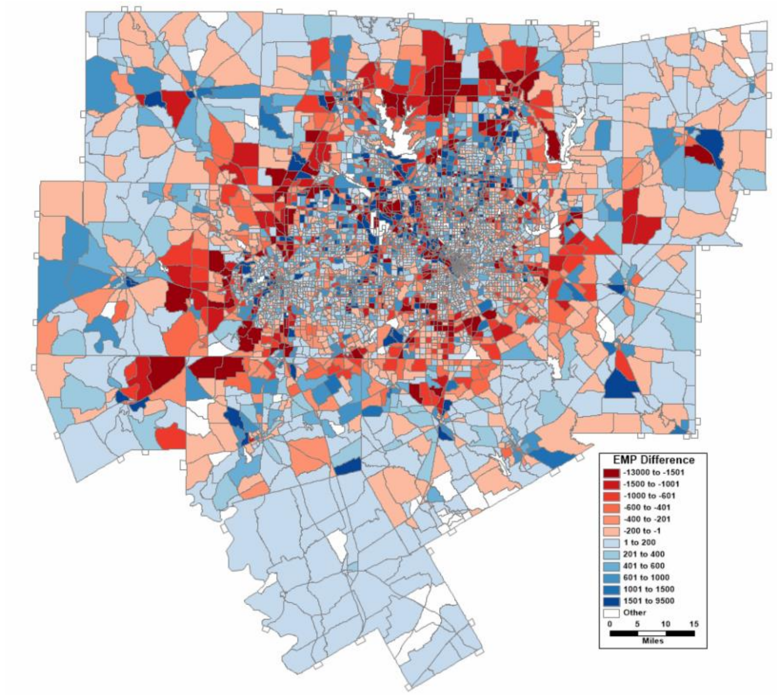


Figure 4. TAZ Employment Difference Map Compared to Original 2045 NCTCOG Model

5 RESULTS AND ANALYSIS OF SCENARIO 1: CAV IMPACT ON ROADWAY NETWORK PERFORMANCE (CAPACITY)

A summary of the set of experiments designed for this scenario is given in Table 2. These experiments are grouped into three subsets. The first subset (S1R1 to S1R6) examines the effect of the improvement in the roadway link capacity associated resulting from higher AV penetration on the overall transportation network performance with and without changing the travelers' value of time. The second subset (S1R7 to S1R12) reexamines the cases in the first subset, assuming CAVs improve the roadway link capacity and enable the traffic to move at a higher average speed. The third subset also reexamines the case of the first subset but with the assumption that CAVs will have lower operating costs than traditional vehicles. The results of these experiments are compared with a base case with no CAVs in the traffic composition (0% penetration rate). In this base scenario, the roadway link capabilities, the travelers' VOT, the travel speed, and the vehicle operating cost are unchanged. The network performance is quantified by comparing the values of four different performance measures to their corresponding value in the base scenario. The performance measures are the vehicle miles traveled (VMT), the vehicle hours traveled (VHT), average speed, total delay, and level of service (LOS).

5.1 Experiments S1R1 to S1R6 (capacity enhancement + value of time)

This subset of experiments examines the effect of the increase of the CAV penetration rate and associated improvement in the roadway capacity on the overall performance of the regional transportation network. As mentioned above, a higher CAV penetration rate is expected to improve the roadway link capacity. According to the *Highway Capacity Manual*[10], at 25%, 50%, and 100% CAV penetration rates, the roadway link capacity could be improved by 3%, 10%, and 33%, respectively. In this subset of experiments, we examine the overall network performance for these three CAV penetration rate levels considering two cases. The first case assumes that travelers' adoption of AVs does not affect their value of time (Experiments S1R1 to S1R3). The second case assumes that travelers adopting AVs could be involved in other productive activities; hence, they are assumed to have less VOT (i.e., they do not mind spending more time in travel). In this case (Experiments S1R4 to S1R6), experiments S1R1 to S1R3 are repeated after reducing the VOT parameter by 35%.

5.1.1. CHANGE IN VMT

The first set of results shows the change in the VMT at different CAV penetration rates. These results are summarized in Figure 5 and Table 5 through Table 7. Figure 5 gives four charts illustrating the increase in VMT (left vertical axis for the solid curves) and its percentage change (right vertical axis for the dotted curves) at different CAV penetration rates. These charts show the results for the morning peak (AM), afternoon peak (PM), off-peak (OP), and the entire day, respectively. The results in these charts are given for two cases. The first case assumes no change in the CAV

[10] National Academies of Sciences, Engineering, and Medicine. 2022. *Highway Capacity Manual 7th Edition: A Guide for Multimodal Mobility Analysis*. Washington, DC: The National Academies Press. https://doi.org/10.17226/26432.

travelers' VOT (blue curves – experiments S1R1 to S1R3), while the second assumes that CAV travelers have a 35% reduction in their VOT (red curves - experiments S1R4 to S1R6).

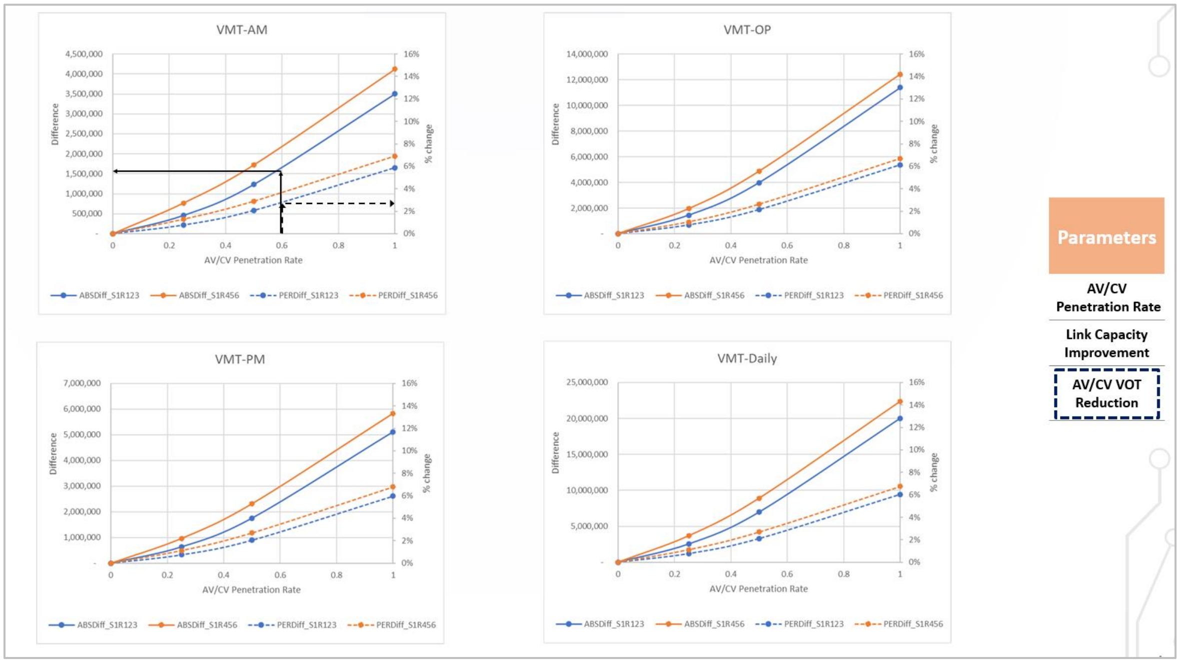


Figure 5. VMT Difference Compared to the Base Scenario (S1R1 to S1R6)

Table 5. VMT Compared to the Base Scenario (Base and S1R1 to S1R6)

VMT					
Scenario Runs	AV/CV Penetration Rate	AM	OP	PM	Daily
Base	0	59,580,295	185,718,743	85,738,403	331,037,442
S1R1	0.25	60,036,147	187,155,745	86,372,991	333,564,883
S1R2	0.5	60,814,905	189,698,858	87,493,591	338,007,354
S1R3	1	63,082,113	197,107,091	90,851,524	351,040,728
S1R4	0.25	60,346,336	187,661,127	86,702,122	334,709,585
S1R5	0.5	61,305,347	190,588,097	88,053,069	339,946,513
S1R6	1	63,701,047	198,145,444	91,567,318	353,413,809

Table 6. VMT Difference Compared to the Base Scenario (S1R1 to S1R6)

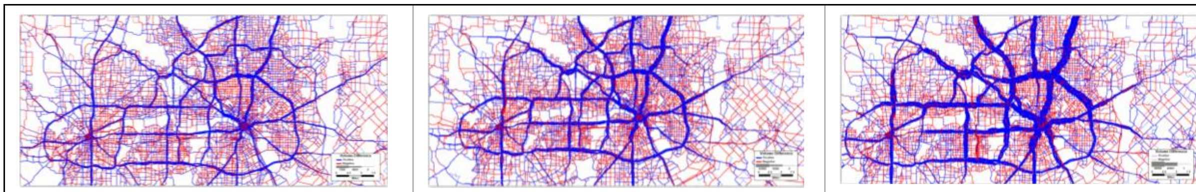
VMT Difference					
Scenario Runs	AV/CV Penetration Rate	AM	OP	PM	Daily
S1R1	0.25	455,852	1,437,002	634,587	2,527,442
S1R2	0.5	1,234,610	3,980,115	1,755,188	6,969,913
S1R3	1	3,501,818	11,388,348	5,113,120	20,003,286
S1R4	0.25	766,041	1,942,384	963,718	3,672,144
S1R5	0.5	1,725,052	4,869,354	2,314,666	8,909,072
S1R6	1	4,120,752	12,426,701	5,828,914	22,376,367

Table 7. VMT Percent Difference Compared to the Base Scenario (S1R1 to S1R6)

VMT Percent Change					
Scenario Runs	AV/CV Penetration Rate	AM	OP	PM	Daily
S1R1	0.25	1%	1%	1%	1%
S1R2	0.5	2%	2%	2%	2%
S1R3	1	6%	6%	6%	6%
S1R4	0.25	1%	1%	1%	1%
S1R5	0.5	3%	3%	3%	3%
S1R6	1	7%	7%	7%	7%

Two main observations can be made based on these figures and tables. First, **increasing the CAV penetration rate and the corresponding increase of the roadway link capacity increased the total VMT**. This trend is observed in all periods (AM, PM, OP) and for the entire day. For example, for the case with no change in the travelers' VOT (blue curves), at a 25% CAV penetration rate (S1R1), an additional 2.5M daily vehicle-miles were traveled, representing a 1% increase compared to the base scenario. At 100% CAV penetration rate (S1R3), the amount of additional traveled daily vehicle-miles increased to 20M vehicle-miles, representing a 6% increase compared to the base case scenario. Second, **a similar increasing pattern is also observed for the case where a 35% reduction in the CAV travelers' VOT is assumed**. However, decreasing the travelers' VOT increased the VMT compared to the case in which travelers' VOT is assumed unchanged. For example, for the case with a 35% reduction in the travelers' VOT (red curves – S1R4), at a 25% CAV penetration rate, an additional 3.7M daily vehicle-miles were traveled, representing a 1% increase compared to the base case scenario. At 100% CAV penetration rate (S1R6), the amount of additional daily traveled vehicle-miles increased to 22M vehicle-miles, representing a 7% increase.

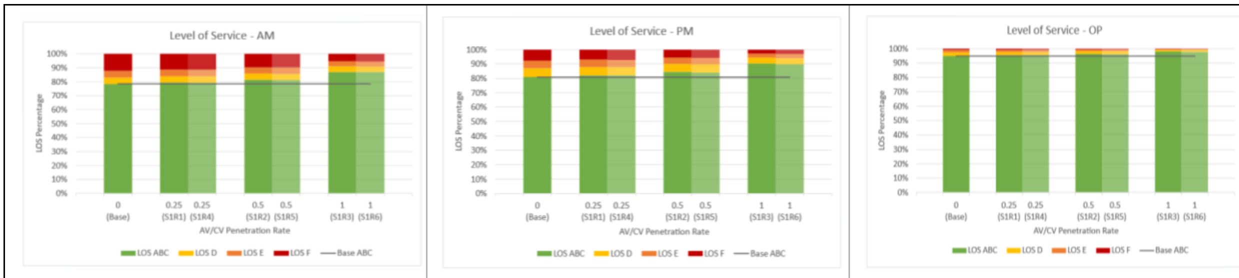
The analysis is extended to obtain a closer look at the change in the VMT among the different roadway facilities and area types. Figure 6 provides maps illustrating the volume change of the S1R3 (100% CAV penetration rate without VOT change) compared to the base scenario for the AM, PM, and OP periods, respectively. Links with an increase in the volume percentage are marked by a blue color, while the red color marks those with volume reduction. As shown in these maps, the increase in the VMT associated with higher CAV penetration generally increased the traffic volume of the freeway facilities with an associated volume reduction on the arterials. As mentioned above, a high CAV penetration rate is expected to improve the capacity of the roadway links by up to 33%. As this improvement is a percentage of the existing roadway link capacity, freeway facilities in the network are expected to have significant capacity improvement. Therefore, traffic that avoided the freeway congestion and used arterial streets in the base scenario was attracted back to the freeway facilities taking advantage of their improved capacity returns to the freeway facilities taking advantage of their capacity improvements.



AM Peak Period	PM Peak Period	OP Period

Figure 6. The AM, PM, and OP Volume Change Map for the scenario with 100% CAV penetration rate (S1R3 VS. Base).

The corresponding change in the level of service (LOS) of the roadway links is given in Figure 7. The Figure shows the percentage of roadway links in each LOS category (ABC, D, E, and F). The results are given for the AM, PM, and OP periods. The results illustrate how the LOS distribution patterns obtained from Experiments S1R1 to S1R6 are compared to the base scenario. The results of Experiments S1R1 to S1R3 are given using the dark green color, while the results of Experiments S1R4 to S1R6 are presented in light green. As shown in the Figure, increasing the CAV penetration rate improved the roadway links' LOS. In the AM and PM periods, the percentage of links with LOS A, B, and C significantly increased in S1R4 and S1R6 compared to the base scenario. As expected, the roadway links' LOS improvement in the off-peak (OP) period is minimal, considering the low congestion level typically reported during this period.



AM Peak Period	PM Peak Period	OP Period

Figure 7. The AM, PM, and OP Roadway Link LOS Percentages (Base and S1R1 to S1R6)

In addition, Figure 8 and Figure 9 provide the daily VMT for the base scenario and experiments S1R1 to S1R6, classifying the results by roadway functional class and by area type. Figure 8 shows the VMT for seven different roadway functional classes. These classes include freeway, principal arterial, minor arterial, collector, freeway ramp, frontage road, and HOV. For example, for scenario S1R3 with 100% CAV penetration rate, the freeway facilities recorded about 161 million vehicle-miles while principal and minor arterials recorded 61 million and 64 million vehicle-miles, respectively. This Figure confirms the results presented in the volume change maps in Figure 6. Increasing the CAV penetration (e.g., S1R3 and S1R6) resulted in traffic shift from arterials to the freeway. Finally, the distribution of the VMT by area type is given in Figure 9. The Figure shows that urban residential areas continue to have the highest VMT under this automation scenario.

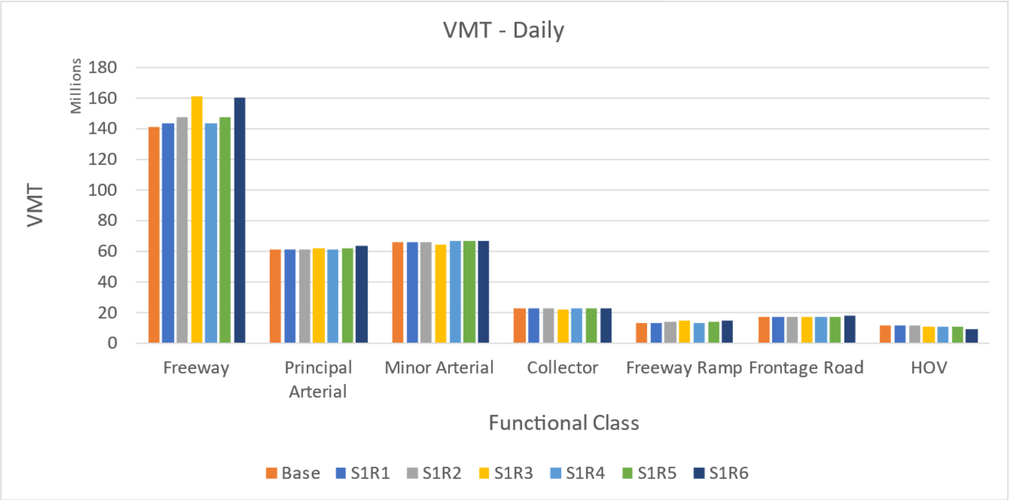


Figure 8. Daily VMT by Roadway Functional Class (Base and S1R1 to S1R6)

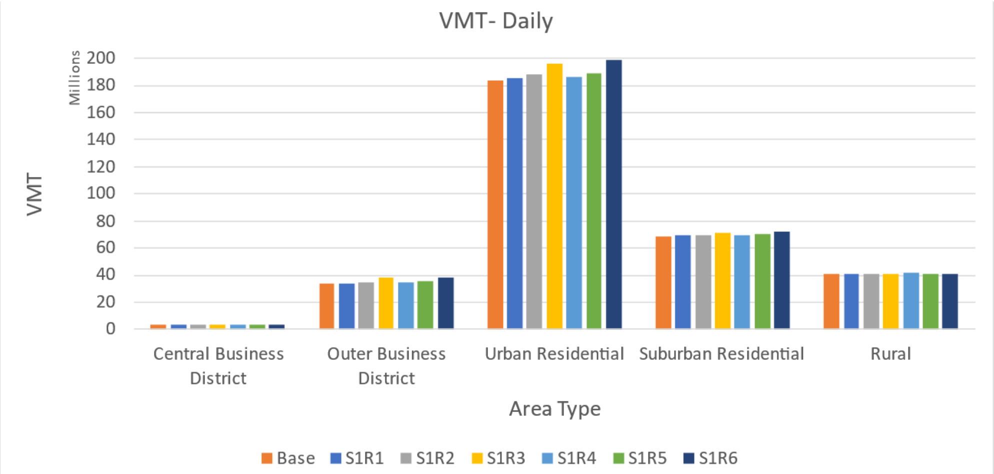


Figure 9. Daily VMT by Area Type (Base and S1R1 to S1R6)

5.1.2. CHANGE IN VHT

The second set of results shows the change in the VMT at different CAV penetration rates. This result is summarized in Figure 10 and Table 8 to

Table 10. Figure 10 gives four charts illustrating the increase in VHT (left vertical axis for the solid curves) and its percentage change (right vertical axis for the dotted curves) at different CAV

penetration rates. The charts are given for the morning peak (AM), afternoon peak (PM), off-peak (OP), and for the entire day. Similar to the results presented above, the results in these sub-figures are given for two cases. The first case assumes no change in the CAV travelers' VOT (blue curves – experiments S1R1 to S1R3), while the second assumes that CAV travelers have a 35% reduction in their VOT (red curves - experiments S1R4 to S1R6).

Two main observations can be made based on these figures. First, **increasing the CAV penetration rate resulted in a decrease in the total daily VHT**. This trend is observed in all periods (AM, PM, and OP) and for the entire day. For example, for the case with no change in the travelers' VOT (blue curves – S1R1), at a 25% CAV penetration rate, the VHT decreased by 0.2M vehicle-hours, representing a 2% reduction compared to the base scenario. At 100% CAV penetration rate (S1R3), the amount of VHT reduction increased to 1.4M vehicle-hours, representing a 12% reduction compared to the base scenario.

Second, **a similar VHT reduction pattern is also observed in the case where a 35% reduction in the CAV travelers' VOT is assumed**. However, the travelers' VOT reduction decreased the VHT compared to the case with no VOT change. For example, for the case with a 35% reduction in the travelers'' VOT (red curves), at a 25% CAV penetration rate (S1R4), a decrease of 0.05M vehicle-hours. At 100% CAV penetration rate (S1R6), the VHT decreased to 1.1M vehicle-hours, representing a 10% reduction compared to the base case scenario. The only exception is in the OP Period where due to low VOTs and relative high cost of traveling on priced facilities, a shift of traffic to free lanes and major arterials results in an increase in the VHT.

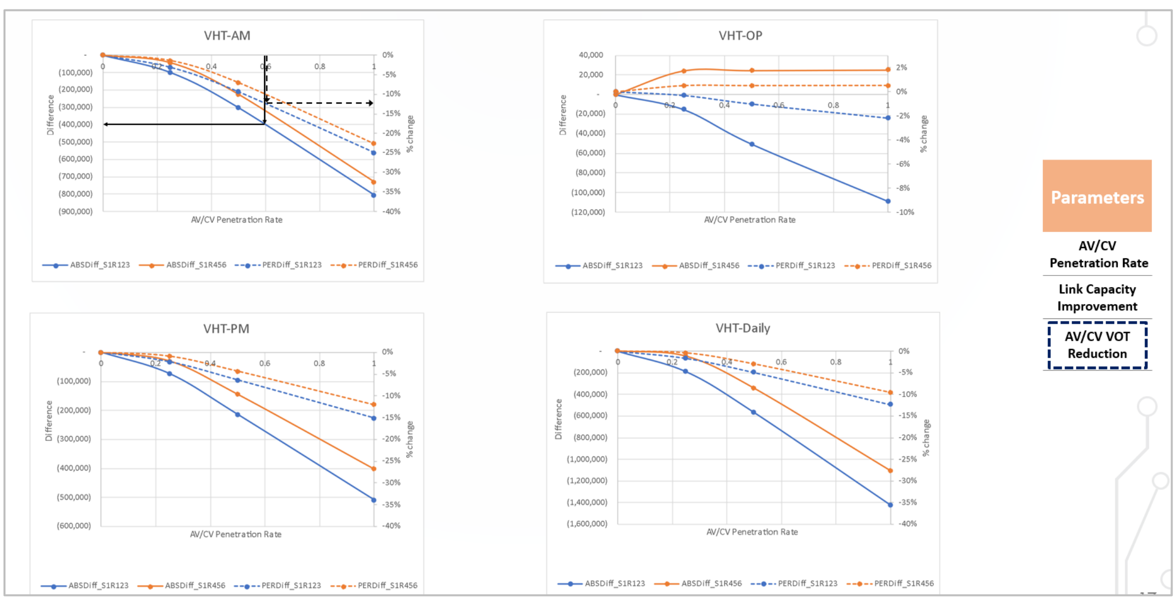


Figure 10. VHT Difference Compared to the Base Scenario (S1R1 to S1R6)

Table 8. VHT Compared to the Base Scenario (Base and S1R1 to S1R6)

VHT					
Scenario Runs	AV/CV Penetration Rate	AM	OP	PM	Daily
Base	0	3,225,458	4,974,597	3,362,522	11,562,578
S1R1	0.25	3,125,636	4,959,477	3,288,793	11,373,905
S1R2	0.5	2,923,320	4,924,158	3,148,257	10,995,734
S1R3	1	2,420,030	4,865,698	2,854,015	10,139,743
S1R4	0.25	3,182,637	4,998,891	3,332,194	11,513,721
S1R5	0.5	3,000,328	4,999,237	3,217,673	11,217,238
S1R6	1	2,495,242	4,999,770	2,960,836	10,455,848

Table 9. VHT Difference Compared to the Base Scenario (S1R1 to S1R6)

VHT Difference					
Scenario Runs	AV/CV Penetration Rate	AM	OP	PM	Daily
S1R1	0.25	(99,823)	(15,121)	(73,730)	(188,673)
S1R2	0.5	(302,138)	(50,440)	(214,266)	(566,843)
S1R3	1	(805,428)	(108,899)	(508,507)	(1,422,834)
S1R4	0.25	(42,822)	24,294	(30,328)	(48,857)
S1R5	0.5	(225,130)	24,640	(144,850)	(345,339)
S1R6	1	(730,216)	25,173	(401,686)	(1,106,730)

Table 10. VHT Difference% Compared to the Base Scenario (S1R1 to S1R6)

VHT Percent Change					
Scenario Runs	AV/CV Penetration Rate	AM	OP	PM	Daily
S1R1	0.25	-3%	0%	-2%	-2%
S1R2	0.5	-9%	-1%	-6%	-5%
S1R3	1	-25%	-2%	-15%	-12%
S1R4	0.25	-1%	0%	-1%	0%
S1R5	0.5	-7%	0%	-4%	-3%
S1R6	1	-23%	1%	-12%	-10%

In addition, Figure 11 and Figure 12 provide the daily VHT for the base scenario and experiments S1R1 to S1R6, classifying the results by roadway functional class and by area type. Figure 11shows the VHT for seven different roadway functional classes. These classes include freeway, principal arterial, minor arterial, collector, freeway ramp, frontage road, and HOV. For example, for scenario S1R3 with a 100% CAV penetration rate, the freeway facilities recorded about VHT of about 3.5M vehicle-hours while principal and minor arterials recorded 2.0M and 2.3M vehicle-hours, respectively. Finally, the distribution of the VHT by area type is given in Figure 12. The Figure shows that urban residential areas continue to have the highest VHT under this automation scenario, where VHT decreases as the CAV penetration rate increases.

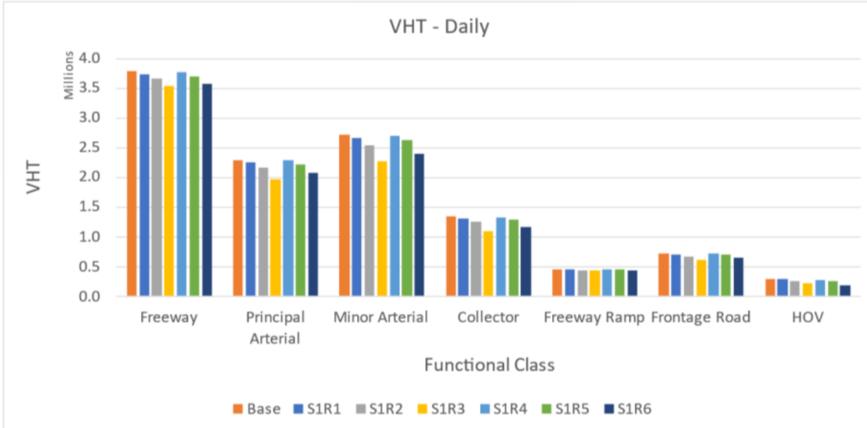


Figure 11. Daily VHT by Roadway Functional Class (Base and S1R1 to S1R6)

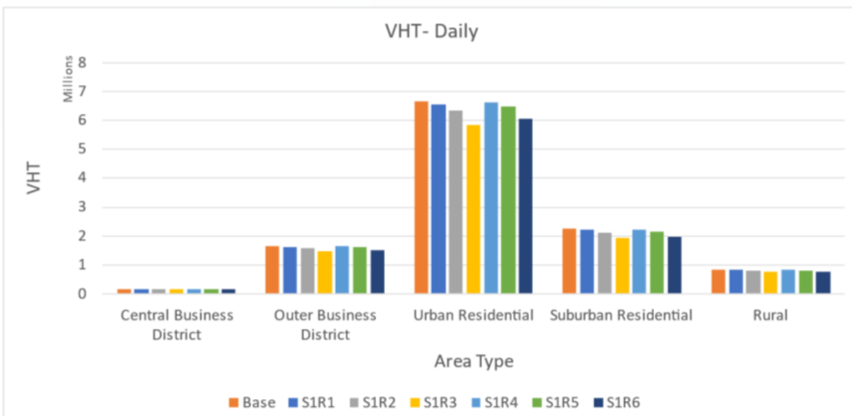


Figure 12. Daily VHT by Area Type (Base and S1R1 to S1R6)

5.1.3. CHANGE IN AVERAGE SPEED

The third set of results shows the average roadway link speed change at different CAV penetration rates. A summary of this set of results is given in Figure 13, and Table 11 to Table 13. Figure 13 gives four charts that show the change in average speed (left vertical axis for the solid curves) and its corresponding percentage value (right vertical axis for the dotted curves) at different CAV penetration rates. The charts are given for the morning peak (AM), afternoon peak (PM), off-peak (OP), and for the entire day. The results in these sub-figures are given for two cases. The first case assumes no change in the CAV travelers' VOT (blue curves – experiments S1R1 to S1R3), while the second case assumes that CAV travelers have a 35% reduction in their VOT (red curves - experiments S1R4 to S1R6).

Two main observations can be made based on these sub-figures. First, **average speed on the roadway links increases due to increasing the CAV penetration rate and the corresponding improvement in the roadway link capacity**. This trend is observed in all periods (AM, PM, OP) and for the entire day. For example, for the case with no change in the travelers' VOT (blue curves), at 25% CAV penetration rate (S1R1), the average speed increased by 0.7 mph, representing a 2%

increase compared to the base scenario. At 100% CAV penetration rate (S1R3), the average speed increased by 6.0 mph, representing a 21% increase compared to the base scenario. This speed improvement is due to reduced congestion because of CAVs improving capacity. It is not about the effect of increased free-flow speeds.

Second, **a similar average speed increase pattern is observed for the case where a 35% reduction in the CAV travelers' VOT is assumed**. However, the reduction in the travelers' VOT resulted in a slight decrease in the average speed compared to the case in which travelers' VOT is assumed unchanged. For example, for the case with a 35% reduction in the travelers' VOT (red curves), at a 25% CAV penetration rate (S1R4), the average speed improved by only 0.4 mph. At 100% CAV penetration rate (S1R6), the improvement in the average speed is 5.2 mph (18%) compared to the base case scenario.

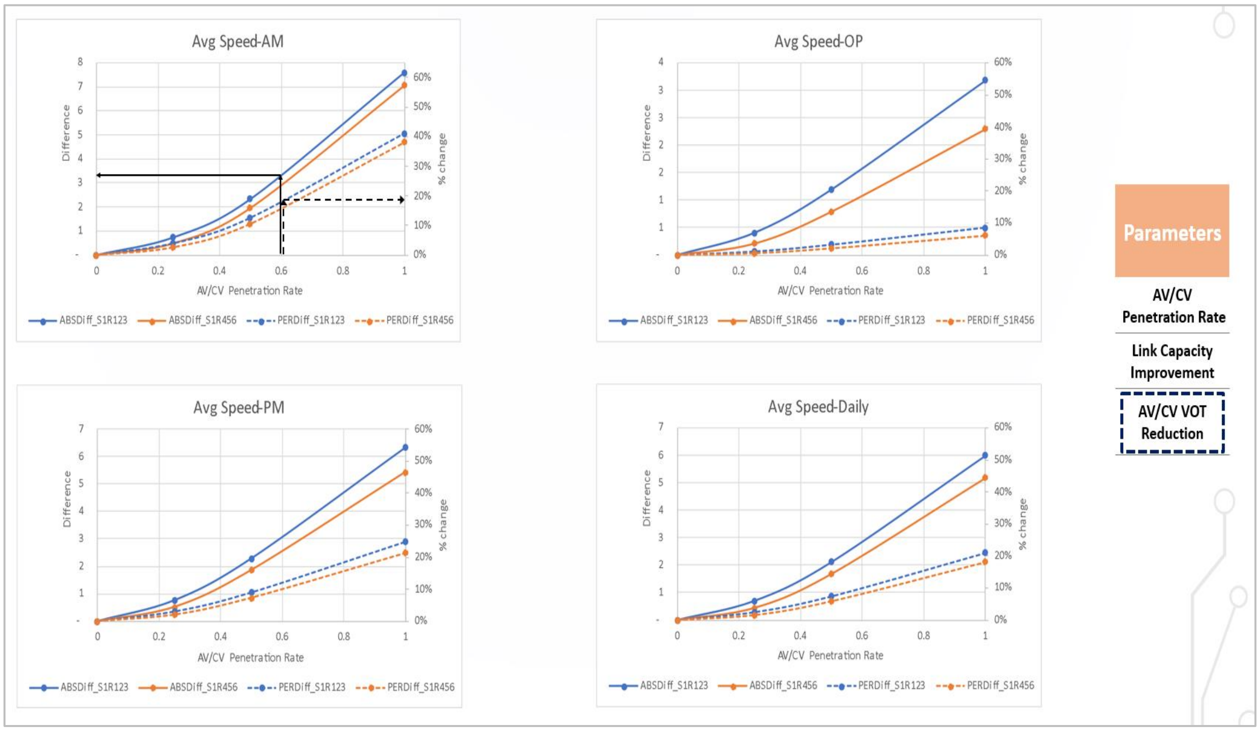


Figure 13. Speed Difference Compared to Base Scenario (S1R1 to S1R6)

Table 11. Average Speed Compared to the Base Scenario (Base and S1R1 to S1R6)

Avg Speed					
Scenario Runs	AV/CV Penetration Rate	AM	OP	PM	Daily
Base	0	18	37	25	29
S1R1	0.25	19	38	26	29
S1R2	0.5	21	39	28	31
S1R3	1	26	41	32	35
S1R4	0.25	19	38	26	29
S1R5	0.5	20	38	27	30
S1R6	1	26	40	31	34

Table 12. Average Speed Difference Compared to the Base Scenario (S1R1 to S1R6)

Avg Speed Difference					
Scenario Runs	AV/CV Penetration Rate	AM	OP	PM	Daily
S1R1	0.25	0.7	0.4	0.8	0.7
S1R2	0.5	2.3	1.2	2.3	2.1
S1R3	1	7.6	3.2	6.3	6.0
S1R4	0.25	0.5	0.2	0.5	0.4
S1R5	0.5	2.0	0.8	1.9	1.7
S1R6	1	7.1	2.3	5.4	5.2

Table 13. Average Speed Difference Percentage Compared to the Base Scenario (S1R1 to S1R6)

Avg Speed Percent Change					
Scenario Runs	AV/CV Penetration Rate	AM	OP	PM	Daily
S1R1	0.25	4%	1%	3%	2%
S1R2	0.5	13%	3%	9%	7%
S1R3	1	41%	9%	25%	21%
S1R4	0.25	3%	1%	2%	2%
S1R5	0.5	11%	2%	7%	6%
S1R6	1	38%	6%	21%	18%

Figure 14 and Figure 15 give the daily average speed for the different roadway functional classes and area types for experiments S1R3 and S1R6, respectively. These two experiments consider a 100% CV/AV penetration rate. Experiment S1R3 assumes no change in the travelers' VOT, while Experiment S1R6 assumes a 35% reduction in the travelers' VOT. As shown in the figures, while there was a noticeable difference in the VMT and VHT of these two scenarios, the difference in the average speed pattern is insignificant.

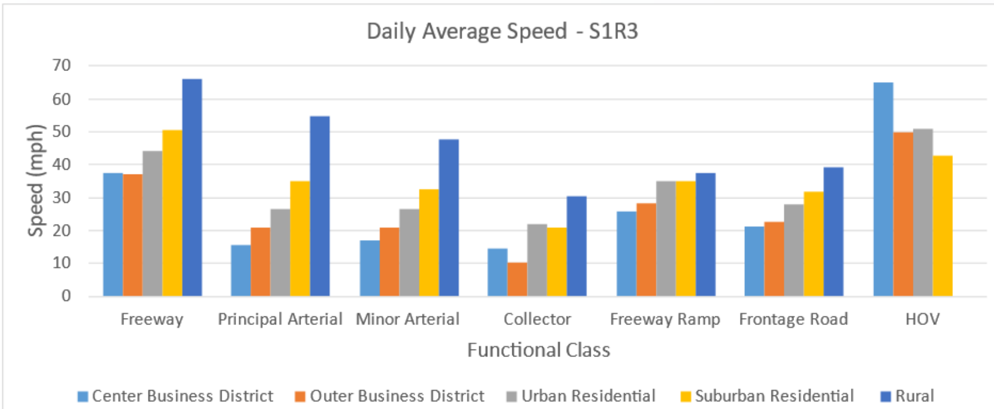


Figure 14. Average Speed by Roadway Functional Class and Area Type (S1R3)

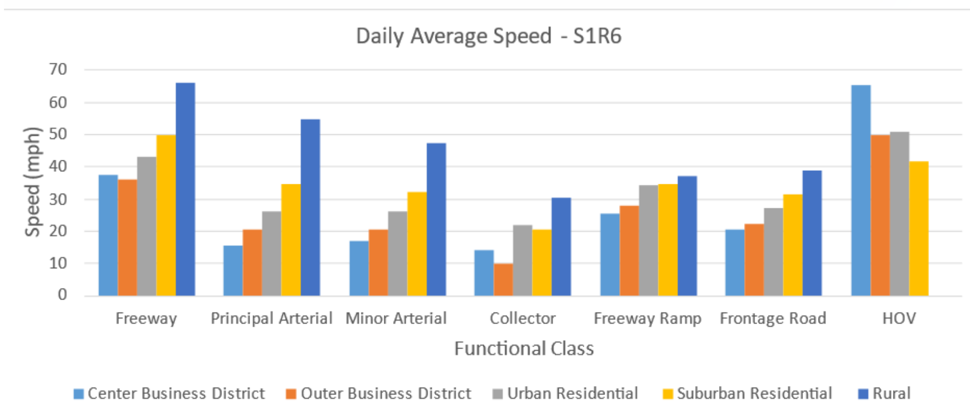


Figure 15. Average Speed by Roadway Functional Class and Area Type (S1R6)

5.1.4. CHANGE IN TOTAL DELAY

The fourth set of results shows the change in the travelers' total delay at different CAV penetration rates. This result is summarized in Figure 16 and Table 14 to Table 16. Figure 16 gives four charts illustrating the amount of delay reduction (left vertical axis for the solid curves) and its corresponding percentage change (right vertical axis for the dotted curves) at different CAV penetration rates. The charts are given for the morning peak (AM), afternoon peak (PM), off-peak (OP), and the entire day. Again, the results in these charts are given for two cases. The first case assumes no change in the CAV travelers' VOT (blue curves – experiments S1R1 to S1R3), while the second assumes that CAV travelers have a 35% reduction in their VOT (red curves - experiments S1R4 to S1R6).

Two main observations can be made based on these figures. First, **increasing the CAV penetration rate decreased the travelers' total delay**. This decreasing trend is observed for all periods (AM, PM, OP) and the entire day. For example, for the case with no change in the travelers' VOT (blue curves), at a 25% CAV penetration rate (S1R1), the total delay is reduced by 0.23M hours, representing a 4% reduction compared to the base scenario. At 100% CAV penetration rate (S1R3), the amount of the delay reduction is 1.70M hours, representing a 33% reduction compared to the base scenario.

Second, **a similar delay reduction pattern is also observed for the case in which a 35% reduction in the CAV travelers' VOT is assumed**. However, lower travelers' VOT reduced the delay compared to the case in which travelers' VOT is assumed unchanged. For example, for the case with a 35% reduction in the travelers' VOT (red curves), at a 25% CAV penetration rate (S1R4), a delay reduction of only 0.12M hours was recorded (2% delay reduction). At 100% CAV penetration rate (S1R6), the decrease in the delay is recorded as 1.5M hours, representing a 29% reduction compared to the base case scenario.

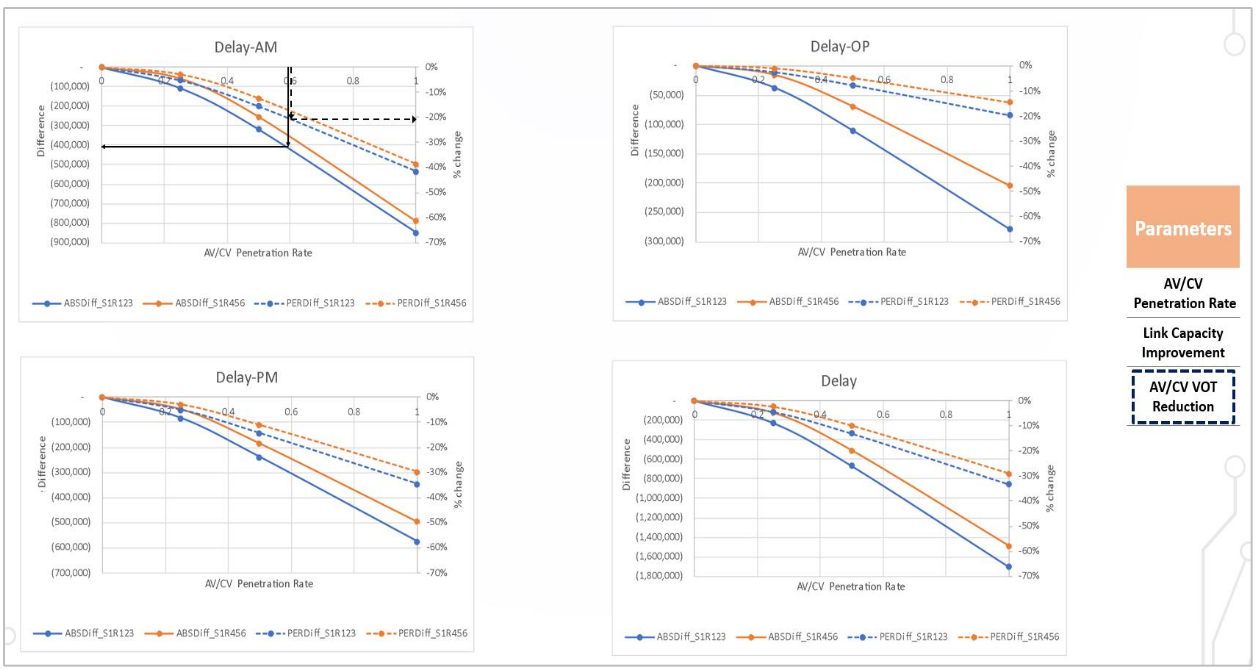


Figure 16. Delay Difference Compared to the Base Scenario (S1R1 to S1R6)

Table 14. Delay Compared to the Base Scenario (S1R1 to S1R6)

Delay					
Scenario Runs	AV/CV Penetration Rate	AM	OP	PM	Daily
Base	0	2,041,895	1,414,540	1,670,096	5,126,531
S1R1	0.25	1,935,261	1,377,180	1,587,379	4,899,820
S1R2	0.5	1,722,684	1,303,877	1,432,220	4,458,780
S1R3	1	1,193,409	1,135,522	1,095,708	3,424,640
S1R4	0.25	1,985,300	1,398,940	1,622,222	5,006,462
S1R5	0.5	1,788,413	1,345,160	1,486,074	4,619,646
S1R6	1	1,252,822	1,209,790	1,175,278	3,637,889

Table 15. Delay Difference Compared to the Base Scenario (S1R1 to S1R6)

Delay Difference					
Scenario Runs	AV/CV Penetration Rate	AM	OP	PM	Daily
S1R1	0.25	(106,635)	(37,360)	(82,717)	(226,712)
S1R2	0.5	(319,211)	(110,663)	(237,877)	(667,751)
S1R3	1	(848,486)	(279,017)	(574,388)	(1,701,891)
S1R4	0.25	(56,596)	(15,600)	(47,874)	(120,070)
S1R5	0.5	(253,483)	(69,380)	(184,023)	(506,885)
S1R6	1	(789,073)	(204,750)	(494,819)	(1,488,642)

Table 16. Delay Difference Percentage Compared to the Base Scenario (S1R1 to S1R6)

Delay Percent Change					
Scenario Runs	AV/CV Penetration Rate	AM	OP	PM	Daily
S1R1	0.25	-5%	-3%	-5%	-4%
S1R2	0.5	-16%	-8%	-14%	-13%
S1R3	1	-42%	-20%	-34%	-33%
S1R4	0.25	-3%	-1%	-3%	-2%
S1R5	0.5	-12%	-5%	-11%	-10%
S1R6	1	-39%	-14%	-30%	-29%

Figure 17 and Figure 18 give the daily delay for the different roadway functional classes and area types for experiments S1R3 and S1R6, respectively. These two experiments consider a 100% CA/AV penetration rate. Experiment S1R3 assumes no change in the travelers' VOT, while Experiment S1R6 assumes a 35% reduction in the travelers' VOT. As shown in the figures, the delay recorded for the different roadway classes for Experiment S1R1 is less than their corresponding values recorded in Experiment S1R6, consistent with the aggregated results presented in Figure 16 and Table 14 to Table 16. The results in these two figures also indicate minimal delay change across the different area types in these two experiments.

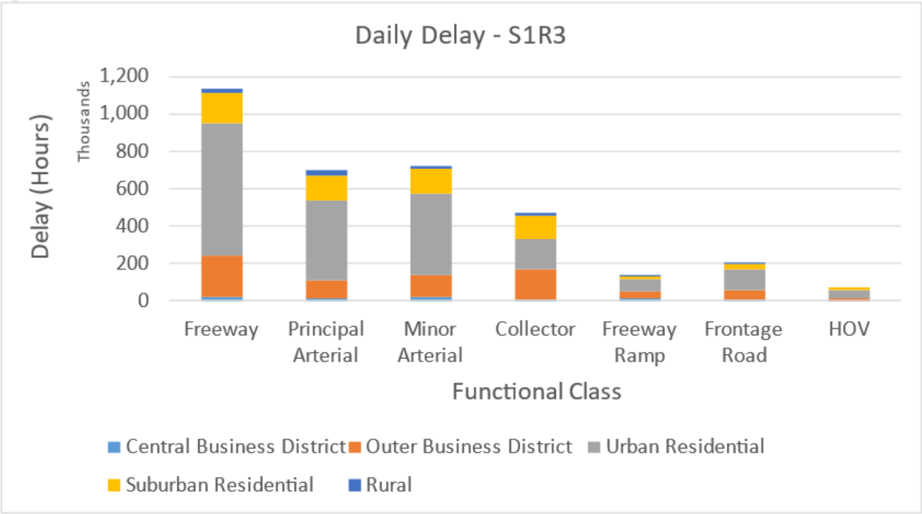


Figure 17. Average Delay by Roadway Functional Class and Area Type for Experiment S1R3

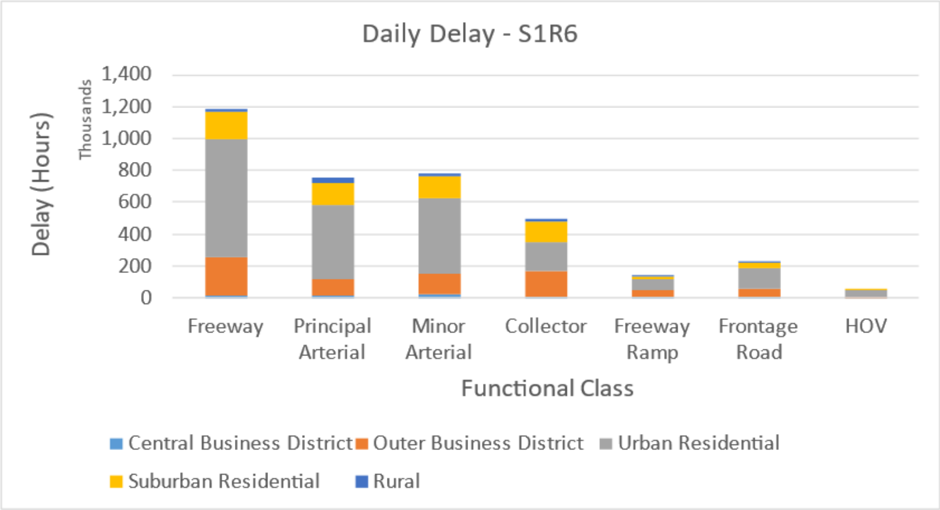


Figure 18. Average Delay by Roadway Functional Class and Area Type for Experiment S1R6

5.1.5. CHANGE IN TRAVEL TIMES

The last set of results provides the travel time contour maps for the region, considering DFW International airport as a focal point (the start or end point of the trips). Figure 19 and Figure 20 provide these maps for the AM and PM peak periods. Each Figure gives the travel time to and from the DFW International airport for the base scenario and Experiments S1R2 (50% CAV penetration) and S1R3 (100 CAV penetration). The color code illustrates the spatial change in the travel time values at 15-minute increments, where the blue color represents the lowest travel time values (0 to 15 minutes), and the dark orange color represents the highest travel time values (> 150 minutes). The figures illustrate how increasing the CAV penetration rate in the traffic composition improves travel time for travelers starting and ending their trips at the DFW International airport in the AM and PM periods. In all cases, the maps show a considerable improvement in the travel time pattern as the CAV penetration rate increases. As CAV increases, it can be noticed that a smaller area is covered by dark orange, and a larger area is covered by the green color, indicating a reduction in the travel time to and from the airport for most points in the region.

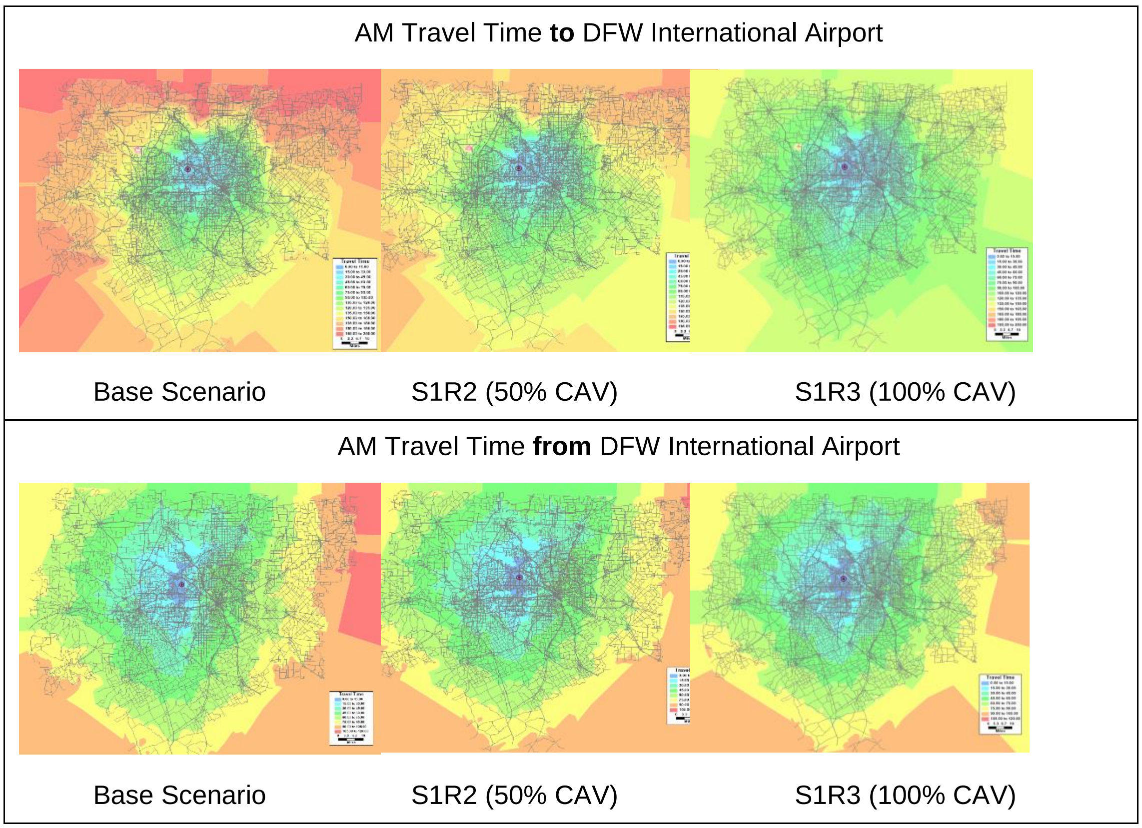


Figure 19. Travel Time Contour Maps for the AM Peak Period Considering the DFW International Airport as a Focal Point

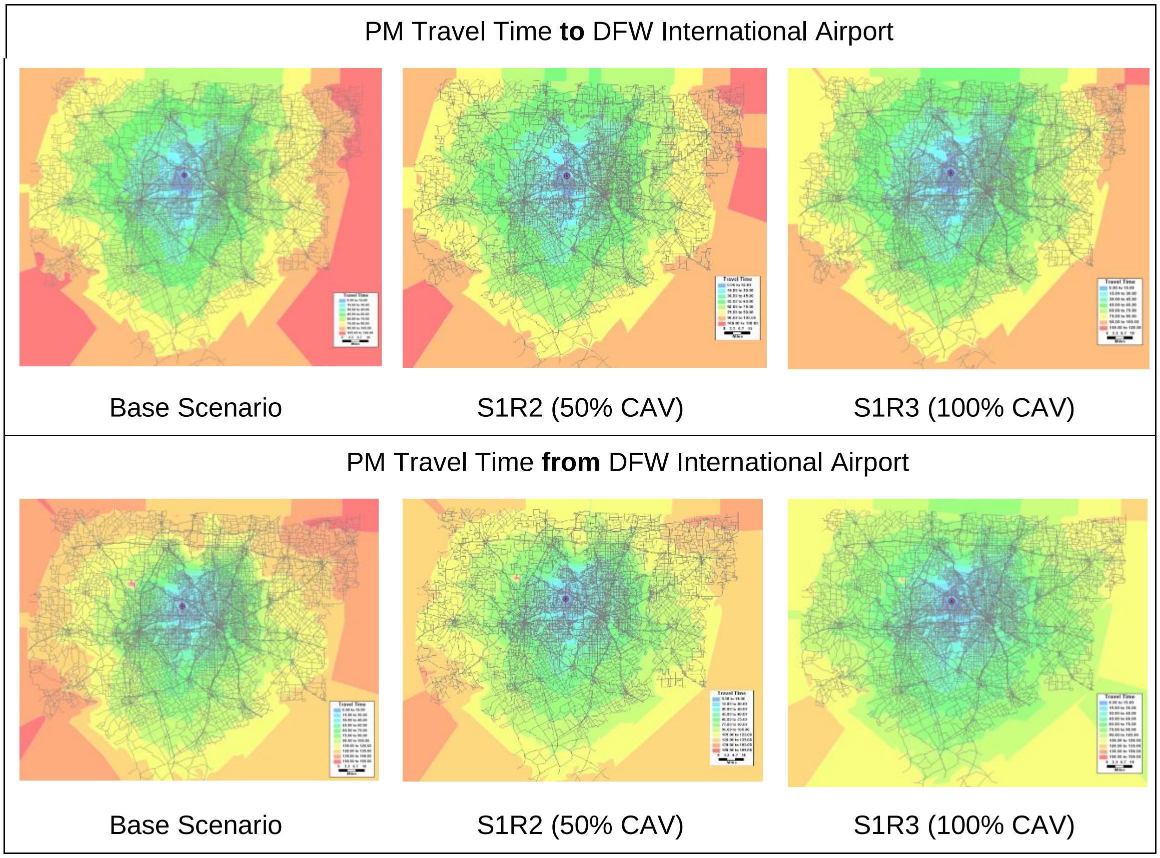


Figure 20. Travel Time Contour Maps for the PM Peak Period Considering the DFW International Airport as a Focal Point

5.2 Experiments S1R7 to S1R712 (travel speed improvement + capacity enhancement + value of time)

In Experiments S1R1 to S1R6, the improvement in the transportation network performance is evaluated, assuming that CAVs only improve the roadway link capacities. Experiments S1R7 to S1R12 extend this analysis considering the potential effect of CAVs in improving the overall traveling speed and roadway link capacities. As shown in Table 2, the settings of Experiments S1R7 to S1R12 are identical to those of Experiments S1R1 to S1R6, except that percentage improvement in the link speeds is considered. This percentage is assumed to be a function of the CAV penetration rate. For CAV penetration rate of 25%, 50% and 100%, improvement percentages of 1.25%, 2.5% and 5%, respectively, are assumed.

The general pattern of the results of Experiments S1R7 to S1R12 is like those presented above for Experiments S1R1 to S1R6. For example, the VMT and average speed increase with the CAV penetration increase. The VHT and delay decrease as the CAV penetration rate increases. Furthermore, the traffic volume change pattern is identical to those presented for Experiments S1R1 to S1R6. An increase in traffic volumes along freeway facilities associated with a decrease in the traffic volumes along principal and minor arterials is reported for all periods. Also, a similar improvement in roadway links' LOS is observed.

The following set of results, presented in Table 17 to Table 20, compare the values and percentage change in VMT, VHT, average speed, and total delay obtained based on Experiments S1R7 to S1R12 to those of Experiments S1R1 to S1R6, presented in the previous section. For Example, Table 17 gives the VMT and corresponding percentage change for Experiments S1R1 to S1R6 (capacity improvement only), and Experiments S1R7 to S1R12 (capacity and speed improvement). For instance, the results of Experiment S1R9 could be compared to the results of S1R3 to quantify the effect of assuming that CAV will improve both the roadway link capacities and speeds (S1R9) versus the assumption that CAV will only enhance the roadway link capacities (S1R3).

These two experiments consider a 100% CAV penetration rate. Experiment S1R3 assumes a 33% improvement in the roadway link capacities. Experiment S1R9 assumes 33% roadway link capacities and 5% improvement in the roadway link travel speeds. The results for these two experiments are given for the AM, PM, and OP periods and the entire day. As shown in the table, assuming CAV improves both the capacity and the speed of the roadway links resulted in an additional 5.5M traveled vehicle-miles for the entire day. The extra traveled vehicle-miles increase the percentage change to 8% compared to the base scenario, which is a 2% increase from the case in which only an improvement in the capacity of the roadway links is assumed.

The results of these two experiments can also be examined for the other performance measures. For the VHT results in Table 18, S1R9 recorded 9.92M vehicle-hours compared to 10.14M vehicle-hours in S1R3, representing a 2% additional reduction of the base scenario. As shown in Table 19, the average speed of these two experiments increased from 35 mph to 36 mph, representing a 4% additional increase compared to the base scenario. Finally, the delay results in Table 20 show that the total delay reduced from 3.4M to 3.1M hours, equivalent to a 7% additional reduction from the base scenario.

The travel time contour maps in Figure 21 and Figure 22 confirm these results. Like the maps in the previous section, the maps presented here illustrate the travel time to and from the DFW international airport in the AM and PM peak periods. The contour maps are given for the base case, Experiment S1R3 (capacity improvement), and Experiment S1R9 (Capacity and Speed Improvement). As shown in all cases, assuming the CAV improves both capacity and the speed of the roadway links resulted in an enhanced travel time pattern in the region. As shown in the Figure, in the maps of S1R9, areas covered by colors representing high travel time values (e.g., dark orange) shrink, and areas covered by colors representing low travel time values expand. This pattern is observed for the AM and PM peak periods and trips to and from the DFW airport.

Table 17. VMT and VMT Percent Change Recorded for Experiments S1R1 to S1R6 (Capacity Improvement) and Experiments S1R7 to S1R12 (Capacity and Speed Improvement)

VMT

Scenario Runs	AV/CV Penetration Rate	VMT AM	VMT OP	VMT PM	VMT Daily
Base	0	59,580,295	185,718,743	85,738,403	331,037,442
S1R1	0.25	60,036,147	187,155,745	86,372,991	333,564,883
S1R2	0.5	60,814,905	189,698,858	87,493,591	338,007,354
S1R3	1	63,082,113	197,107,091	90,851,524	351,040,728
S1R4	0.25	60,346,336	187,661,127	86,702,122	334,709,585
S1R5	0.5	61,305,347	190,588,097	88,053,069	339,946,513
S1R6	1	63,701,047	198,145,444	91,567,318	353,413,809

Capacity Improvement

Scenario Runs	AV/CV Penetration Rate	VMT AM	VMT OP	VMT PM	VMT Daily
Base	0	59,580,295	185,718,743	85,738,403	331,037,442
S1R7	0.25	60,261,875	187,871,450	86,716,391	334,849,717
S1R8	0.5	61,202,418	191,028,864	88,117,487	340,348,769
S1R9	1	63,960,388	200,197,391	92,282,083	356,439,862
S1R10	0.25	60,515,172	188,244,216	86,975,722	335,735,110
S1R11	0.5	61,660,921	191,869,584	88,649,265	342,179,770
S1R12	1	64,687,397	201,534,483	93,156,386	359,378,266

Capacity and Speed Improvement

VMT Percent Change

Scenario Runs	AV/CV Penetration Rate	VMT Percent Change AM	VMT Percent Change OP	VMT Percent Change PM	VMT Percent Change Daily
S1R1	0.25	1%	1%	1%	1%
S1R2	0.5	2%	2%	2%	2%
S1R3	1	6%	6%	6%	6%
S1R4	0.25	1%	1%	1%	1%
S1R5	0.5	3%	3%	3%	3%
S1R6	1	7%	7%	7%	7%

Capacity Improvement

Scenario Runs	AV/CV Penetration Rate	VMT Percent Change AM	VMT Percent Change OP	VMT Percent Change PM	VMT Percent Change Daily
S1R7	0.25	1%	1%	1%	1%
S1R8	0.5	3%	3%	3%	3%
S1R9	1	7%	8%	8%	8%
S1R10	0.25	2%	1%	1%	1%
S1R11	0.5	3%	3%	3%	3%
S1R12	1	9%	9%	9%	9%

Capacity and Speed Improvement

Table 18. VHT and VHT Percent Change Recorded for Experiments S1R1 to S1R6 (Capacity Improvement) and Experiments S1R7 to S1R12 (Capacity and Speed Improvement)

VHT

Scenario Runs	AV/CV Penetration Rate	VHT AM	VHT OP	VHT PM	VHT Daily
Base	0	3,225,458	4,974,597	3,362,522	11,562,578
S1R1	0.25	3,125,636	4,959,477	3,288,793	11,373,905
S1R2	0.5	2,923,320	4,924,158	3,148,257	10,995,734
S1R3	1	2,420,030	4,865,698	2,854,015	10,139,743
S1R4	0.25	3,182,637	4,998,891	3,332,194	11,513,721
S1R5	0.5	3,000,328	4,999,237	3,217,673	11,217,238
S1R6	1	2,495,242	4,999,770	2,960,836	10,455,848

Capacity Improvement

Scenario Runs	AV/CV Penetration Rate	VHT AM	VHT OP	VHT PM	VHT Daily
Base	0	3,225,458	4,974,597	3,362,522	11,562,578
S1R7	0.25	3,114,780	4,931,331	3,279,411	11,325,522
S1R8	0.5	2,892,034	4,864,603	3,121,731	10,878,368
S1R9	1	2,366,666	4,751,677	2,802,907	9,921,250
S1R10	0.25	3,164,494	4,965,536	3,316,281	11,446,311
S1R11	0.5	2,962,576	4,935,564	3,186,886	11,085,026
S1R12	1	2,444,763	4,895,287	2,917,572	10,257,622

Capacity and Speed Improvement

VHT Percent Change

Scenario Runs	AV/CV Penetration Rate	VHT Percent Change AM	VHT Percent Change OP	VHT Percent Change PM	VHT Percent Change Daily
S1R1	0.25	-3%	0%	-2%	-2%
S1R2	0.5	-9%	-1%	-6%	-5%
S1R3	1	-25%	-2%	-15%	-12%
S1R4	0.25	-1%	0%	-1%	0%
S1R5	0.5	-7%	0%	-4%	-3%
S1R6	1	-23%	1%	-12%	-10%

Capacity Improvement

Scenario Runs	AV/CV Penetration Rate	VHT Percent Change AM	VHT Percent Change OP	VHT Percent Change PM	VHT Percent Change Daily
S1R7	0.25	-3%	-1%	-2%	-2%
S1R8	0.5	-10%	-2%	-7%	-6%
S1R9	1	-27%	-4%	-17%	-14%
S1R10	0.25	-2%	0%	-1%	-1%
S1R11	0.5	-8%	-1%	-5%	-4%
S1R12	1	-24%	-2%	-13%	-11%

Capacity and Speed Improvement

Table 19. Average Speed and Average Speed Percent Change Recorded for Experiments S1R1 to S1R6 (Capacity Improvement) and Experiments S1R7 to S1R12 (Capacity and Speed Improvement)

Average Speed

Avg Speed					
Scenario Runs	AV/CV Penetration Rate	AM	OP	PM	Daily
Base	0	18	37	25	29
S1R1	0.25	19	38	26	29
S1R2	0.5	21	39	28	31
S1R3	1	26	41	32	35
S1R4	0.25	19	38	26	29
S1R5	0.5	20	38	27	30
S1R6	1	26	40	31	34

Capacity Improvement

Avg Speed					
Scenario Runs	AV/CV Penetration Rate	AM	OP	PM	Daily
Base	0	18	37	25	29
S1R7	0.25	19	38	26	30
S1R8	0.5	21	39	28	31
S1R9	1	27	42	33	36
S1R10	0.25	19	38	26	29
S1R11	0.5	21	39	28	31
S1R12	1	26	41	32	35

Capacity and Speed Improvement

Average Speed Percent Change

Avg Speed Percent Change					
Scenario Runs	AV/CV Penetration Rate	AM	OP	PM	Daily
S1R1	0.25	4%	1%	3%	2%
S1R2	0.5	13%	3%	9%	7%
S1R3	1	41%	9%	25%	21%
S1R4	0.25	3%	1%	2%	2%
S1R5	0.5	11%	2%	7%	6%
S1R6	1	38%	6%	21%	18%

Capacity Improvement

Avg Speed Percent Change					
Scenario Runs	AV/CV Penetration Rate	AM	OP	PM	Daily
S1R7	0.25	5%	2%	4%	3%
S1R8	0.5	15%	5%	11%	9%
S1R9	1	46%	13%	29%	25%
S1R10	0.25	4%	2%	3%	2%
S1R11	0.5	13%	4%	9%	8%
S1R12	1	43%	10%	25%	22%

Capacity and Speed Improvement

Table 20. Delay and Delay Percent Change Recorded for Experiments S1R1 to S1R6 (Capacity Improvement) and Experiments S1R7 to S1R12 (Capacity and Speed Improvement)

Delay

Delay					
Scenario Runs	AV/CV Penetration Rate	AM	OP	PM	Daily
Base	0	2,041,895	1,414,540	1,670,096	5,126,531
S1R1	0.25	1,935,261	1,377,180	1,587,379	4,899,820
S1R2	0.5	1,722,684	1,303,877	1,432,220	4,458,780
S1R3	1	1,193,409	1,135,522	1,095,708	3,424,640
S1R4	0.25	1,985,300	1,398,940	1,622,222	5,006,462
S1R5	0.5	1,788,413	1,345,160	1,486,074	4,619,646
S1R6	1	1,252,822	1,209,790	1,175,278	3,637,889

Capacity Improvement

Delay					
Scenario Runs	AV/CV Penetration Rate	AM	OP	PM	Daily
Base	0	2,041,895	1,414,540	1,670,096	5,126,531
S1R7	0.25	1,919,887	1,334,374	1,570,814	4,825,076
S1R8	0.5	1,683,664	1,216,926	1,392,599	4,293,188
S1R9	1	1,122,972	960,889	1,015,649	3,099,510
S1R10	0.25	1,963,821	1,353,429	1,600,570	4,917,821
S1R11	0.5	1,743,599	1,254,969	1,442,789	4,441,358
S1R12	1	1,183,069	1,037,812	1,099,542	3,320,423

Capacity and Speed Improvement

Delay Percent Change

Delay Percent Change					
Scenario Runs	AV/CV Penetration Rate	AM	OP	PM	Daily
S1R1	0.25	-5%	-3%	-5%	-4%
S1R2	0.5	-16%	-8%	-14%	-13%
S1R3	1	-42%	-20%	-34%	-33%
S1R4	0.25	-3%	-1%	-3%	-2%
S1R5	0.5	-12%	-5%	-11%	-10%
S1R6	1	-39%	-14%	-30%	-29%

Capacity Improvement

Delay Percent Change					
Scenario Runs	AV/CV Penetration Rate	AM	OP	PM	Daily
S1R7	0.25	-6%	-6%	-6%	-6%
S1R8	0.5	-18%	-14%	-17%	-16%
S1R9	1	-45%	-32%	-39%	-40%
S1R10	0.25	-4%	-4%	-4%	-4%
S1R11	0.5	-15%	-11%	-14%	-13%
S1R12	1	-42%	-27%	-34%	-35%

Capacity and Speed Improvement

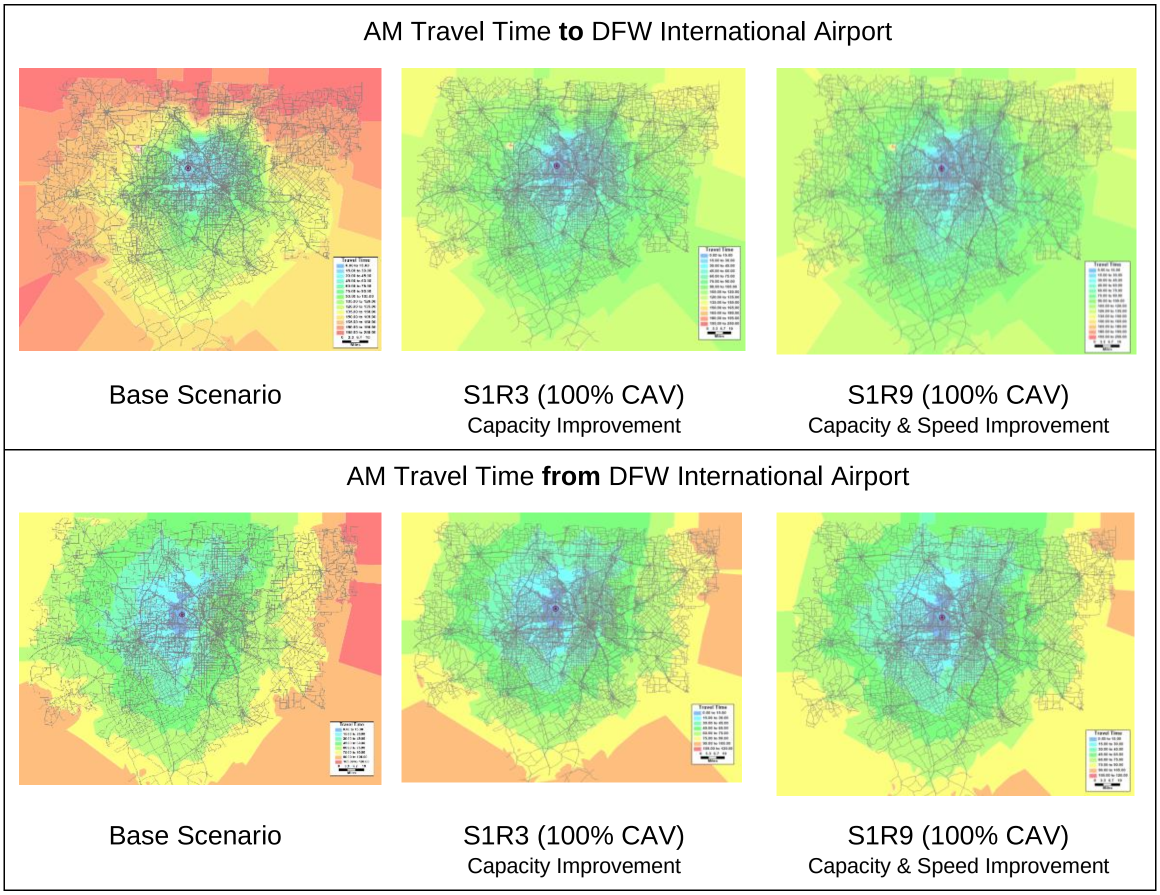


Figure 21. Travel Time Contour Maps for the AM Peak Period Considering the DFW International Airport as a Focal Point

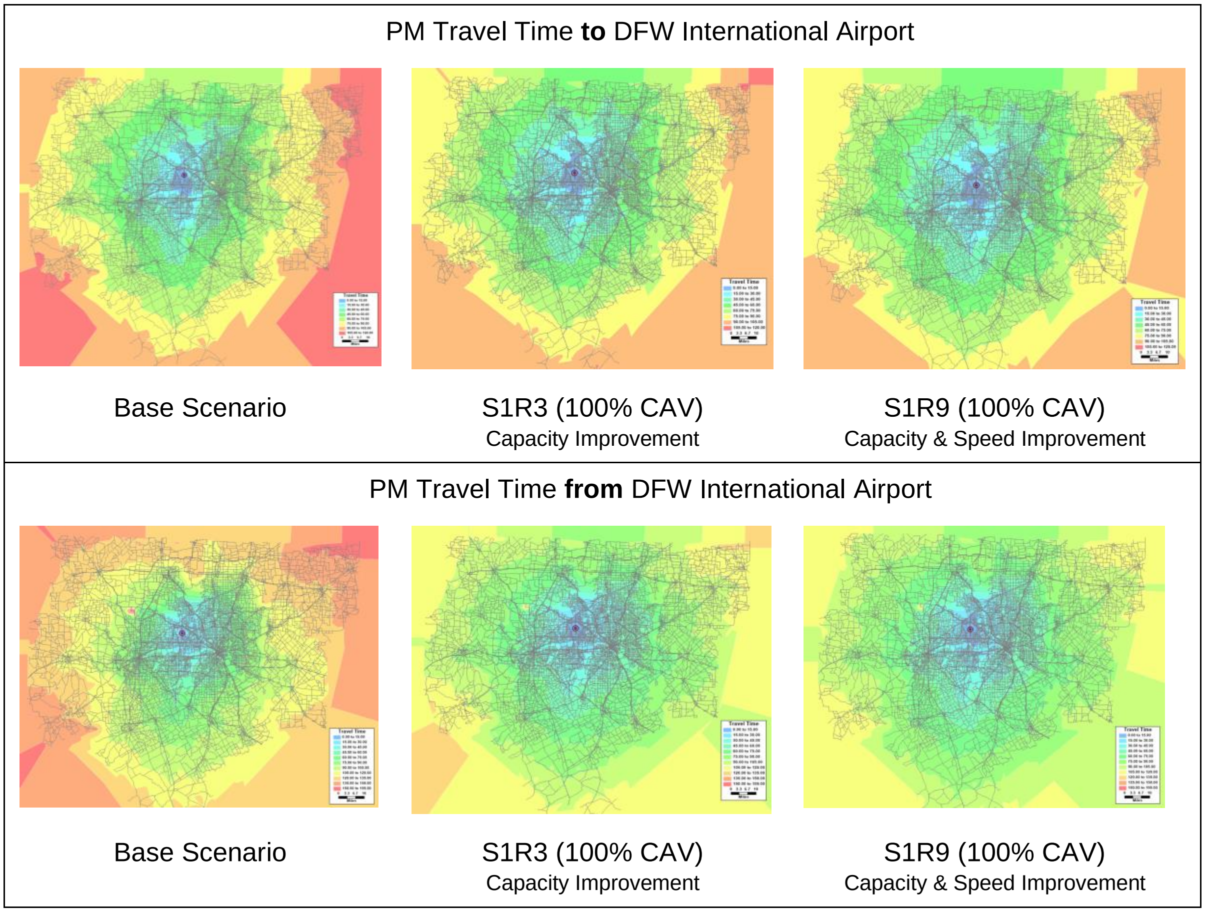


Figure 22. Travel Time Contour Maps for the PM Peak Period Considering the DFW International Airport as a Focal Point

5.3 Experiments S1R13 to S1R15 (vehicle operating cost reduction + capacity improvement)

Experiments S1R13 to S1R15 are designed to quantify the effect of the assumption that CAV will be operating at a lower operating cost. These three experiments use the same settings as Experiments S1R1 to S1R3 after reducing the vehicle operating cost variable by 10%.

Table 21 to Table 24 compare the VMT, VHT, average speed, and delay for Experiments S1R13 to S1R15 (with operating cost reduction) and Experiments S1R1 to S1R3 (without operating cost reduction).

The results of these three experiments show that the **reduction in the CAV operating cost does not significantly impact the regional traffic pattern**. When the results of both sets of experiments were compared, a very slight change was recorded for VMT, VHT, and delay. No change in the average speed was reported between these two sets of experiments. The percentage changes in all these performance measures are identical.

Table 21. VMT and VMT Percent Change Recorded for Experiments S1R1 to S1R3 (No Change in CAV Operating Cost) and Experiments S1R13 to S1R15 (10% Reduction in CAV Operating Cost)

VMT

Scenario Runs	AV/CV Penetration rate	AM	OP	PM	Daily
Base	0	59,580,295	185,718,743	85,738,403	331,037,442
S1R1	0.25	60,036,147	187,155,745	86,372,991	333,564,883
S1R2	0.5	60,814,905	189,698,858	87,493,591	338,007,354
S1R3	1	63,082,113	197,107,091	90,851,524	351,040,728
S1R13	0.25	60,092,804	187,320,112	86,451,747	333,864,663
S1R14	0.5	60,830,500	189,783,780	87,523,892	338,138,172
S1R15	1	63,030,981	197,037,473	90,797,000	350,865,454

VMT Percent Change

Scenario Runs	AV/CV Penetration Rate	AM	OP	PM	Daily
S1R1	0.25	1%	1%	1%	1%
S1R2	0.5	2%	2%	2%	2%
S1R3	1	6%	6%	6%	6%
S1R13	0.25	1%	1%	1%	1%
S1R14	0.5	2%	2%	2%	2%
S1R15	1	6%	6%	6%	6%

Table 22. VHT and VHT Percent Change Recorded for Experiments S1R1 to S1R3 (No Change in CAV Operating Cost) and Experiments S1R13 to S1R15 (10% Reduction in CAV Operating Cost)

VHT

Scenario Runs	AV/CV Penetration Rate	AM	OP	PM	Daily
Base	0	3,225,458	4,974,597	3,362,522	11,562,578
S1R1	0.25	3,125,636	4,959,477	3,288,793	11,373,905
S1R2	0.5	2,923,320	4,924,158	3,148,257	10,995,734
S1R3	1	2,420,030	4,865,698	2,854,015	10,139,743
S1R13	0.25	3,132,911	4,964,866	3,295,834	11,393,611
S1R14	0.5	2,923,683	4,925,330	3,149,232	10,998,245
S1R15	1	2,428,516	4,865,368	2,857,960	10,151,845

VHT Percent Change

Scenario Runs	AV/CV Penetration Rate	AM	OP	PM	Daily
S1R1	0.25	-3%	0%	-2%	-2%
S1R2	0.5	-9%	-1%	-6%	-5%
S1R3	1	-25%	-2%	-15%	-12%
S1R13	0.25	-3%	0%	-2%	-1%
S1R14	0.5	-9%	-1%	-6%	-5%
S1R15	1	-25%	-2%	-15%	-12%

Table 23. Average Speed and Average Speed Percent Change Recorded for Experiments S1R1 to S1R3 (No Change in CAV Operating Cost) and Experiments S1R13 to S1R15 (10% Reduction in CAV Operating Cost)

Average Speed

Scenario Runs	AV/CV Penetration Rate	AM	OP	PM	Daily
Base	0	18	37	25	29
S1R1	0.25	19	38	26	29
S1R2	0.5	21	39	28	31
S1R3	1	26	41	32	35
S1R13	0.25	19	38	26	29
S1R14	0.5	21	39	28	31
S1R15	1	26	40	32	35

Average Speed Percent Change

Scenario Runs	AV/CV Penetration Rate	AM	OP	PM	Daily
S1R1	0.25	4%	1%	3%	2%
S1R2	0.5	13%	3%	9%	7%
S1R3	1	41%	9%	25%	21%
S1R13	0.25	4%	1%	3%	2%
S1R14	0.5	13%	3%	9%	7%
S1R15	1	41%	8%	25%	21%

Table 24. Delay and Delay Percent Change Recorded for Experiments S1R1 to S1R3 (No Change in CAV Operating Cost) and Experiments S1R13 to S1R15 (10% Reduction in CAV Operating Cost)

Delay

Scenario Runs	AV/CV Penetration Rate	AM	OP	PM	Daily
Base	0	2,041,895	1,414,540	1,670,096	5,126,531
S1R1	0.25	1,935,261	1,377,180	1,587,379	4,899,820
S1R2	0.5	1,722,684	1,303,877	1,432,220	4,458,780
S1R3	1	1,193,409	1,135,522	1,095,708	3,424,640
S1R13	0.25	1,941,438	1,380,200	1,592,961	4,914,598
S1R14	0.5	1,722,796	1,304,726	1,432,849	4,460,371
S1R15	1	1,202,623	1,138,782	1,100,837	3,442,242

Delay Percent Change

Scenario Runs	AV/CV Penetration Rate	AM	OP	PM	Daily
S1R1	0.25	-5%	-3%	-5%	-4%
S1R2	0.5	-16%	-8%	-14%	-13%
S1R3	1	-42%	-20%	-34%	-33%
S1R13	0.25	-5%	-2%	-5%	-4%
S1R14	0.5	-16%	-8%	-14%	-13%
S1R15	1	-41%	-19%	-34%	-33%

6 RESULTS AND ANALYSIS OF SCENARIO 2: CAV IMPACT ON INTERSECTION PERFORMANCE

As mentioned earlier, this automation scenario assumes that CAVs are connected to the intersection control infrastructure (V2I). The connection allows vehicles and intersections to share data. For example, vehicles share information on their locations and speeds as they approach the intersection. Also, the intersection shares information on its signal timing (e.g., remaining green interval) with the vehicles. The vehicle-intersection information sharing is expected to enhance the intersection's capacities, minimize vehicle delays, and improve the signal progression. A summary of the set of experiments designed for this scenario is given in Table 3. The table shows that this automation scenario (S2) is studied using six experiments, numbered S2R16 to S2R21. These experiments use the settings of Experiments S1R7 to S1R12, considering two main modifications. The first modification assumes higher saturation flow rates for all non-freeway links. At CAV penetration rates of 25%, 50%, and 100%, the saturation flow rate for the non-freeway links is increased by 5%, 10%, and 33%, respectively. The second modification assumes a lower signal control delay for all links with signal control at their downstream intersections. At CAV penetration rates of 25%, 50%, and 100%, the control delay is assumed to be reduced by 2.5%, 5%, and 10%, respectively. Like the analysis presented in the previous section, the results of these experiments are compared with a base scenario that assumes no CAVs in the traffic composition (0% penetration rate). In this base scenario, the roadway link capabilities, the travelers' VOT, the travel speed, and the vehicle operating cost are unchanged. The network performance is quantified by comparing the values of several performance measures to their corresponding value in the base scenario. The performance measures are VMT, VHT, average speed, and total delay.

The results presented in Table 21 to Table 24 compare the values and percentage change in VMT, VHT, average speed, and total delay obtained based on Experiments S2R16 to S2R21 to those of Experiments S1R7 to S1R12, presented above in Section 5. For Example, Table 21 gives the VMT and corresponding percentage change for Experiments S1R7 to S1R12 (S1 - capacity improvement only) and Experiments S2R16 to S2R21 (S2 - capacity improvement and connected intersections). The results show **an insignificant change in VMT with the addition of connected intersection technology in the region**. As shown in this Figure, the percent changes in VMT, compared to the base scenario, are almost identical for both cases indicating the improvement in the intersection capacity and the reduction in the delays did not cause changes in the travelers' route choice behavior. Traversers are satisfied with their routes under S1 (roadway capacity improvement only) and do not gain additional benefits from changing them when intersection automation technology is introduced. This result is confirmed by comparing the links' traffic volumes in both scenarios. Figure 23 presents the link volume changes for the AM, PM, and OP periods, compared to the base scenario for Experiments S2R18 and S1R9. The Figure shows that the volume change pattern is identical for these two experiments, where no significant changes in the travelers' routes occurred with the introduction of the intersection automation technology.

Table 25. VMT and VMT Percent Change Recorded for Experiments S1R7 to S1R12 (Capacity Improvement) and Experiments S2R16 to S2R21 (Capacity and Speed Improvement)

VMT

Scenario Runs	AV/CV Penetration Rate	VMT AM	OP	PM	Daily
Base	0	59,580,295	185,718,743	85,738,403	331,037,442
S1R7	0.25	60,261,875	187,871,450	86,716,391	334,849,717
S1R8	0.5	61,202,418	191,028,864	88,117,487	340,348,769
S1R9	1	63,960,388	200,197,391	92,282,083	356,439,862
S1R10	0.25	60,515,172	188,244,216	86,975,722	335,735,110
S1R11	0.5	61,660,921	191,869,584	88,649,265	342,179,770
S1R12	1	64,687,397	201,534,483	93,156,386	359,378,266

Capacity Improvement

Scenario Runs	AV/CV Penetration rate	VMT AM	OP	PM	Daily
Base	0	59,580,295	185,718,743	85,738,403	331,037,442
S2R16	0.25	60,256,297	187,900,335	86,732,683	335,000,000
S2R17	0.5	61,264,292	191,303,235	88,244,384	340,811,911
S2R18	1	64,186,835	200,969,551	92,646,459	357,802,845
S2R19	0.25	60,548,935	188,356,157	87,034,333	335,939,425
S2R20	0.5	61,714,523	192,079,448	88,748,114	342,542,085
S2R21	1	64,897,917	202,289,089	93,499,610	360,686,616

Capacity Improvement & Connected Intersections

VMT Percent Change

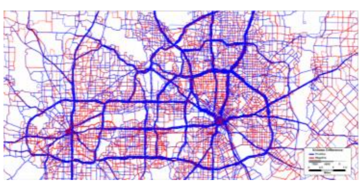
Scenario Runs	AV/CV Penetration Rate	VMT Percent Change AM	OP	PM	Daily
S1R7	0.25	1%	1%	1%	1%
S1R8	0.5	3%	3%	3%	3%
S1R9	1	7%	8%	8%	8%
S1R10	0.25	2%	1%	1%	1%
S1R11	0.5	3%	3%	3%	3%
S1R12	1	9%	9%	9%	9%

Capacity Improvement

Scenario Runs	AV/CV Penetration Rate	VMT Percent Change AM	OP	PM	Daily
S2R16	0.25	1%	1%	1%	1%
S2R17	0.5	3%	3%	3%	3%
S2R18	1	8%	8%	8%	8%
S2R19	0.25	2%	1%	2%	1%
S2R20	0.5	4%	3%	4%	3%
S2R21	1	9%	9%	9%	9%

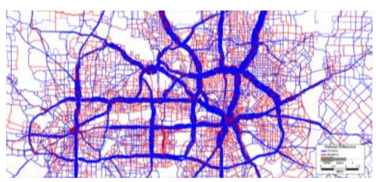
Capacity Improvement & Connected Intersections

S1R9 (Capacity Improvement Only)



AM Peak Period

PM Peak Period

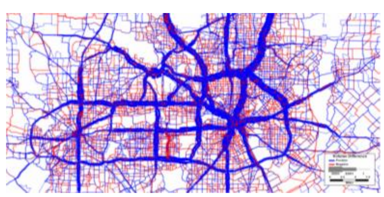


OP Period

S2R18 VS. Base Case (Capacity Improvement and Connected Intersections)

AM Peak Period

PM Peak Period



OP Period

Figure 23. The AM, PM, and OP Volume Change Map for the Scenarios S1R9 and S2R18 (Both Scenarios are compared with the base case).

While VMT did not significantly change, the results show that there are improvements in VHT. As shown in Table 26, experiments that consider intersection automation (S2R16 to S2R21) recorded an additional VHT reduction compared to experiments that do not consider this technology (S1R7 to S1R12). For instance, Experiment S2R18 could be compared to the results of S1R9 to quantify the additional benefits associated with introducing intersection automation. These two experiments consider a 100% CAV penetration rate. Experiment S1R9 assumes 33% roadway link capacities and 5% improvement in the roadway link travel speeds. Experiment S2R18 makes the same assumptions as Experiment S1R9. However, it further assumes that the saturation flow rate for non-freeway links increases by 33%, and the control delay is reduced by 10% at all intersections. The results for these two experiments are given for the AM, PM, and OP periods and the entire day. As shown in the Figure, adopting the intersection automation technology resulted in a daily VHT reduction of 15% (Experiment S2R18), compared to only a 14% reduction when the technology was not considered (Experiment S1R9). This additional VHT saving is about 0.12M vehicle-hours daily.

The results of these two experiments are also examined for the average speed and the delay. As shown in Table 27, the results show no change in the average speed as both experiments recorded an average speed of 36 mph. Finally, the results in Table 28 indicate that the total delay was reduced by an additional 3%.

The contour maps in Figure 24 and Figure 25 show the travel time values to and from the DFW International airport in the AM and PM peak periods. The contour maps are given for the base scenario, Experiment S1R9 (capacity improvement), and Experiment S2R18 (Capacity and Connected Intersections). As shown in all cases, slight differences in the travel time contour maps of Experiments S2R18 and S1R9 are observed, confirming that i**ntersection automation technology did not contribute significantly to the average speed and delay**.

Table 26. VHT and VHT Percent Change Recorded for Experiments S1R7 to S1R12 (Capacity Improvement) and Experiments S2R16 to S2R21 (Capacity and Speed Improvement)

VHT

Scenario Runs	AV/CV Penetration Rate	VHT AM	VHT OP	VHT PM	VHT Daily
Base	0	3,225,458	4,974,597	3,362,522	11,562,578
S1R7	0.25	3,114,780	4,931,331	3,279,411	11,325,522
S1R8	0.5	2,892,034	4,864,603	3,121,731	10,878,368
S1R9	1	2,366,666	4,751,677	2,802,907	9,921,250
S1R10	0.25	3,164,494	4,965,536	3,316,281	11,446,311
S1R11	0.5	2,962,576	4,935,564	3,186,886	11,085,026
S1R12	1	2,444,763	4,895,287	2,917,572	10,257,622

Capacity Improvement

Scenario Runs	AV/CV Penetration Rate	VHT AM	VHT OP	VHT PM	VHT Daily
Base	0	3,225,458	4,974,597	3,362,522	11,562,578
S2R16	0.25	3,102,191	4,919,812	3,269,148	11,291,151
S2R17	0.5	2,868,223	4,843,618	3,102,139	10,813,980
S2R18	1	2,323,207	4,716,305	2,763,545	9,803,057
S2R19	0.25	3,157,733	4,957,464	3,310,702	11,425,899
S2R20	0.5	2,939,119	4,912,786	3,165,620	11,017,524
S2R21	1	2,386,170	4,849,540	2,865,804	10,101,514

Capacity Improvement & Connected Intersections

VHT Percent Change

Scenario Runs	AV/CV Penetration Rate	VHT Percent Change AM	VHT Percent Change OP	VHT Percent Change PM	VHT Percent Change Daily
S1R7	0.25	-3%	-1%	-2%	-2%
S1R8	0.5	-10%	-2%	-7%	-6%
S1R9	1	-27%	-4%	-17%	-14%
S1R10	0.25	-2%	0%	-1%	-1%
S1R11	0.5	-8%	-1%	-5%	-4%
S1R12	1	-24%	-2%	-13%	-11%

Capacity Improvement

Scenario Runs	AV/CV Penetration Rate	VHT Percent Change AM	VHT Percent Change OP	VHT Percent Change PM	VHT Percent Change Daily
S2R16	0.25	-4%	-1%	-3%	-2%
S2R17	0.5	-11%	-3%	-8%	-6%
S2R18	1	-28%	-5%	-18%	-15%
S2R19	0.25	-2%	0%	-2%	-1%
S2R20	0.5	-9%	-1%	-6%	-5%
S2R21	1	-26%	-3%	-15%	-13%

Capacity Improvement & Connected Intersections

Table 27. Average Speed and Average Speed Percent Change Recorded for Experiments S1R7 to S1R12 (Capacity Improvement) and Experiments S1R16 to S1R21 (Capacity and Speed Improvement)

Average Speed

Avg Speed					
Scenario Runs	AV/CV Penetration Rate	AM	OP	PM	Daily
Base	0	18	37	25	29
S1R7	0.25	19	38	26	30
S1R8	0.5	21	39	28	31
S1R9	1	27	42	33	36
S1R10	0.25	19	38	26	29
S1R11	0.5	21	39	28	31
S1R12	1	26	41	32	35

Capacity Improvement

Avg Speed					
Scenario Runs	AV/CV Penetration Rate	AM	OP	PM	Daily
Base	0	18	37	25	29
S2R16	0.25	19	38	27	30
S2R17	0.5	21	39	28	32
S2R18	1	28	43	34	36
S2R19	0.25	19	38	26	29
S2R20	0.5	21	39	28	31
S2R21	1	27	42	33	36

Capacity Improvement & Connected Intersections

Average Speed Percent Change

Avg Speed Percent Change					
Scenario Runs	AV/CV Penetration Rate	AM	OP	PM	Daily
S1R7	0.25	5%	2%	4%	3%
S1R8	0.5	15%	5%	11%	9%
S1R9	1	46%	13%	29%	25%
S1R10	0.25	4%	2%	3%	2%
S1R11	0.5	13%	4%	9%	8%
S1R12	1	43%	10%	25%	22%

Capacity Improvement

Avg Speed Percent Change					
Scenario Runs	AV/CV Penetration Rate	AM	OP	PM	Daily
S2R16	0.25	5%	2%	4%	4%
S2R17	0.5	16%	6%	12%	10%
S2R18	1	50%	14%	31%	27%
S2R19	0.25	4%	2%	3%	3%
S2R20	0.5	14%	5%	10%	9%
S2R21	1	47%	12%	28%	25%

Capacity Improvement & Connected Intersections

Table 28. Delay and Delay Percent Change Recorded for Experiments S1R7 to S1R12 (Capacity Improvement) and Experiments S2R16 to S2R21 (Capacity and Speed Improvement)

Delay

Delay					
Scenario Runs	AV/CV Penetration Rate	AM	OP	PM	Daily
Base	0	2,041,895	1,414,540	1,670,096	5,126,531
S1R7	0.25	1,919,887	1,334,374	1,570,814	4,825,076
S1R8	0.5	1,683,664	1,216,926	1,392,599	4,293,188
S1R9	1	1,122,972	960,889	1,015,649	3,099,510
S1R10	0.25	1,963,821	1,353,429	1,600,570	4,917,821
S1R11	0.5	1,743,599	1,254,969	1,442,789	4,441,358
S1R12	1	1,183,069	1,037,812	1,099,542	3,320,423

Capacity Improvement

Delay					
Scenario Runs	AV/CV Penetration Rate	AM	OP	PM	Daily
Base	0	2,041,895	1,414,540	1,670,096	5,126,531
S2R16	0.25	1,907,078	1,320,551	1,559,573	4,787,202
S2R17	0.5	1,657,917	1,187,073	1,369,054	4,214,044
S2R18	1	1,072,580	900,815	964,461	2,937,856
S2R19	0.25	1,956,025	1,341,401	1,593,143	4,890,569
S2R20	0.5	1,718,310	1,224,163	1,418,079	4,360,552
S2R21	1	1,118,168	966,695	1,036,394	3,121,256

Capacity Improvement & Connected Intersections

Delay Percent Change

Delay Percent Change					
Scenario Runs	AV/CV Penetration Rate	AM	OP	PM	Daily
S1R7	0.25	-6%	-6%	-6%	-6%
S1R8	0.5	-18%	-14%	-17%	-16%
S1R9	1	-45%	-32%	-39%	-40%
S1R10	0.25	-4%	-4%	-4%	-4%
S1R11	0.5	-15%	-11%	-14%	-13%
S1R12	1	-42%	-27%	-34%	-35%

Capacity Improvement

Delay Percent Change					
Scenario Runs	AV/CV Penetration Rate	AM	OP	PM	Daily
S2R16	0.25	-7%	-7%	-7%	-7%
S2R17	0.5	-19%	-16%	-18%	-18%
S2R18	1	-47%	-36%	-42%	-43%
S2R19	0.25	-4%	-5%	-5%	-5%
S2R20	0.5	-16%	-13%	-15%	-15%
S2R21	1	-45%	-32%	-38%	-39%

Capacity Improvement & Connected Intersections

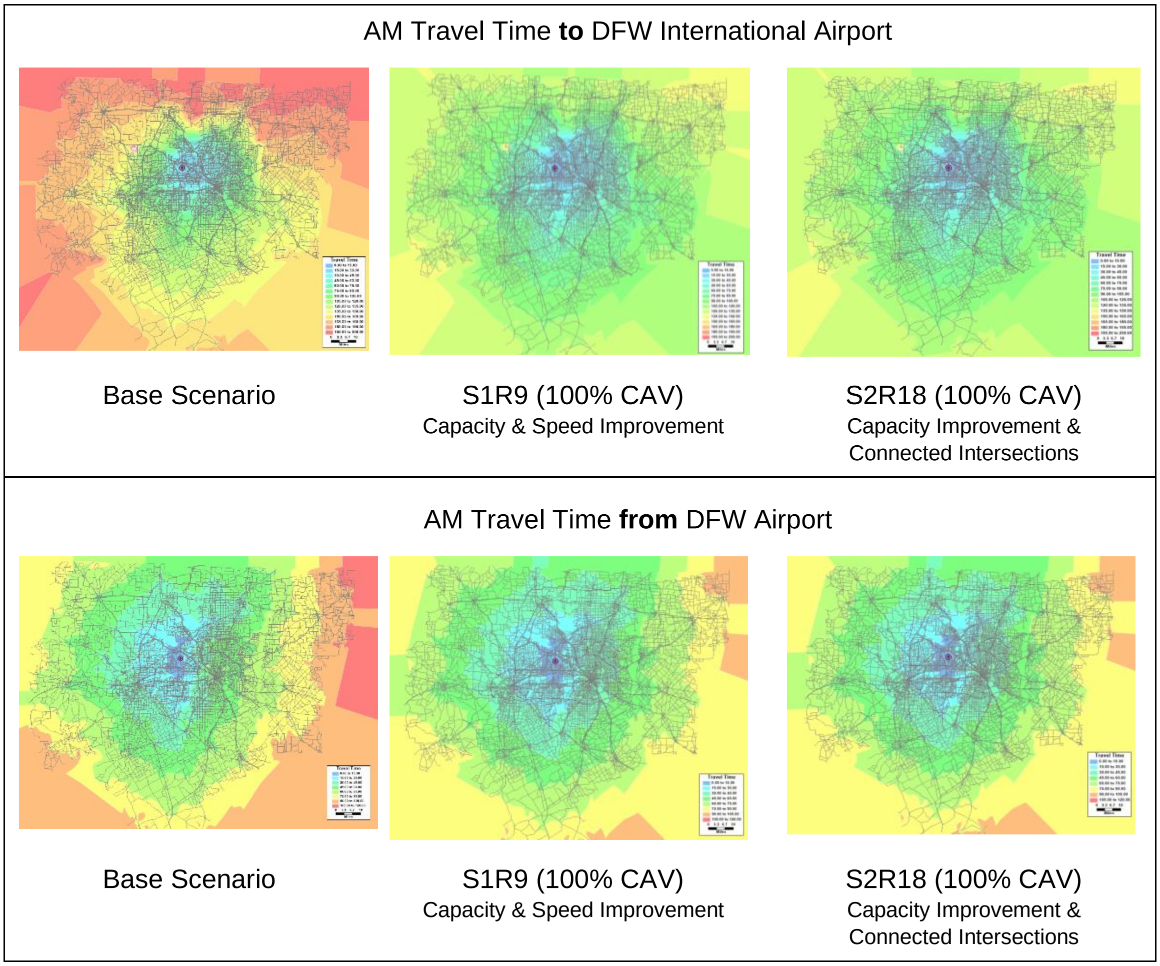
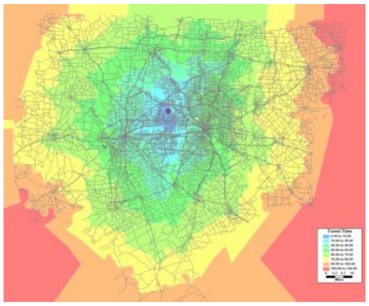
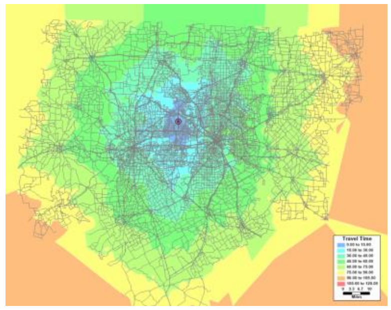


Figure 24. Travel Time Contour Maps for the AM Peak Period Considering the DFW International Airport as a Focal Point

PM Travel Time **to** DFW International Airport

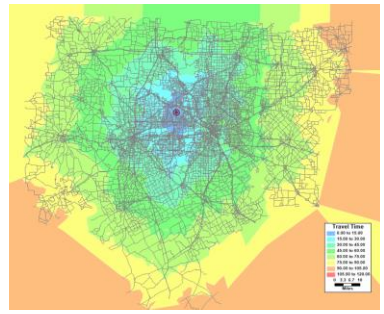


Base Scenario



S1R9 (100% CAV)

Capacity Improvement

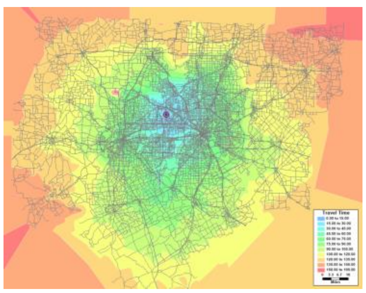


S2R18 (100% CAV)

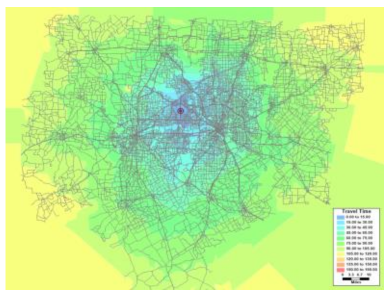
Capacity Improvement &

Connected Intersections

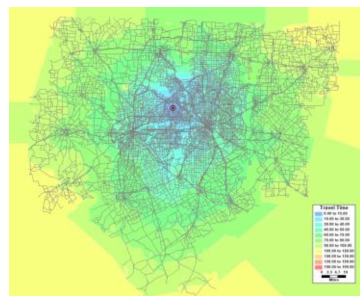
PM Travel Time **from** DFW International Airport



Base Scenario



S1R9 (100% CAV)
Capacity Improvement



S2R18 (100% CAV)
Capacity Improvement &
Connected Intersections

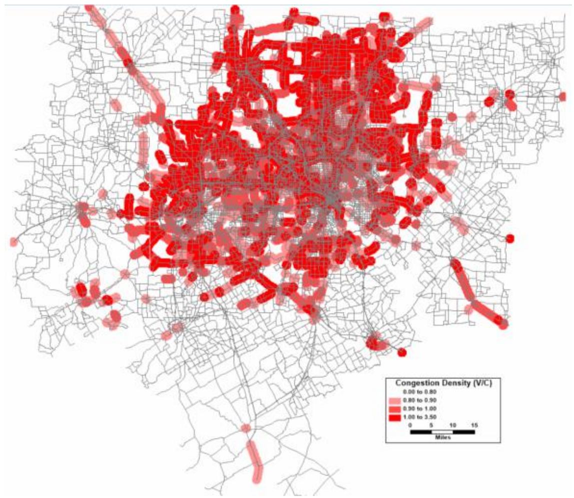
Figure 25. Travel Time Contour Maps for the PM Peak Period Considering the DFW International Airport as a Focal Point

7 RESULTS AND ANALYSIS OF SCENARIO 2 WITH NO-BUILD IN TARGET YEAR

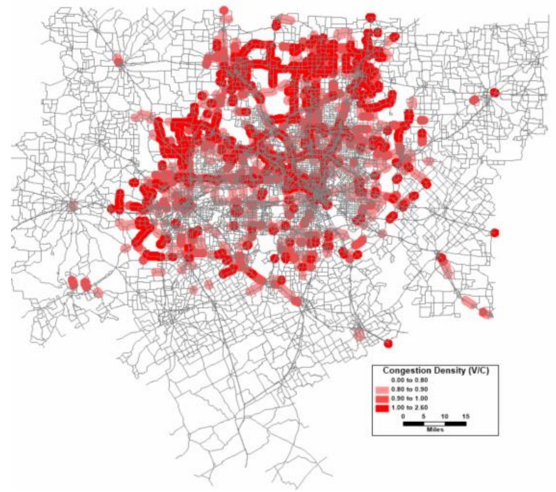
Additional analysis is conducted to investigate a hypothetical scenario where all capacity improvement projects planned for the target year are not built. At the same time, AV technologies were adopted in the region considering 100% CAV penetration rate, and all intersections are connected (S1 plus S2). Table 29 shows the settings of the experiments used to evaluate the no-build scenario. A new base scenario is considered for this analysis, which uses the demographics of the target year (i.e., 2045) and the network of the base year (i.e., 2019). In this new base scenario, no CAVs exist; hence, the roadway link capacity, travel speed, saturation flow, and control delay are not changed. Experiment S2R18 is again used in this analysis. However, instead of using the roadway network of the target year that includes all planned capacity improvement projects, the roadway of the base year is used. The target year demographics are used for this experiment. As shown in the table, this experiment assumes a 33% increase in roadway link capacities, a 5% increase in speed, a 33% increase in the saturation flow rate of links with signalized control, and a 10% reduction in the control delay at all intersections. Figure 26 illustrates the congestion density maps for this experiment and the base scenario. The 2045 No-Build V/C ratio map (a less-refined concept as of the NCTCOG's blob maps) under 100% CAV scenario (S2R18) shows significantly less congestion when compared to Base No-Build conditions. The currently planned capital improvements are in the correct corridors; however, less capital investment might need to be planned if CAVs were in the traffic mix today. Having said that, since no mass implementation of CAVs exist at this time, the region will still need to invest a considerable amount of capital to address the network congestion as we move towards a transportation system with more CAV share and readjust the plans as needed.

Table 29. The Settings of the Experiments used to Evaluate the No-Build Scenario

Scenario Runs	AV/CV Penetration Rate	Link Capacity Improvement	AV/CV VOT Reduction	Increase Speed	Increased Non-Freeway Saturation Flow Rate	Lower Signal Control Delay	Roadway Network	Demographic Input
Base (No AV/CV)	0	0%	0%	0%	0%	0%	2019	2045
AV/CV Scenario (S2R18)	1	33%	0%	5.00%	33%	10.0%	2019	2045



Base Scenario (No-Build)



Experiment S2R18 (S2 No-Build)

Figure 26. The Congestion Density Maps Considering Transportation Automation in a Hypothetical No-Build Scenario

Improvements happen across all functional classes not only arterials. However, freeways have higher volumes so they will need more improvements to show the same level of improvements as low volume arterials.

8 RESULTS AND ANALYSIS OF SCENARIO 3: CAV IMPACT ON POPULATION AND EMPLOYMENT DISTRIBUTIONS

As described in Section 4, four experiments are designed to study the impact of the population and employment redistribution associated with the adoption of CAVs. Experiments S3R24 and S3R28 extend S2R18 to consider the effect of population and employment redistribution scenarios. S3R24 considers the POP/HH/EMP redistribution, while Experiment S3R24 considers the POP/HH redistribution only. These two experiments assume no change in the travelers' VOT. Similarly, Experiment S3R27 and S3R29 extend S2R21 to consider the POP/HH/EMP redistribution and the POP/HH redistribution. These two experiments assume travelers' VOT is reduced by 35%.

Like the results presented for Scenario S1 and S2, the network performance under scenario S3 is quantified by reporting VMT, VHT, average speed, and total delay. These performance measures are recorded for the AM, PM, and OP periods and the entire day. In addition, travel time contour maps are provided. These contour maps demonstrate the travel time to and from the DFW International airport during the AM ad PM peak periods.

The set of results, presented in Table 30 to Table 33, give the values and percentage change in VMT, VHT, average speed, and total delay obtained for these four experiments. However, to benchmark the network performance under this scenario (S3) with those recorded for scenario S1 (capacity improvement only) and scenario S2 (capacity improvement and connected intersections), the results of Experiments S1R9 and S1R12 for scenario S1 and Experiments S2R18 and S2R21 for scenario S2 are included in these figures. Experiments S1R9, S2R18, S3R24, and S3R28 (Set A) assume 100% CAV penetration and no reduction in the travelers' VOT. Experiments S1R12, S2R21, S3R27, and S3R29 (Set B) also assume 100% CAV but with a 35% reduction in the travelers' VOT. The results of these four experiments provide insight into transportation network performance change associated with the evolution of the automation scenarios from S1 to S3.

Table 30 gives the VMT and corresponding percentage change for these two sets of experiments Set A (S1R9, S2R18, S3R24, and S3R28) and Set B (S1R12, S2R21, S3R27, and S3R29). The pattern of these two sets is almost identical. For example, considering the four experiments of Set A, the daily VMT increased by 8% compared to the base scenario in Experiment S1R9, which assume a 100% CAV penetration rate. Deploying connected intersection technology (S2R18) did not result in a significant VMT change as the percentage changes remained at 8% for the daily VMT. The joint redistribution of population/households and the employment (Experiment S3R24) brings the increase in the VMT to 6%. When the redistribution is assumed only for the population/households (Experiment S3R28), the daily VMT increased only to 5%. Thus, assuming the redistribution of population/households while fixing the employment locations resulted in more daily VMT (6%) compared to where jobs in the region were also assumed to be redistributed (5%). The same pattern is observed for all peak periods considered in this analysis.

Table 30. VMT and VMT Percent Change Recorded for Experiments S1R7 to S1R12 (Capacity Improvement), Experiments S2R16 to S2R21 (Capacity and Speed Improvement), and Experiments S3R24 to S3R29 (Capacity, Speed Improvement, and POP/EMP Redistribution).

VMT

VMT					
Scenario Runs	AV/CV Penetration Rate	AM	OP	PM	Daily
Base	0	59,580,295	185,718,743	85,738,403	331,037,442
S1R7	0.25	60,261,875	187,871,450	86,716,391	334,849,717
S1R8	0.5	61,202,418	191,028,864	88,117,487	340,348,769
S1R9	1	63,960,388	200,197,391	92,282,083	356,439,862
S1R10	0.25	60,515,172	188,244,216	86,975,722	335,735,110
S1R11	0.5	61,660,921	191,869,584	88,649,265	342,179,770
S1R12	1	64,687,397	201,534,483	93,156,386	359,378,266

Capacity Improvement

VMT					
Scenario Runs	AV/CV Penetration rate	AM	OP	PM	Daily
Base	0	59,580,295	185,718,743	85,738,403	331,037,442
S2R16	0.25	60,256,297	187,900,335	86,732,683	335,000,000
S2R17	0.5	61,264,292	191,303,235	88,244,384	340,811,911
S2R18	1	64,186,835	200,969,551	92,646,459	357,802,845
S2R19	0.25	60,548,935	188,356,157	87,034,333	335,939,425
S2R20	0.5	61,714,523	192,079,448	88,748,114	342,542,085
S2R21	1	64,897,917	202,289,089	93,499,610	360,686,616

Capacity Improvement & Connected Intersections

VMT					
Scenario Runs	AV/CV Penetration Rate	AM	OP	PM	Daily
Base	0	59,580,295	185,718,743	85,738,403	331,037,442
S3R24	1	62,135,627	196,946,816	90,421,602	349,504,045
S3R27	1	62,726,817	197,934,095	91,114,402	351,775,314
S3R28	1	61,535,178	195,676,556	89,812,844	347,024,578
S3R29	1	61,932,113	196,177,128	90,253,363	348,362,603

Capacity Improvement + Connected Intersections + POP/EMP Redistribution

VMT Percent Change

VMT Percent Change					
Scenario Runs	AV/CV Penetration Rate	AM	OP	PM	Daily
S1R7	0.25	1%	1%	1%	1%
S1R8	0.5	3%	3%	3%	3%
S1R9	1	7%	8%	8%	8%
S1R10	0.25	2%	1%	1%	1%
S1R11	0.5	3%	3%	3%	3%
S1R12	1	9%	9%	9%	9%

Capacity Improvement

VMT Percent Change					
Scenario Runs	AV/CV Penetration Rate	AM	OP	PM	Daily
S2R16	0.25	1%	1%	1%	1%
S2R17	0.5	3%	3%	3%	3%
S2R18	1	8%	8%	8%	8%
S2R19	0.25	2%	1%	2%	1%
S2R20	0.5	4%	3%	4%	3%
S2R21	1	9%	9%	9%	9%

Capacity Improvement & Connected Intersections

VMT Percent Change to Base					
Scenario Runs	AV/CV Penetration Rate	AM	OP	PM	Daily
S3R24	1	4%	6%	5%	6%
S3R27	1	5%	7%	6%	6%
S3R28	1	3%	5%	5%	5%
S3R29	1	4%	6%	5%	5%

Capacity Improvement + Connected Intersections + POP/EMP Redistribution

Table 31 gives the VHT for these two sets of experiments for the AM, PM, and OP periods and for the entire day. Again, the results of the experiments in both sets follow the same pattern. For example, following the experiment sequence in Set A, a reduction of 14% is reported for the daily VHT when CAVs were fully adopted (S1R9). Deploying the connected intersection technology (S2R18) reduced the daily VHT slightly. A reduction of 15% is recorded compared to the base scenario. The joint redistribution of the population/households and employment (S3R24) further reduced the daily VHT by 19%. The daily VHT is reduced to 21% when only population/households are assumed to be redistributed in the region (S3R28).

Similar patterns are obtained for the average speed and delay. As shown in Table 32, the average speed increased from 29 mph in the base scenario to 36 mph in S1R9 and in S2R18. In S3R24 and S3R28, representing the population and employment redistribution scenario, the average speed increased to 37 mph and 38 mph, respectively. Finally, as presented in Table 33, the delay was reduced by 40% and 43% in Experiments S1R9 and S2R18, respectively. In Experiments S3R24 and S3R28, the delay was further reduced by 49% and 52%, respectively.

Finally, the contour maps in Figure 27 and Figure 28 show the travel time pattern to and from the DFW International airport in the AM and PM peak periods. The contour maps are given for the base scenario, Experiment S1R9 (capacity improvement), Experiment S2R18 (Capacity and Connected Intersections), Experiment S3R24 (POP/HH/EMP redistribution), and Experiment S3R28 (POP/HH/EM redistribution). As shown in these figures, the main reduction in the travel time occurred under the first scenario (S1). A slight difference in the travel time contour pattern of Experiments S2R18 and S1R9 is observed. **The redistribution of the population and employment did not result in a significant travel time improvement in the region.**

The increase of speed due to all other factors is more than the effect of the population/ employment redistribution. Therefore, we see a small effect on travel times in the population/ employment scenario when compared to the S2R18 and S1R9.

The greater benefit is the potential of having the region grow more uniformly with people and jobs moving out where land is currently more affordable.

We did not model a scenario that assumes denser than predicted population/employment areas (like making central business districts denser). Every TAZ got its share of uniform growth. Although we did put some pop/emp back to areas that are currently dense as the result of uniform growth patterns.

Table 31. VHT and VHT Percent Change Recorded for Experiments S1R7 to S1R12 (Capacity Improvement), Experiments S2R16 to S2R21 (Capacity and Speed Improvement), and Experiments S3R24 to S3R29 (Capacity, Speed Improvement and POP/EMP Redistribution).

VHT

VHT					
Scenario Runs	AV/CV Penetration Rate	AM	OP	PM	Daily
Base	0	3,225,458	4,974,597	3,362,522	11,562,578
S1R7	0.25	3,114,780	4,931,331	3,279,411	11,325,522
S1R8	0.5	2,892,034	4,864,603	3,121,731	10,878,368
S1R9	1	2,366,666	4,751,677	2,802,907	9,921,250
S1R10	0.25	3,164,494	4,965,536	3,316,281	11,446,311
S1R11	0.5	2,962,576	4,935,564	3,186,886	11,085,026
S1R12	1	2,444,763	4,895,287	2,917,572	10,257,622

Capacity Improvement

VHT					
Scenario Runs	AV/CV Penetration Rate	AM	OP	PM	Daily
Base	0	3,225,458	4,974,597	3,362,522	11,562,578
S2R16	0.25	3,102,191	4,919,812	3,269,148	11,291,151
S2R17	0.5	2,868,223	4,843,618	3,102,139	10,813,980
S2R18	1	2,323,207	4,716,305	2,763,545	9,803,057
S2R19	0.25	3,157,733	4,957,464	3,310,702	11,425,899
S2R20	0.5	2,939,119	4,912,786	3,165,620	11,017,524
S2R21	1	2,386,170	4,849,540	2,865,804	10,101,514

Capacity Improvement & Connected Intersections

VHT					
Scenario Runs	AV/CV Penetration Rate	AM	OP	PM	Daily
Base	0	3,225,458	4,974,597	3,362,522	11,562,578
S3R24	1	2,099,809	4,604,679	2,644,364	9,348,853
S3R27	1	2,143,887	4,724,099	2,728,108	9,596,094
S3R28	1	1,980,846	4,558,361	2,586,154	9,125,361
S3R29	1	2,018,882	4,660,979	2,662,560	9,342,422

Capacity Improvement + Connected Intersections + POP/EMP Redistribution

VHT Percent Change

VHT Percent Change					
Scenario Runs	AV/CV Penetration Rate	AM	OP	PM	Daily
S1R7	0.25	-3%	-1%	-2%	-2%
S1R8	0.5	-10%	-2%	-7%	-6%
S1R9	1	-27%	-4%	-17%	-14%
S1R10	0.25	-2%	0%	-1%	-1%
S1R11	0.5	-8%	-1%	-5%	-4%
S1R12	1	-24%	-2%	-13%	-11%

Capacity Improvement

VHT Percent Change					
Scenario Runs	AV/CV Penetration Rate	AM	OP	PM	Daily
S2R16	0.25	-4%	-1%	-3%	-2%
S2R17	0.5	-11%	-3%	-8%	-6%
S2R18	1	-28%	-5%	-18%	-15%
S2R19	0.25	-2%	0%	-2%	-1%
S2R20	0.5	-9%	-1%	-6%	-5%
S2R21	1	-26%	-3%	-15%	-13%

Capacity Improvement & Connected Intersections

VHT Percent Change to Base					
Scenario Runs	AV/CV Penetration Rate	AM	OP	PM	Daily
S3R24	1	-35%	-7%	-21%	-19%
S3R27	1	-34%	-5%	-19%	-17%
S3R28	1	-39%	-8%	-23%	-21%
S3R29	1	-37%	-6%	-21%	-19%

Capacity Improvement + Connected Intersections + POP/EMP Redistribution

Table 32. Average Speed and Average Speed Percent Change Recorded for Experiments S1R7 to S1R12 (Capacity Improvement), Experiments S2R16 to S2R21 (Capacity and Speed Improvement), and Experiments S3R24 to S3R29 (Capacity, Speed Improvement and POP/EMP Redistribution).

Average Speed

Scenario Runs	AV/CV Penetration Rate	Avg Speed AM	OP	PM	Daily
Base	0	18	37	25	29
S1R7	0.25	19	38	26	30
S1R8	0.5	21	39	28	31
S1R9	1	27	42	33	36
S1R10	0.25	19	38	26	29
S1R11	0.5	21	39	28	31
S1R12	1	26	41	32	35

Capacity Improvement

Scenario Runs	AV/CV Penetration Rate	Avg Speed AM	OP	PM	Daily
Base	0	18	37	25	29
S2R16	0.25	19	38	27	30
S2R17	0.5	21	39	28	32
S2R18	1	28	43	34	36
S2R19	0.25	19	38	26	29
S2R20	0.5	21	39	28	31
S2R21	1	27	42	33	36

Capacity Improvement & Connected Intersections

Scenario Runs	AV/CV Penetration Rate	Avg Speed AM	OP	PM	Daily
Base	0	18	37	25	29
S3R24	1	30	43	34	37
S3R27	1	29	42	33	37
S3R28	1	31	43	35	38
S3R29	1	31	42	34	37

Capacity Improvement + Connected Intersections + POP/EMP Redistribution

Average Speed Percent Change

Scenario Runs	AV/CV Penetration Rate	Avg Speed Percent Change AM	OP	PM	Daily
S1R7	0.25	5%	2%	4%	3%
S1R8	0.5	15%	5%	11%	9%
S1R9	1	46%	13%	29%	25%
S1R10	0.25	4%	2%	3%	2%
S1R11	0.5	13%	4%	9%	8%
S1R12	1	43%	10%	25%	22%

Capacity Improvement

Scenario Runs	AV/CV Penetration Rate	Avg Speed Percent Change AM	OP	PM	Daily
S2R16	0.25	5%	2%	4%	4%
S2R17	0.5	16%	6%	12%	10%
S2R18	1	50%	14%	31%	27%
S2R19	0.25	4%	2%	3%	3%
S2R20	0.5	14%	5%	10%	9%
S2R21	1	47%	12%	28%	25%

Capacity Improvement & Connected Intersections

Scenario Runs	AV/CV Penetration Rate	Avg Speed Percent Change to Base AM	OP	PM	Daily
S3R24	1	60%	15%	34%	31%
S3R27	1	58%	12%	31%	28%
S3R28	1	68%	15%	36%	33%
S3R29	1	66%	13%	33%	30%

Capacity Improvement + Connected Intersections + POP/EMP Redistribution

Table 33. Delay and Delay Percent Change Recorded for Experiments S1R7 to S1R12 (Capacity Improvement), Experiments S2R16 to S2R21 (Capacity and Speed Improvement), and Experiments S3R24 to S3R29 (Capacity, Speed Improvement and POP/EMP Redistribution).

Delay

Scenario Runs	AV/CV Penetration Rate	Delay AM	OP	PM	Daily
Base	0	2,041,895	1,414,540	1,670,096	5,126,531
S1R7	0.25	1,919,887	1,334,374	1,570,814	4,825,076
S1R8	0.5	1,683,664	1,216,926	1,392,599	4,293,188
S1R9	1	1,122,972	960,889	1,015,649	3,099,510
S1R10	0.25	1,963,821	1,353,429	1,600,570	4,917,821
S1R11	0.5	1,743,599	1,254,969	1,442,789	4,441,358
S1R12	1	1,183,069	1,037,812	1,099,542	3,320,423

Capacity Improvement

Scenario Runs	AV/CV Penetration Rate	Delay AM	OP	PM	Daily
Base	0	2,041,895	1,414,540	1,670,096	5,126,531
S2R16	0.25	1,907,078	1,320,551	1,559,573	4,787,202
S2R17	0.5	1,657,917	1,187,073	1,369,054	4,214,044
S2R18	1	1,072,580	900,815	964,461	2,937,856
S2R19	0.25	1,956,025	1,341,401	1,593,143	4,890,569
S2R20	0.5	1,718,310	1,224,163	1,418,079	4,360,552
S2R21	1	1,118,168	966,695	1,036,394	3,121,256

Capacity Improvement & Connected Intersections

Scenario Runs	AV/CV Penetration Rate	Delay AM	OP	PM	Daily
Base	0	2,041,895	1,414,540	1,670,096	5,126,531
S3R24	1	891,226	855,333	886,447	2,633,006
S3R27	1	920,273	915,261	944,074	2,779,607
S3R28	1	788,785	836,177	843,286	2,468,248
S3R29	1	815,013	889,645	897,949	2,602,607

Capacity Improvement + Connected Intersections + POP/EMP Redistribution

Delay Percent Change

Scenario Runs	AV/CV Penetration Rate	Delay Percent Change AM	OP	PM	Daily
S1R7	0.25	-6%	-6%	-6%	-6%
S1R8	0.5	-18%	-14%	-17%	-16%
S1R9	1	-45%	-32%	-39%	-40%
S1R10	0.25	-4%	-4%	-4%	-4%
S1R11	0.5	-15%	-11%	-14%	-13%
S1R12	1	-42%	-27%	-34%	-35%

Capacity Improvement

Scenario Runs	AV/CV Penetration Rate	Delay Percent Change AM	OP	PM	Daily
S2R16	0.25	-7%	-7%	-7%	-7%
S2R17	0.5	-19%	-16%	-18%	-18%
S2R18	1	-47%	-36%	-42%	-43%
S2R19	0.25	-4%	-5%	-5%	-5%
S2R20	0.5	-16%	-13%	-15%	-15%
S2R21	1	-45%	-32%	-38%	-39%

Capacity Improvement & Connected Intersections

Scenario Runs	AV/CV Penetration Rate	Delay Percent Change to Base AM	OP	PM	Daily
S3R24	1	-56%	-40%	-47%	-49%
S3R27	1	-55%	-35%	-43%	-46%
S3R28	1	-61%	-41%	-50%	-52%
S3R29	1	-60%	-37%	-46%	-49%

Capacity Improvement + Connected Intersections + POP/EMP Redistribution

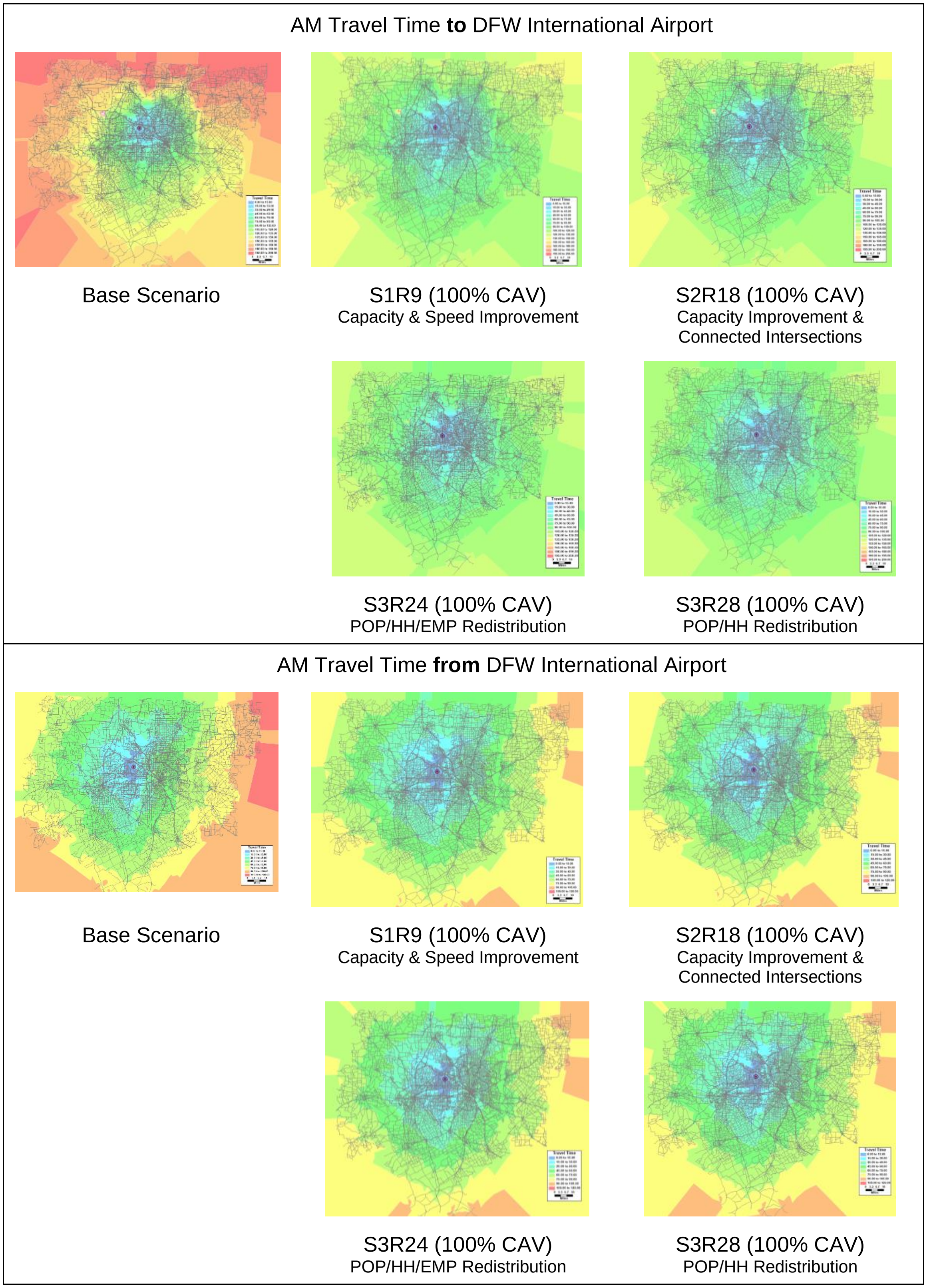


Figure 27. Travel Time Contour Maps for the AM Peak Period Considering the DFW International Airport as a Focal Point

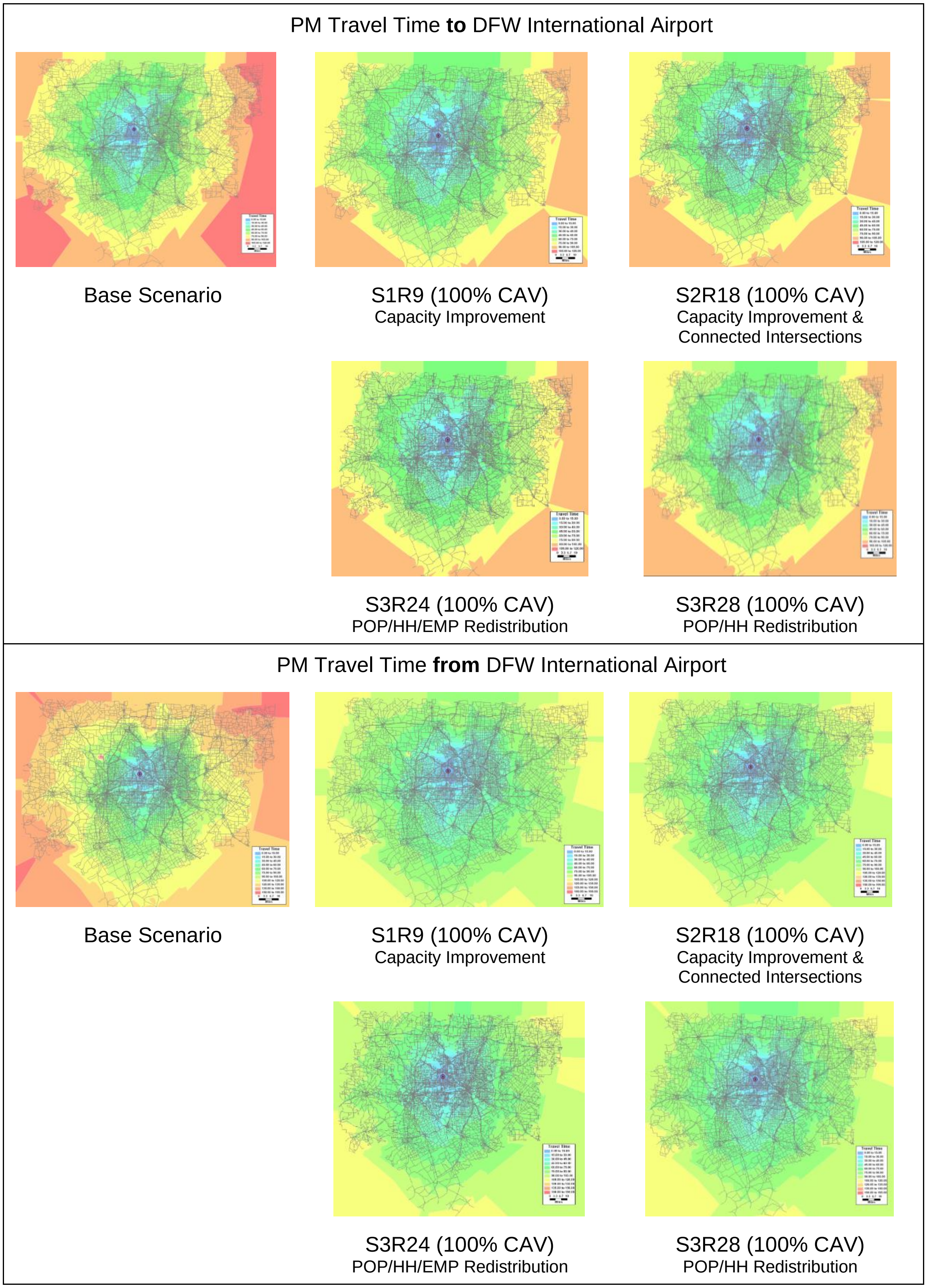


Figure 28. Travel Time Contour Maps for the PM Peak Period Considering the DFW International Airport as a Focal Point

9 MODEL RUNS ON NCTCOG FINAL MTP NETWORK AND DEMOGRAPHIC

As mentioned earlier, the files provided for this study were pre-final MTP. Therefore, when the final MTP data became available, the team ran one CAV scenario (S2R18) in addition to the base to see what the analysis results would look like if the final MTP data was used in all the other CAV runs. The scenario definitions for these runs are shown in Table 34. The "NCTCOG MOD" Demographic and Roadway setting refers to the final MTP network.

Table 34. Scenario Definitions for Final MTP Model Runs.

Scenario Runs	AV/CV Penetration Rate	Link Capacity Improvement	AV/CV VOT Reduction	Increase Speed	Increased Non-Freeway Saturation Flow Rate	Lower Signal Control Delay	Demographic and Roadway Change
Base	0	0%	0%	0%	0%	0%	None
S2R18	1	33%	0%	5.00%	33%	10.0%	None
New Base	0	0%	0%	0%	0%	0%	NCTCOG MOD
New R18	1	33%	0%	5.00%	33%	10.0%	NCTCOG MOD

The comparison between the two demographic dataset (final and pre-MTP) are shown in Figure 29 through Figure 31. In the final MTP dataset the highest reduction in population is in the periphery of the four core counties. The employment re-distribution shows a different trend where Hunt and Tarrant county show most of the reductions and Collin county shows most of the increases.

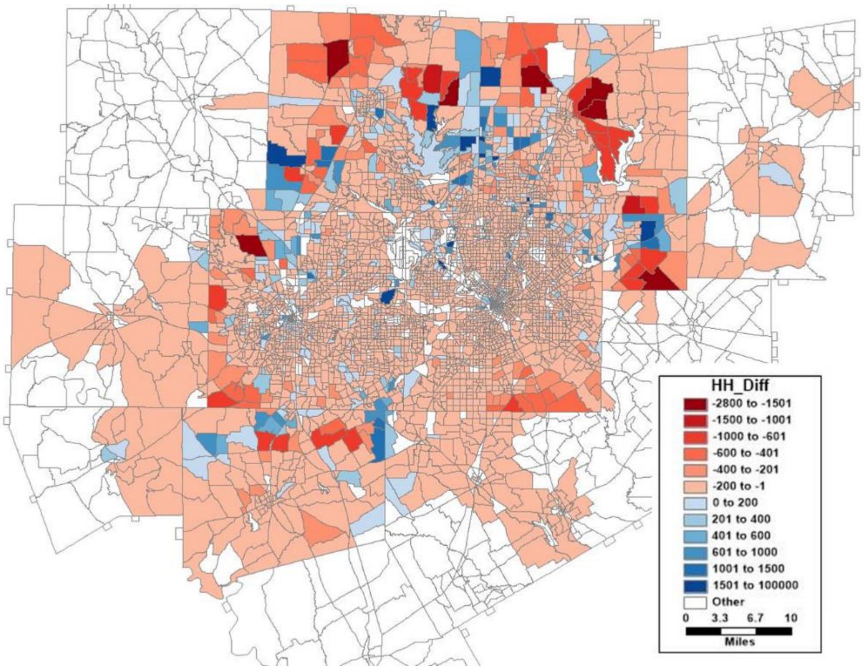


Figure 29. Difference in Number of Households in TAZs (year 2045).

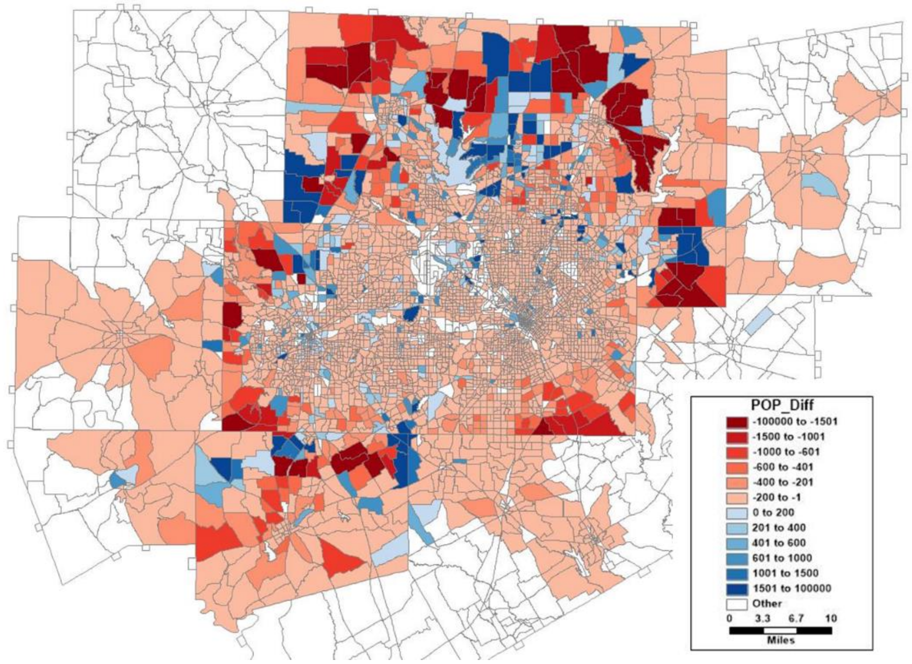


Figure 30. Difference in TAZ Population (year 2045).

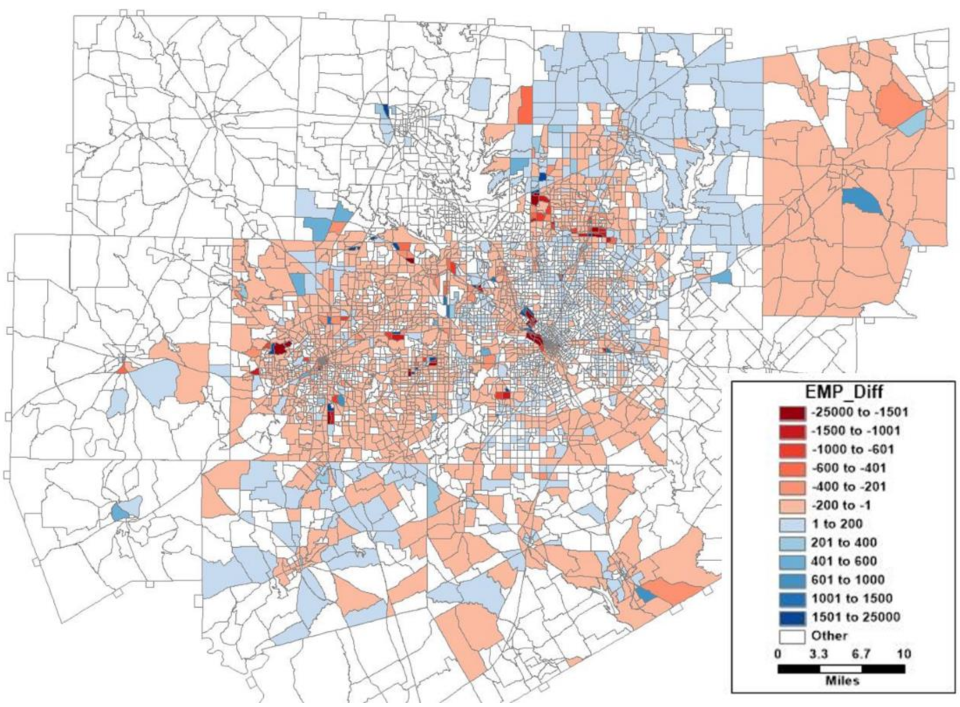


Figure 31. Difference in TAZ Total Employment (year 2045).

In addition to the differences in the demographic data between the two datasets, there has also been a change in the roadway network. The centerline-mile of roadway networks by functional classification is shown in Table 35 for reference. This difference also effects the observed differences in the network-level MOEs. The more significant differences are in the centerline miles of freeway, principal arterial, and minor arterial classifications.

Table 35. Roadway Centerline Miles Comparison Pre-Final (Top), Final MTP (Bottom).

	CBD	Outer Business District	Urban Residential	Suburban Residential	Rural	ALL
Freeway	18.64	162.58	1,029.51	565.07	458.39	**2,234.19**
Principal Arterial	16.70	100.05	803.58	492.32	1,009.77	**2,422.42**
Minor Arterial	38.50	181.32	1,616.49	840.01	1,911.05	**4,587.37**
Collector	24.24	224.04	2,281.27	1,649.86	3,670.69	**7,850.10**
Freeway Ramp	26.98	130.60	647.77	255.23	126.62	**1,187.20**
Frontage Road	11.39	119.64	817.18	554.87	362.15	**1,865.23**
HOV	-	-	-	-	-	-
Managed HOV	5.92	51.90	280.72	26.75	-	**365.29**
ALL	**142.37**	**970.13**	**7,476.52**	**4,384.11**	**7,538.67**	**20,511.80**

	CBD	Outer Business District	Urban Residential	Suburban Residential	Rural	ALL
Freeway	16.89	159.26	1,064.49	585.33	562.74	**2,388.71**
Principal Arterial	19.41	97.52	864.89	361.82	520.89	**1,864.53**
Minor Arterial	36.39	177.25	1,602.78	966.68	2,370.98	**5,154.08**
Collector	24.47	216.85	2,259.7	1,608.67	3,694.85	**7,804.54**
Freeway Ramp	27.66	128.82	657.69	251.67	160.43	**1,226.27**
Frontage Road	11.18	117.28	856.85	619.39	413.47	**2,018.17**
HOV	-	12.53	28.31	-	-	**40.84**
Managed HOV*	5.54	56.41	287.57	27.79	-	**377.31**
ALL	**141.54**	**965.92**	**7,622.28**	**4,421.35**	**7,723.36**	**20,874.45**

Table 36 shows the daily and time-period regional VMT comparisons. Under the final MTP scenario with CAV assumptions, the increase in VMT compared to the corresponding base is slightly more than the run with the pre-final model due to differences in demographic and roadway network. The observed trend in regional VMT of the model runs with the final-MTP dataset is like the results shown for the runs with pre-final dataset.

Table 36. Regional VMT Comparison (Year 2045).

VMT					
Scenario Runs	AV/CV Penetration Rate	AM	OP	PM	Daily
Base	0	59,580,295	185,718,743	85,738,403	331,037,442
S2R18	1	64,186,835	200,969,551	92,646,459	357,802,845
New Base	0	59,044,132	183,559,681	84,661,919	327,265,732
New R18	1	66,251,716	202,761,408	93,975,103	362,988,227

VMT Difference					
Scenario Runs	AV/CV Penetration Rate	AM	OP	PM	Daily
S2R18 to Base	-	4,606,539	15,250,808	6,908,056	26,765,404
New R18 to New Base	-	7,207,584	19,201,727	9,313,184	35,722,495

VMT Percent Change					
Scenario Runs	AV/CV Penetration Rate	AM	OP	PM	Daily
S2R18 to Base	-	8%	8%	8%	8%
New R18 to New Base	-	12%	10%	11%	11%

The daily regional VHT is presented in Table 38. The improvement in daily VHT compared to base in run S2R18 is -15%. However, this improvement is only at -8% when CAV assumptions are applied to the final MTP dataset. The differences in daily VHT by functional class is shown in Table 39. The comparison of average speeds in Table 40 indicates that the speed improvements under the CAV scenario and final MTP dataset is slightly less than the pre-final dataset. For example, in S2R18 the average daily speeds improve by 27% whereas in the final MTP dataset, this improvement is only at 21% compared to the corresponding base scenario. The average speed comparisons by functional class between the two sets of runs is shown in Table 41.

Table 37. Regional VMT Comparison by Functional Classification (Year 2045).

Daily VMT by FUNCL				
Scenarios	Base	S2R18	New Base	New R18
Freeway	141,217,024	162,099,949	142,925,951	167,265,449
Principal Arterial	60,698,051	64,681,640	51,445,318	56,604,956
Minor Arterial	66,100,136	66,752,729	69,894,203	72,410,194
Collector	22,497,582	21,774,435	21,125,526	21,072,834
Freeway Ramp	12,819,121	14,620,787	13,110,719	15,232,963
Frontage Road	16,765,598	17,276,779	17,119,050	18,436,562
HOV	-	-	479,530	402,840
Managed HOV	10,939,930	10,596,526	11,165,434	11,562,428
ALL	331,037,442	357,802,845	327,265,732	362,988,227

Table 38. Regional VHT Comparison (Year 2045).

VHT					
Scenario Runs	AV/CV Penetration Rate	AM	OP	PM	Daily
Base	0	3,225,458	4,974,597	3,362,522	11,562,578
S2R18	1	2,323,207	4,716,305	2,763,545	9,803,057
New Base	0	3,033,052	4,782,444	3,168,555	10,984,051
New R18	1	2,523,950	4,678,334	2,857,609	10,059,892

VHT Difference					
Scenario Runs	AV/CV Penetration Rate	AM	OP	PM	Daily
S2R18 to Base	-	(902,251)	(258,293)	(598,977)	(1,759,521)
New R18 to New Base	-	(509,101)	(104,110)	(310,947)	(924,159)

VHT Percent Change					
Scenario Runs	AV/CV Penetration Rate	AM	OP	PM	Daily
S2R18 to Base	-	-28%	-5%	-18%	-15%
New R18 to New Base	-	-17%	-2%	-10%	-8%

Table 39. Regional VHT Comparison by Functional Classification (Year 2045).

Daily VHT by FUNCL				
Scenarios	Base	S2R18	New Base	New R18
Freeway	3,778,705	3,390,755	3,706,543	3,608,869
Principal Arterial	2,286,762	1,947,802	2,006,527	1,837,839
Minor Arterial	2,708,919	2,212,304	2,690,825	2,351,762
Collector	1,335,625	1,051,403	1,202,507	989,458
Freeway Ramp	446,387	418,061	451,408	446,901
Frontage Road	714,937	582,775	713,315	639,528
HOV	-	-	16,855	10,245
Managed HOV	291,241	199,956	196,071	175,292
ALL	11,562,578	9,803,057	10,984,051	10,059,892

Table 40. Regional Average Speed Comparison (Year 2045).

Avg Speed					
Scenario Runs	AV/CV Penetration Rate	AM	OP	PM	Daily
Base	0	18	37	25	29
S2R18	1	28	43	34	36
New Base	0	19	38	27	30
New R18	1	26	43	33	36

Avg Speed Difference					
Scenario Runs	AV/CV Penetration Rate	AM	OP	PM	Daily
S2R18 to Base	-	9.2	5.3	8.0	7.9
New R18 to New Base	-	6.8	5.0	6.2	6.3

Avg Speed Percent Change					
Scenario Runs	AV/CV Penetration Rate	AM	OP	PM	Daily
S2R18 to Base	-	50%	14%	31%	27%
New R18 to New Base	-	35%	13%	23%	21%

At 100% CAV penetration and 33% increased capacity, the speeds go up. The percentage is high, but the magnitude of the speed increase is reasonable (less than 10 mph).

Table 41. Regional Average Speed Comparison by Functional Classification (Year 2045).

Avg Speed by FUNCL				
Scenarios	Base	S2R18	New Base	New R18
Freeway	37	48	39	46
Principal Arterial	27	33	26	31
Minor Arterial	24	30	26	31
Collector	17	21	18	21
Freeway Ramp	29	35	29	34
Frontage Road	23	30	24	29
HOV	-	-	28	39
Managed HOV	38	53	57	66
ALL	29	36	30	36

The differences in the traffic assignment results of the pre-final and final MTP datasets are shown in Figure 32 through Figure 34. The difference in the demographic data and capacity assumptions between the pre-final and final MTP datasets results in changes in travel patterns in the region hence changing the effectiveness of the CAV integration in the network performance.

The above set of runs indicate that if all the CAV scenarios would have been applied to the final-MTP dataset, the final outcomes would have been like the pre-final MTP dataset but with a lesser effectiveness for the CAV scenarios.

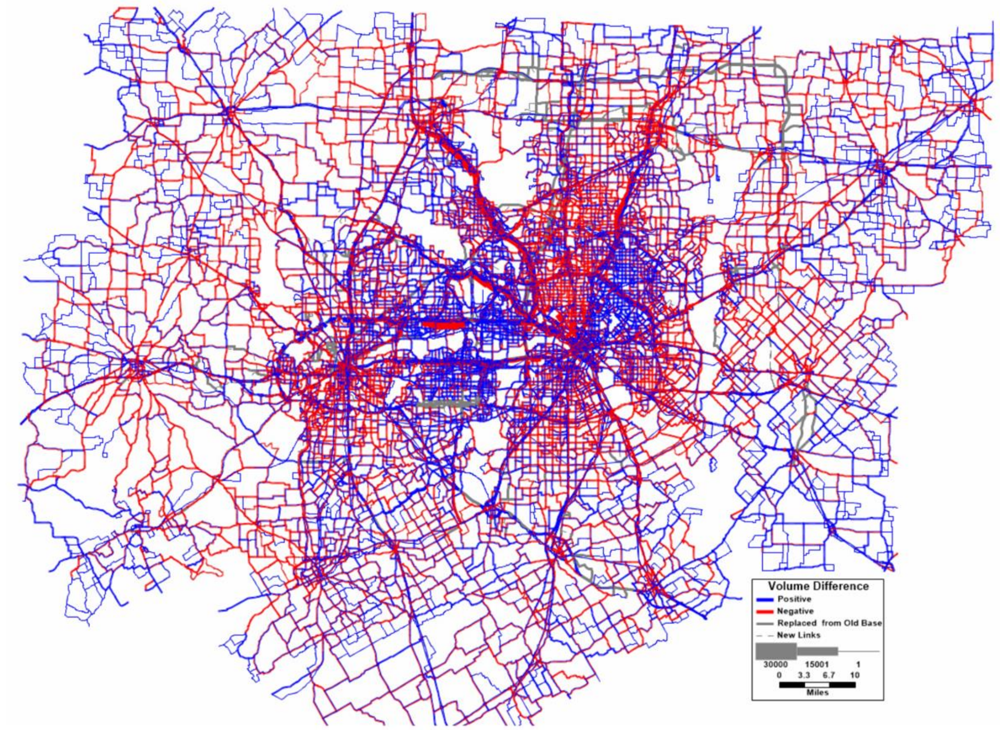


Figure 32. Difference in AM Peak Period Traffic Volumes (Year 2045).

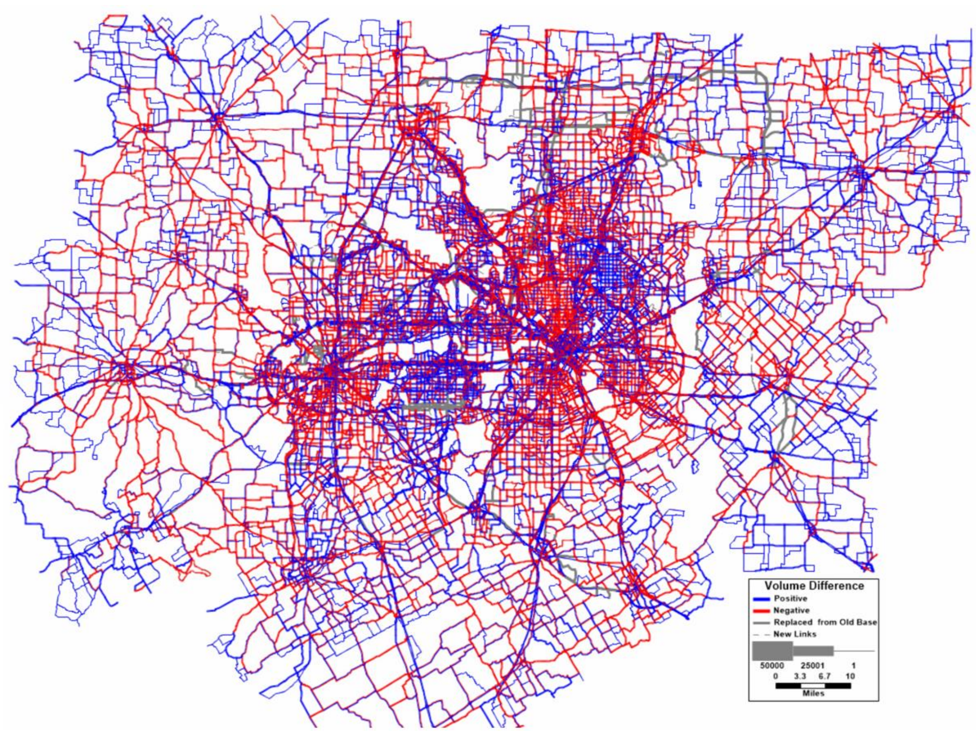


Figure 33. Difference in PM Peak Period Traffic Volumes (Year 2045).

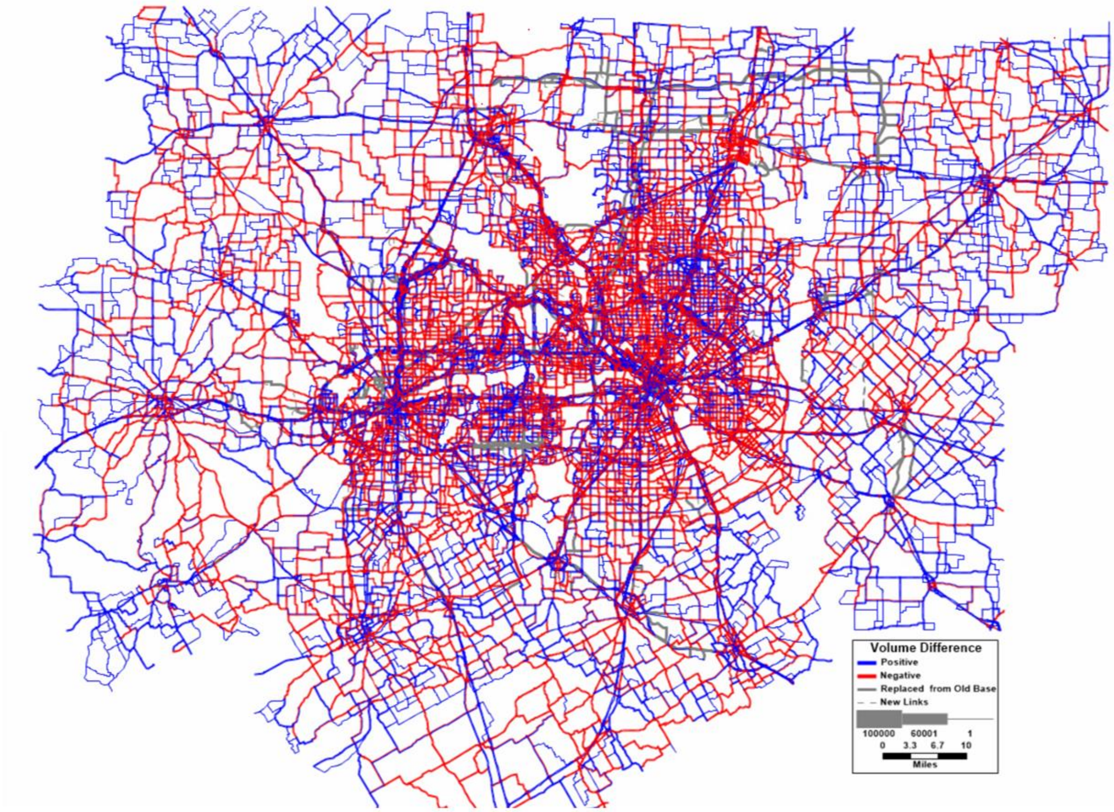


Figure 34. Difference in OP Period Traffic Volumes (Year 2045).

10 RESULT SUMMARIES

This section summarizes the performance measures of all runs in a more concise set of graphs and tables to assist with comparing the model run results for each scenario. It also presents a new set of performance measures for a select set of more significant scenarios which digs a bit deeper in the effect of CAV on the network performance. Table 42 through

Table 50 summarize the regional VMT, VHT and average speed values and differences in comparison to base for the AM, OP, and PM periods and daily.

Table 42. Regional VMT for all Modeling Scenarios.

VMT					
Scenario Runs	AV/CV Penetration Rate	AM	OP	PM	Daily
Base	0	59,580,295	185,718,743	85,738,403	331,037,442
S1R1	0.25	60,036,147	187,155,745	86,372,991	333,564,883
S1R2	0.5	60,814,905	189,698,858	87,493,591	338,007,354
S1R3	1	63,082,113	197,107,091	90,851,524	351,040,728
S1R4	0.25	60,346,336	187,661,127	86,702,122	334,709,585
S1R5	0.5	61,305,347	190,588,097	88,053,069	339,946,513
S1R6	1	63,701,047	198,145,444	91,567,318	353,413,809
S1R7	0.25	60,261,875	187,871,450	86,716,391	334,849,717
S1R8	0.5	61,202,418	191,028,864	88,117,487	340,348,769
S1R9	1	63,960,388	200,197,391	92,282,083	356,439,862
S1R10	0.25	60,515,172	188,244,216	86,975,722	335,735,110
S1R11	0.5	61,660,921	191,869,584	88,649,265	342,179,770
S1R12	1	64,687,397	201,534,483	93,156,386	359,378,266
S1R13	0.25	60,092,804	187,320,112	86,451,747	333,864,663
S1R14	0.5	60,830,500	189,783,780	87,523,892	338,138,172
S1R15	1	63,030,981	197,037,473	90,797,000	350,865,454
S2R16	0.25	60,256,297	187,900,335	86,732,683	335,000,000
S2R17	0.5	61,264,292	191,303,235	88,244,384	340,811,911
S2R18	1	64,186,835	200,969,551	92,646,459	357,802,845
S2R19	0.25	60,548,935	188,356,157	87,034,333	335,939,425
S2R20	0.5	61,714,523	192,079,448	88,748,114	342,542,085
S2R21	1	64,897,917	202,289,089	93,499,610	360,686,616
S3R24	1	62,135,627	196,946,816	90,421,602	349,504,045
S3R27	1	62,726,817	197,934,095	91,114,402	351,775,314
S3R28	1	61,535,178	195,676,556	89,812,844	347,024,578
S3R29	1	61,932,113	196,177,128	90,253,363	348,362,603

Table 43. Regional VMT Difference compared to Base.

VMT Difference					
Scenario Runs	AV/CV Penetration Rate	AM	OP	PM	Daily
S1R1	0.25	455,852	1,437,002	634,587	2,527,442
S1R2	0.5	1,234,610	3,980,115	1,755,188	6,969,913
S1R3	1	3,501,818	11,388,348	5,113,120	20,003,286
S1R4	0.25	766,041	1,942,384	963,718	3,672,144
S1R5	0.5	1,725,052	4,869,354	2,314,666	8,909,072
S1R6	1	4,120,752	12,426,701	5,828,914	22,376,367
S1R7	0.25	681,580	2,152,708	977,988	3,812,275
S1R8	0.5	1,622,123	5,310,121	2,379,084	9,311,328
S1R9	1	4,380,093	14,478,648	6,543,679	25,402,420
S1R10	0.25	934,877	2,525,473	1,237,319	4,697,669
S1R11	0.5	2,080,626	6,150,841	2,910,861	11,142,329
S1R12	1	5,107,101	15,815,740	7,417,982	28,340,824
S1R13	0.25	512,509	1,601,369	713,344	2,827,221
S1R14	0.5	1,250,205	4,065,037	1,785,488	7,100,731
S1R15	1	3,450,686	11,318,730	5,058,596	19,828,012
S2R16	0.25	676,002	2,181,592	994,280	3,962,558
S2R17	0.5	1,683,997	5,584,492	2,505,981	9,774,469
S2R18	1	4,606,539	15,250,808	6,908,056	26,765,404
S2R19	0.25	968,640	2,637,414	1,295,929	4,901,983
S2R20	0.5	2,134,228	6,360,705	3,009,710	11,504,643
S2R21	1	5,317,622	16,570,346	7,761,207	29,649,175
S3R24	1	2,555,332	11,228,073	4,683,199	18,466,603
S3R27	1	3,146,522	12,215,352	5,375,999	20,737,872
S3R28	1	1,954,883	9,957,813	4,074,440	15,987,136
S3R29	1	2,351,818	10,458,385	4,514,959	17,325,162

Table 44. Regional VMT Percentage Difference compared to Base.

VMT Percent Change					
Scenario Runs	AV/CV Penetration Rate	AM	OP	PM	Daily
S1R1	0.25	1%	1%	1%	1%
S1R2	0.5	2%	2%	2%	2%
S1R3	1	6%	6%	6%	6%
S1R4	0.25	1%	1%	1%	1%
S1R5	0.5	3%	3%	3%	3%
S1R6	1	7%	7%	7%	7%
S1R7	0.25	1%	1%	1%	1%
S1R8	0.5	3%	3%	3%	3%
S1R9	1	7%	8%	8%	8%
S1R10	0.25	2%	1%	1%	1%
S1R11	0.5	3%	3%	3%	3%
S1R12	1	9%	9%	9%	9%
S1R13	0.25	1%	1%	1%	1%
S1R14	0.5	2%	2%	2%	2%
S1R15	1	6%	6%	6%	6%
S2R16	0.25	1%	1%	1%	1%
S2R17	0.5	3%	3%	3%	3%
S2R18	1	8%	8%	8%	8%
S2R19	0.25	2%	1%	2%	1%
S2R20	0.5	4%	3%	4%	3%
S2R21	1	9%	9%	9%	9%
S3R24	1	4%	6%	5%	6%
S3R27	1	5%	7%	6%	6%
S3R28	1	3%	5%	5%	5%
S3R29	1	4%	6%	5%	5%

Table 45. Regional VHT for all Modeling Scenarios.

VHT					
Scenario Runs	AV/CV Penetration Rate	AM	OP	PM	Daily
Base	0	3,225,458	4,974,597	3,362,522	11,562,578
S1R1	0.25	3,125,636	4,959,477	3,288,793	11,373,905
S1R2	0.5	2,923,320	4,924,158	3,148,257	10,995,734
S1R3	1	2,420,030	4,865,698	2,854,015	10,139,743
S1R4	0.25	3,182,637	4,998,891	3,332,194	11,513,721
S1R5	0.5	3,000,328	4,999,237	3,217,673	11,217,238
S1R6	1	2,495,242	4,999,770	2,960,836	10,455,848
S1R7	0.25	3,114,780	4,931,331	3,279,411	11,325,522
S1R8	0.5	2,892,034	4,864,603	3,121,731	10,878,368
S1R9	1	2,366,666	4,751,677	2,802,907	9,921,250
S1R10	0.25	3,164,494	4,965,536	3,316,281	11,446,311
S1R11	0.5	2,962,576	4,935,564	3,186,886	11,085,026
S1R12	1	2,444,763	4,895,287	2,917,572	10,257,622
S1R13	0.25	3,132,911	4,964,866	3,295,834	11,393,611
S1R14	0.5	2,923,683	4,925,330	3,149,232	10,998,245
S1R15	1	2,428,516	4,865,368	2,857,960	10,151,845
S2R16	0.25	3,102,191	4,919,812	3,269,148	11,291,151
S2R17	0.5	2,868,223	4,843,618	3,102,139	10,813,980
S2R18	1	2,323,207	4,716,305	2,763,545	9,803,057
S2R19	0.25	3,157,733	4,957,464	3,310,702	11,425,899
S2R20	0.5	2,939,119	4,912,786	3,165,620	11,017,524
S2R21	1	2,386,170	4,849,540	2,865,804	10,101,514
S3R24	1	2,099,809	4,604,679	2,644,364	9,348,853
S3R27	1	2,143,887	4,724,099	2,728,108	9,596,094
S3R28	1	1,980,846	4,558,361	2,586,154	9,125,361
S3R29	1	2,018,882	4,660,979	2,662,560	9,342,422

Table 46. Regional VHT Difference compared to Base.

VHT Difference					
Scenario Runs	AV/CV Penetration Rate	AM	OP	PM	Daily
S1R1	0.25	(99,823)	(15,121)	(73,730)	(188,673)
S1R2	0.5	(302,138)	(50,440)	(214,266)	(566,843)
S1R3	1	(805,428)	(108,899)	(508,507)	(1,422,834)
S1R4	0.25	(42,822)	24,294	(30,328)	(48,857)
S1R5	0.5	(225,130)	24,640	(144,850)	(345,339)
S1R6	1	(730,216)	25,173	(401,686)	(1,106,730)
S1R7	0.25	(110,678)	(43,267)	(83,111)	(237,056)
S1R8	0.5	(333,424)	(109,994)	(240,791)	(684,209)
S1R9	1	(858,792)	(222,920)	(559,615)	(1,641,328)
S1R10	0.25	(60,964)	(9,062)	(46,241)	(116,267)
S1R11	0.5	(262,882)	(39,033)	(175,636)	(477,551)
S1R12	1	(780,695)	(79,310)	(444,950)	(1,304,956)
S1R13	0.25	(92,547)	(9,731)	(66,688)	(168,966)
S1R14	0.5	(301,775)	(49,267)	(213,290)	(564,332)
S1R15	1	(796,942)	(109,229)	(504,562)	(1,410,733)
S2R16	0.25	(123,267)	(54,785)	(93,374)	(271,427)
S2R17	0.5	(357,236)	(130,979)	(260,383)	(748,598)
S2R18	1	(902,251)	(258,293)	(598,977)	(1,759,521)
S2R19	0.25	(67,725)	(17,134)	(51,820)	(136,679)
S2R20	0.5	(286,340)	(61,811)	(196,902)	(545,053)
S2R21	1	(839,288)	(125,057)	(496,718)	(1,461,063)
S3R24	1	(1,125,649)	(369,918)	(718,158)	(2,213,725)
S3R27	1	(1,081,571)	(250,498)	(634,414)	(1,966,483)
S3R28	1	(1,244,612)	(416,236)	(776,368)	(2,437,216)
S3R29	1	(1,206,576)	(313,618)	(699,962)	(2,220,156)

Table 47. Regional VHT Percent Difference compared to Base.

VHT Percent Change					
Scenario Runs	AV/CV Penetration Rate	AM	OP	PM	Daily
S1R1	0.25	-3%	0%	-2%	-2%
S1R2	0.5	-9%	-1%	-6%	-5%
S1R3	1	-25%	-2%	-15%	-12%
S1R4	0.25	-1%	0%	-1%	0%
S1R5	0.5	-7%	0%	-4%	-3%
S1R6	1	-23%	1%	-12%	-10%
S1R7	0.25	-3%	-1%	-2%	-2%
S1R8	0.5	-10%	-2%	-7%	-6%
S1R9	1	-27%	-4%	-17%	-14%
S1R10	0.25	-2%	0%	-1%	-1%
S1R11	0.5	-8%	-1%	-5%	-4%
S1R12	1	-24%	-2%	-13%	-11%
S1R13	0.25	-3%	0%	-2%	-1%
S1R14	0.5	-9%	-1%	-6%	-5%
S1R15	1	-25%	-2%	-15%	-12%
S2R16	0.25	-4%	-1%	-3%	-2%
S2R17	0.5	-11%	-3%	-8%	-6%
S2R18	1	-28%	-5%	-18%	-15%
S2R19	0.25	-2%	0%	-2%	-1%
S2R20	0.5	-9%	-1%	-6%	-5%
S2R21	1	-26%	-3%	-15%	-13%
S3R24	1	-35%	-7%	-21%	-19%
S3R27	1	-34%	-5%	-19%	-17%
S3R28	1	-39%	-8%	-23%	-21%
S3R29	1	-37%	-6%	-21%	-19%

Table 48. Regional Average Speed for all Modeling Scenarios.

Avg Speed					
Scenario Runs	AV/CV Penetration Rate	AM	OP	PM	Daily
Base	0	18	37	25	29
S1R1	0.25	19	38	26	29
S1R2	0.5	21	39	28	31
S1R3	1	26	41	32	35
S1R4	0.25	19	38	26	29
S1R5	0.5	20	38	27	30
S1R6	1	26	40	31	34
S1R7	0.25	19	38	26	30
S1R8	0.5	21	39	28	31
S1R9	1	27	42	33	36
S1R10	0.25	19	38	26	29
S1R11	0.5	21	39	28	31
S1R12	1	26	41	32	35
S1R13	0.25	19	38	26	29
S1R14	0.5	21	39	28	31
S1R15	1	26	40	32	35
S2R16	0.25	19	38	27	30
S2R17	0.5	21	39	28	32
S2R18	1	28	43	34	36
S2R19	0.25	19	38	26	29
S2R20	0.5	21	39	28	31
S2R21	1	27	42	33	36
S3R24	1	30	43	34	37
S3R27	1	29	42	33	37
S3R28	1	31	43	35	38
S3R29	1	31	42	34	37

Table 49. Regional Average Speed Difference compared to Base.

Avg Speed Difference					
Scenario Runs	AV/CV Penetration Rate	AM	OP	PM	Daily
S1R1	0.25	0.7	0.4	0.8	0.7
S1R2	0.5	2.3	1.2	2.3	2.1
S1R3	1	7.6	3.2	6.3	6.0
S1R4	0.25	0.5	0.2	0.5	0.4
S1R5	0.5	2.0	0.8	1.9	1.7
S1R6	1	7.1	2.3	5.4	5.2
S1R7	0.25	0.9	0.8	0.9	0.9
S1R8	0.5	2.7	1.9	2.7	2.7
S1R9	1	8.6	4.8	7.4	7.3
S1R10	0.25	0.7	0.6	0.7	0.7
S1R11	0.5	2.3	1.5	2.3	2.2
S1R12	1	8.0	3.8	6.4	6.4
S1R13	0.25	0.7	0.4	0.7	0.7
S1R14	0.5	2.3	1.2	2.3	2.1
S1R15	1	7.5	3.2	6.3	5.9
S2R16	0.25	1.0	0.9	1.0	1.0
S2R17	0.5	2.9	2.2	2.9	2.9
S2R18	1	9.2	5.3	8.0	7.9
S2R19	0.25	0.7	0.7	0.8	0.8
S2R20	0.5	2.5	1.8	2.5	2.5
S2R21	1	8.7	4.4	7.1	7.1
S3R24	1	11.1	5.4	8.7	8.8
S3R27	1	10.8	4.6	7.9	8.0
S3R28	1	12.6	5.6	9.2	9.4
S3R29	1	12.2	4.8	8.4	8.7

Table 50. Regional Average Speed Percent Difference compared to Base.

Avg Speed Percent Change					
Scenario Runs	AV/CV Penetration Rate	AM	OP	PM	Daily
S1R1	0.25	4%	1%	3%	2%
S1R2	0.5	13%	3%	9%	7%
S1R3	1	41%	9%	25%	21%
S1R4	0.25	3%	1%	2%	2%
S1R5	0.5	11%	2%	7%	6%
S1R6	1	38%	6%	21%	18%
S1R7	0.25	5%	2%	4%	3%
S1R8	0.5	15%	5%	11%	9%
S1R9	1	46%	13%	29%	25%
S1R10	0.25	4%	2%	3%	2%
S1R11	0.5	13%	4%	9%	8%
S1R12	1	43%	10%	25%	22%
S1R13	0.25	4%	1%	3%	2%
S1R14	0.5	13%	3%	9%	7%
S1R15	1	41%	8%	25%	21%
S2R16	0.25	5%	2%	4%	4%
S2R17	0.5	16%	6%	12%	10%
S2R18	1	50%	14%	31%	27%
S2R19	0.25	4%	2%	3%	3%
S2R20	0.5	14%	5%	10%	9%
S2R21	1	47%	12%	28%	25%
S3R24	1	60%	15%	34%	31%
S3R27	1	58%	12%	31%	28%
S3R28	1	68%	15%	36%	33%
S3R29	1	66%	13%	33%	30%

All scenarios were run over the 2045 Build network. Comparing the scenario runs against the 2045 Build scenario shows the impact of CAV adoption. Trying to identify which proposed improvements in the 2045 Build Plan might not be needed depending on the level of CAV penetration will require additional analysis, which NCTCOG could consider for a future study.

The average trip length and travel times for select scenarios are presented in Table 51. The results indicate a significant increase in average travel times across the region in the AM/PM periods of the 2045 No-Build conditions when compared to the base year conditions (56.0/31.7 minutes vs 22.5/18.6 minutes)). Generally, the introduction of CAVs will increase the average trip length but reduce the average travel times when compared to the 2045 build scenario. The redistribution of population and employment also promotes shorter average trip lengths and faster average travel times.

Table 51. Average AM/PM Trip Length and Travel Time for selected scenarios.

Performance Metric	2019 Base Model		2045 No Build		2045 Build		S2R17		S2R18		S3R24		S3R28	
TOD	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM
Average Trip Length	10.3	9.5	11.6	10.1	11.4	10.2	11.5	10.4	11.9	10.8	11.4	10.4	11.2	10.4
Average Travel Time	22.5	18.6	56.0	31.7	38.0	24.2	34.1	22.5	28.1	20.3	25.2	19.5	23.9	19.1

Table 52 summarizes the average AM/PM speeds for the select scenarios by functional class. These results also indicate a general improvement in average network speeds across all functional classes with the introduction of CAVs in the vehicle composition.

Table 52. Average Speed by Functional Class for selected scenarios.

FUNCL	2018 Base Model		2045 No Build		2045 Build		S2R17		S2R18		S3R24		S3R28	
	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM
Freeway	36	41	14	22	23	32	27	36	35	43	37	44	40	45
Principal Arterial	28	31	10	17	17	24	20	26	25	31	28	31	29	32
Minor Arterial	25	28	11	17	17	23	19	25	24	29	25	29	27	30
Collector	19	21	9	13	12	15	14	17	16	19	18	20	17	19
Freeway Ramp	29	31	14	20	20	26	23	29	29	33	30	33	30	33
Frontage Road	23	26	9	14	16	22	18	24	24	28	25	28	26	29
HOV	42	59	13	26	20	37	25	44	35	56	37	56	40	58
ALL	29	32	11	18	18	25	21	28	28	34	30	34	31	35

Table 53 summarizes the percentage of link lane-miles with different level-of-service (ABC, D, E and F) for the select scenarios in the AM and PM peak periods. These results also indicate a general improvement in network LOS with the introduction of CAVs in the vehicle composition. The results indicate that the network LOS in year 2045 under the S3R28 scenario is remarkably similar to the 2019 base model LOS.

Table 53. Roadway Level-of-Service Percentages for AM and PM Peak Periods.

Scenario	2019 Base Model		2045 No Build		2045 Build		S2R17		S2R18		S3R24		S3R28	
Peak Period	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM
Less than 0.8	87%	89%	65%	65%	74%	76%	77%	80%	83%	87%	85%	87%	86%	88%
[0.8 to 0.9)	5%	6%	5%	9%	6%	8%	5%	7%	5%	6%	5%	6%	5%	6%
[0.9 to 1)	4%	3%	6%	8%	6%	6%	5%	6%	5%	4%	4%	4%	4%	3%
Greater than or equal to 1.0	5%	3%	23%	18%	15%	9%	12%	7%	7%	4%	6%	3%	5%	3%

The performance measures for each scenario have been presented in the previous sections of this report. However, considering the number of unknowns regarding the future effects of the CAV integration on the regional network performance, it would be beneficial to show the results as a range of potential effects instead of looking at them as individual scenarios.

Figure 35 shows the daily regional VMTs for the performed model runs. The top part filled in with solid color represents the outcomes of scenarios 1 and 2 (S1 and S2). The data points corresponding to these runs are shown in blue. The bottom part of the graph shown with a dotted pattern represents the run results of scenario 3 (S3) with corresponding data points shown in orange. As the S3 runs were only performed for 0% and 100% CAV penetration rates, the points corresponding to 25% and 50% rates were estimated based on available data from other model runs shown with orange dots with a black border. The middle part which fills in the gap between the data obtained from the model run results represents the potential outcomes of scenarios that were not included in the project. All three areas together represent the potential range of daily regional VMT within the general ranges of the variables considered in the study.

A similar graphic is shown in Figure 36 for the daily regional VHT range followed by Figure 37 summarizing the data on average daily speeds and Figure 38 for the total daily network delay.

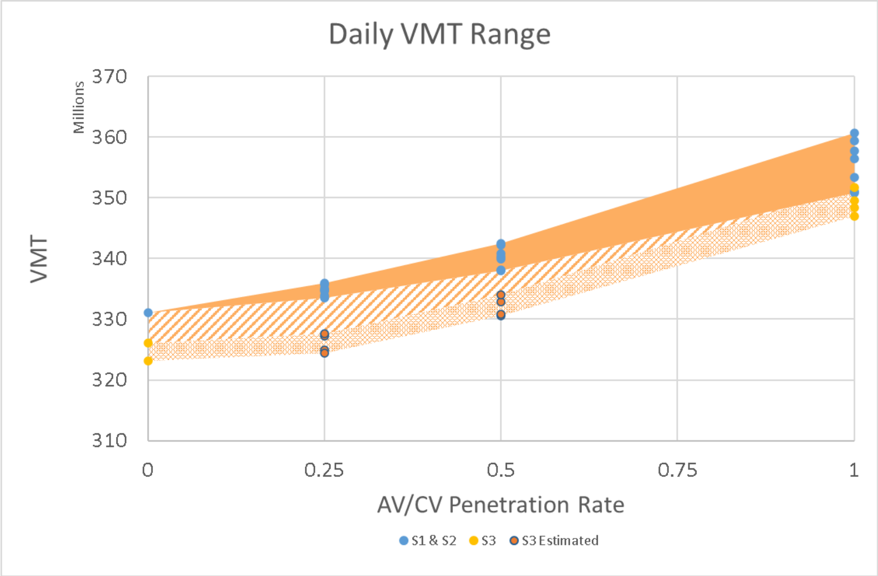


Figure 35. The Potential Ranges for Daily Regional VMT under different CAV Scenarios.

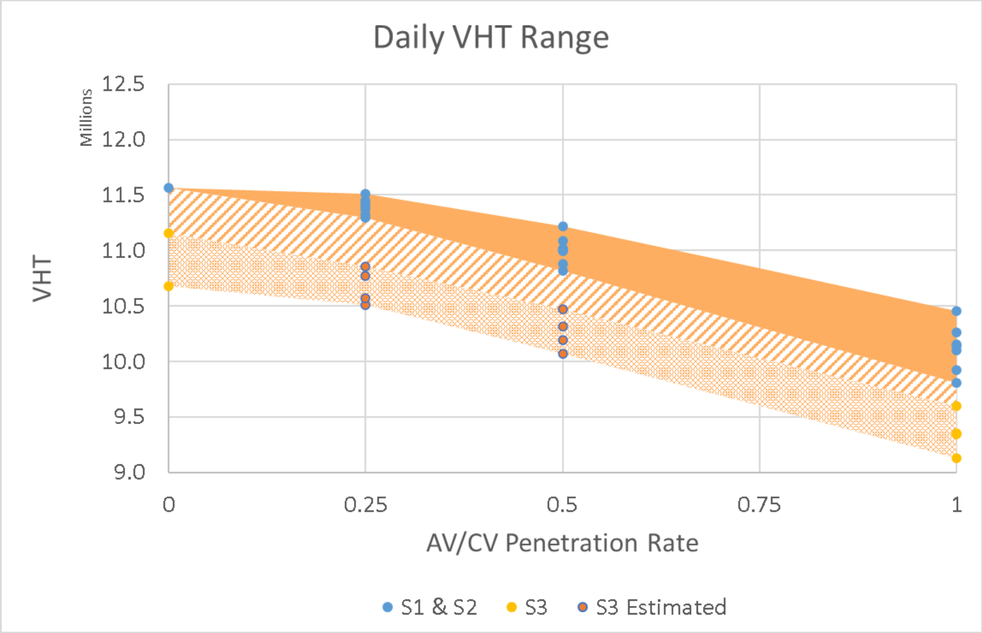


Figure 36. The Potential Ranges for Daily Regional VHT under different CAV Scenarios.

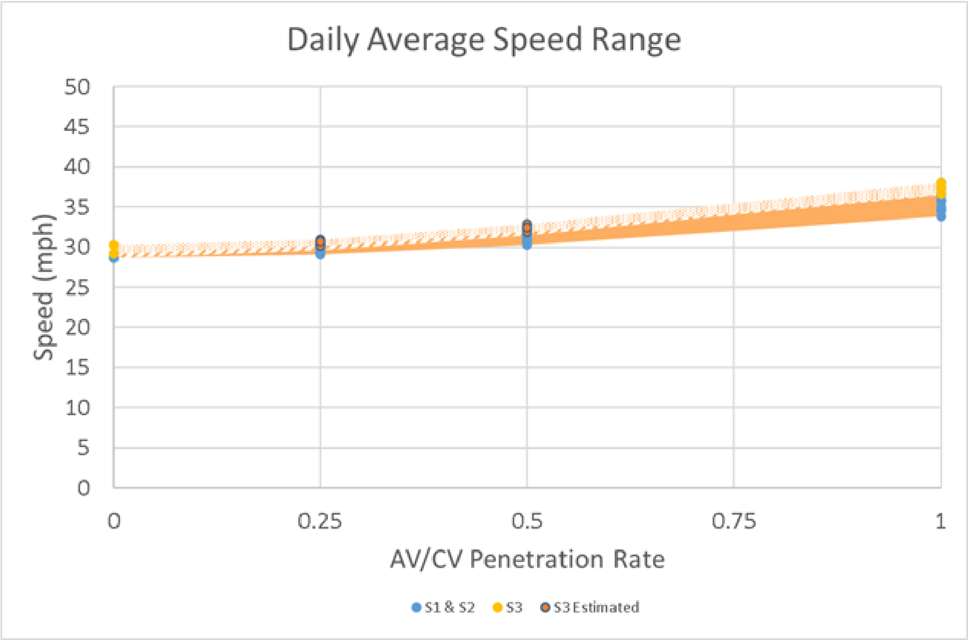


Figure 37. The Potential Ranges for Daily average Speed under different CAV Scenarios.

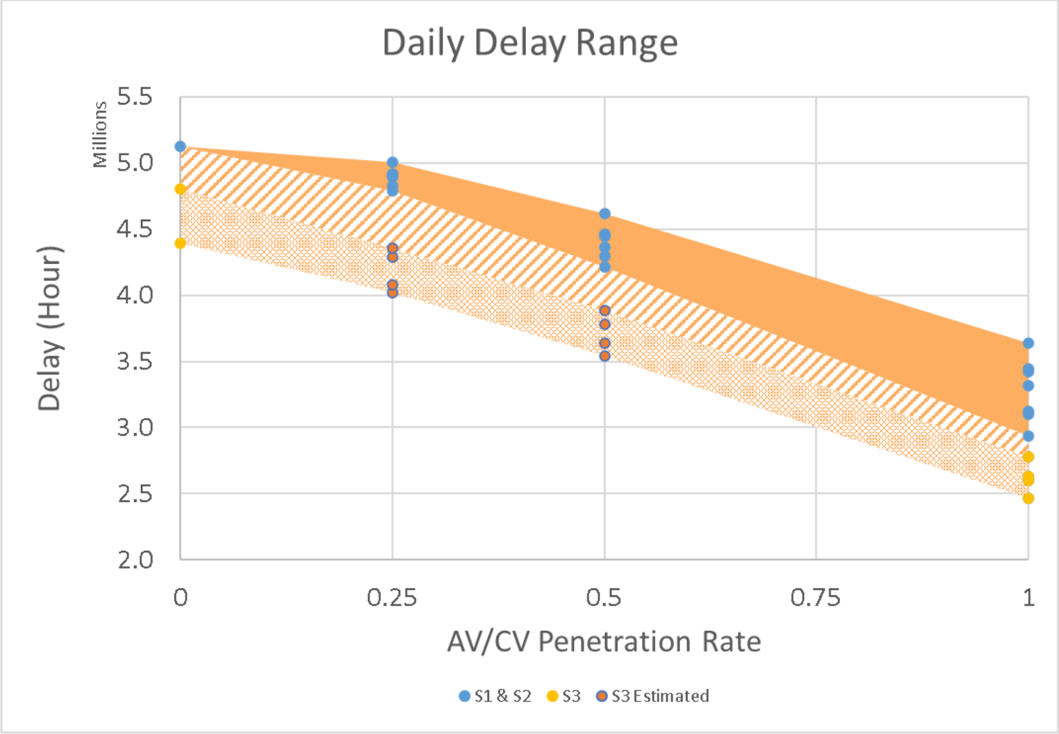


Figure 38. The Potential Ranges for Daily Total delay under different CAV Scenarios.

11 CONCLUSION

This report summarizes the analysis and modeling effort conducted as part of the NCTCOG AV2.1 project.

11.1 Scenarios

The effort focused on modeling three main automation scenarios identified as an outcome of a previous task. The three scenarios are:

1. **CAV Impact on Roadway Network Performance.** This scenario assumes that vehicles that are both connected and automated will enhance network capacity and reduce the time value for drivers.

2. **CAV Impact on Intersection Performance.** This scenario assumes connected vehicle-to-infrastructure technology will improve intersection capacity and reduce delays.

3. **CAV Impact on Population and Employment Distributions.** This scenario assumes that connected-automated vehicles (CAVs) will cause households and businesses to redistribute in the region, taking advantage of inexpensive real estate in the region's periphery zones.

A set of experiments was designed to model each of these scenarios. Scenario 1 (S1) is modeled using 15 experiments, numbered S1R1 to S1R15. These experiments examine the effect of five experimental factors, which are the CAV penetration rate, the percentage improvement in the capacity of the roadway links, the percentage improvement in the vehicles' traveling speed, the percentage reduction in the travelers' value of time (VOT), and the percentage reduction in the vehicles' operating cost.

Scenario 2 (S2) is modeled using six experiments numbered S2R16 to S2R21. The experiments focus on examining the impact of two experimental factors related to the connected intersection technology: the percentage improvement in the saturation flow rate of the intersections' inbound links and the percentage reduction in the amount of control delay experienced by the vehicles at these intersections.

Scenario 3 S(S3) is modeled using four experiments, S3R24, S3R27, S3R28, and S3R29. Two main experimental factors are considered in this set of experiments. The first factor compares the case in which both population/households and businesses are redistributed versus the case in which only population/households are redistributed. The second factor examines the effect of reducing the travelers' VOT.

11.2 Model

Considering the planning scope of this study and the ongoing effort to upgrade the DFW regional travel demand model to account for CAV technologies, the study team followed NCTCOG's guidance to adopt an upgraded version of the regional travel demand model for this study. This version, AV-TAFT, was developed based on a previous project administered by NCTCOG in collaboration with the University of Texas at Austin and slightly modified in this project to develop CMAV-TAFT for addressing the project's modeling needs. It should be noted that the DFW model is limited to standard vehicle travel and currently lacks the capacity to predict how people do and will move around by walking, biking, e-biking, and scooters. CMAV-TAFT enables evaluating the proposed transportation automation scenarios at the regional level and benchmarking the performance of the transportation system considering the region's other transportation improvement activities.

The roadway and transit networks utilized in this project are pre-final MTP networks since the latest updates became available as the project was getting close to its end. However, some analysis was performed to verify the potential effects of the CAV scenarios on the final MTP network. All reference made to the HOV functional class in future networks refers to priced managed-HOV facilities.

11.3 Evaluation

Based on the CMAV-TAFT modeling platform, all experiments assume the demographics and the roadway network planned for the 2045 target year. The transportation system performances obtained for all experiments are benchmarked against a base scenario that assumes there are no CAVs in the traffic composition. The transportation system performance is compared using several performance measures, including VMT, VHT, average speed, and delay. In addition, maps that demonstrate percentage change in the link volumes under the different scenarios are presented. Finally, travel time contour maps for the region are given. These maps depict the travel time to and from the DFW International airport (as a regional focal point) for the AM and PM peak periods.

Several main observations could be made based on the results of these experiments:

- The improvement in the regional transportation system performance is proportional to the increase in the CAV penetration rate.
- Generally, the adoption of CAVs increases the daily VMT, reduces daily VHT, increases the average speed, and reduces the total daily delay compared to the base scenario. The percentage changes vary depending on the settings of the modeled scenario, as described in detail in this report.
- *Scenario 1: CAV Roadway Performance* has the most impact on the overall system performance compared to *Scenario 2: CV Intersection* and *Scenario 3: CAV Demographic Distribution*. This scenario accounts for an increase in the roadway capacities across all functional classes based on different CAV penetration rates. The incremental changes in the network performance under Scenario 2 and then Scenario 3 are smaller than the change recorded for Scenario 1. Thus, one can conclude that deploying connected intersection technology and the redistribution of population and employment has less impact than the basic scenario in which CAVs penetrate the system. Similar trends can be observed in the peak period results with some exceptions.
- The adoption of CAVs will significantly increase VMT in the region. The anticipated redistribution of population and employment reduces the VMT increase by about 30% to 40%, which is still higher than the VMT for the base scenario.
- Finally, CAV technologies could reduce the need for significant typical capital improvements eventually and result in a potential shift of investments from adding

concrete to adding technology. The technology reduces the congestion in a hypothetical no-build scenario in the target year.

These conclusions were based on a set of model runs performed under specific assumptions regarding each of the modeling steps of a four-step travel demand model. Considering that no large deployments of CAVs yet exist in the world, these results should be used as a general guideline on how the regional traffic patterns and network performance could change during and after the integration of CAVs into the traffic stream. North Central Texas needs to continuously monitor its transportation system as CAVs are deployed and integrated into the system to improve our understanding of the incremental effects of CAVs on system operations and safety performance.

11.4 Future Research Needs

This analysis was an initial effort to understand the potential impacts of CAV adoption in the North Central Texas region. The assumptions should be reviewed and updated as more information becomes available about the real-world impacts of CAVs. Below is a list of additional actions and analysis to consider.

Model additional scenarios. The analysis could be extended to consider other transportation automation scenarios, including automated trucks, teleworking, and automated vehicle ride-hailing services.

Model different adoption patterns. The modeled scenarios could be extended to represent diverse levels of access to or ownership of CAVs by zone and by socioeconomic characteristics. Similarly, a uniform investment on infrastructure connectivity in the region is assumed. This assumption could be relaxed by assuming that connectivity is only available in certain parts of the region.

The analysis assumes that CAV and traditional vehicles are mixed in the traffic stream. Scenarios that consider dedicating some facilities to the CAV traffic should also be considered.

Update assumptions based on real-world observations. Agencies should collect and monitor model performance measures from real-world deployments to determine if our assumptions should be revised in future modeling efforts.

Create a Data Repository. The region needs a data repository for the different transportation automation pilot studies conducted in the DFW region. This data repository is essential for calibrating and validating models that can accurately predict the transportation system's performance under adopting these technologies.

Model local deployments with microsimulation. The regional model enables quantifying the performance of the entire region and benchmarking it against other capital improvement projects. However, there is a need to model these scenarios at the city or county level using higher-resolution modeling platforms capable of capturing CAV traffic flow characteristics, especially those related to car-following behavior and data-sharing at connected intersections.