Simulation-Based Evaluation of Autonomous Vehicle Penetration on Urban Traffic Efficiency and CO_2 Emissions via Integrated PTV VISSIM and Bosch ESTM

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Presenter’s Experience

Research/ Work experience

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Publications

- User Experience of Navigating Work Zones with Autonomous Vehicles: Insights from YouTube on Challenges and Strengths, Journal of Smart Cities, 2025
- Autonomous Vehicles in Rural Areas: A Review of Challenges, Opportunities, and Solutions, Journal of Applied Sciences, 2025
- Assessing the Efficacy of Pre-trained Large Language Models in Analyzing Autonomous Vehicle Field Test Disengagements; Journal of Accident Analysis & Prevention; 2025
- Analyzing the Safety and Operational Dynamics of a Freeway Under Adverse Weather Conditions in Mixed Traffic Flow: A Microsimulation Model Approach Examining Different Market Penetration Rates of Autonomous Vehicles; Road Safety and Simulation Conference (RSS); Lexington- KY; 2024
- Safety and operational impacts of different Autonomous Vehicle operations on freeway work zones; Journal of Advances in Transportation Studies; 2024
- Huang, Y; Ansarinejad, M; Lu, P; Assessing Mobility under Inclement Weather Using VISSIM Microsimulation- A Case Study in US; Proceedings of the 9th International Conference on Civil Structural and Transportation Engineering (ICCSTE'24); Toronto, Canada; 2024
- Ansarinejad, M.; Huang, Y., and Qiu, A.; Impact of Fog on Vehicular Emissions and Fuel Consumption in a Mixed Traffic Flow of Autonomous Vehicles (AV) and Traditional Vehicles (TVs)- ASCE International. Conference on Transportation and Development; Austin- Texas; June 2023

Autonomous Vehicles (AVs) Overview

AVs, also known as self-driving cars, are transforming transportation through advanced technologies that enable them to operate with minimal or no human intervention.

Anticipated Future Trends

Privately owned Level 4 AVs will make up approximately 24.8% of vehicles on roadways in the U.S. by 2045[1] .

AV Manufacturer with Driverless Testing Permit

(CA DMV, 2024)

1. Apollo Autonomous Driving USA LLC,
2. AutoX Technologies,Inc.
3. Nuro Inc.
4. R3 Nuro Robot
5. Waymo LLC.
6. WeRide Corp
7. DBA WeRide AI
8. Zoox Inc.

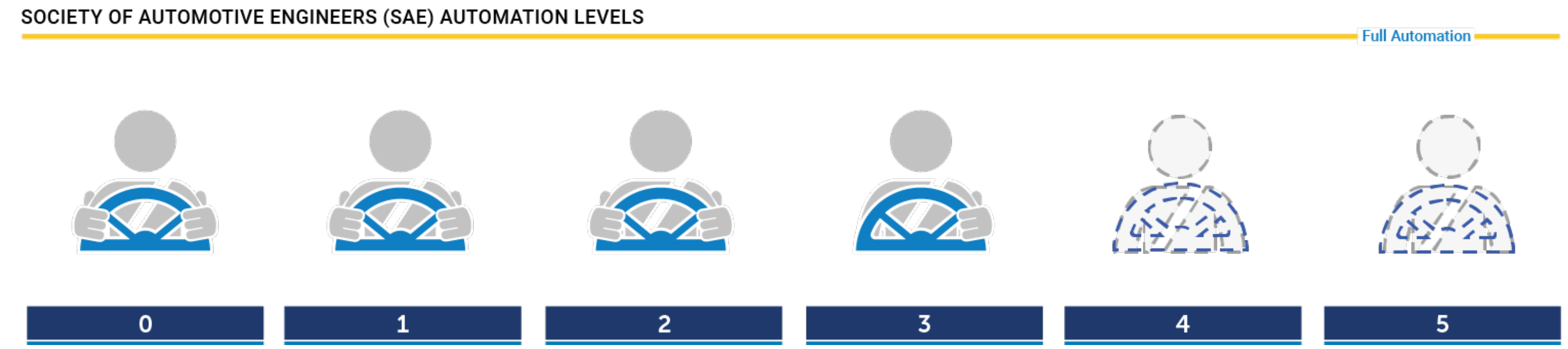


Figure 1: Levels of Autonomy ; Source: Society of Automotive Engineers

Figure 2: Amazons' Zoox Robotaxi, Las Vegas, Nevada- Sept. 2025
Source: Bloomberg

Author(s)	Study Focus	Key Findings	Methodology/Tools
Alessandrini et al.(2012)[2]	Impact of driving style on fuel consumption (Eco Index)	Eco-driving reduces CO_2 emissions by up to 30% at 10 km/h (gasoline) and 22% at 40 km/h (diesel); no significant reduction at speeds >80-90 km/h.	Real-world data, COPERT program
Olia et al.(2016)[3]	Impact of penetration rate of connected autonomous vehicle (CAV) on emission	Increasing CAV penetration reduces emissions, with the maximum benefit at 50% CAV penetration.	PARAMICS microsimulation, CMEM emission model
Stogios et al.(2019)[4]	Impact of AV (aggressive and Cautious) mixed traffic flows on Emissions	Headway time significantly impacts emissions under different AV penetration rates in mixed traffic.	VISSIM microscopic traffic simulation, MOVES emission model
Conlon & Lin(2019)[5]	Impact of congested urban road networks on CO_2 emissions of AVs	Emissions increase at lower AV penetration rates but reduce significantly and plateau between 40%-90% AV penetration.	SUMO microsimulation, Newton-based greenhouse gas model (NGM)
Szumska & Jurecki(2020)[6]	Impact of driving behavior on fuel consumption and emissions	Aggressive driving in urban areas increases pollutant emissions by ~40% compared to calm driving.	Onboard emission analyzers, real-world tests
Miotti et al. (2021)[7]	Impact of Eco-driving on emissions	Eco-driving, whether human-driven or with low-level automation, significantly reduces GHG emissions.	Trip Energy simulation
Suarez et al.(2022)[8]	Impact of acceleration behavior on CO_2 emissions	Aggressive acceleration increases CO_2 emissions by up to 5% compared to mild acceleration.	WLTP tests, CO2MPAS simulations

Vehicular Emissions Measurement Methods

***1) Lab Tests** (Figure3)*

- Conducted in a **controlled** environment, Based on **predetermined** driving patterns
- Tool for developing average or instantaneous speed models

***2) Field/ Real-world Measurement** (Figure4)*

- Dynamometer-based models: steady-state nature, not represent the variability of actual driving conditions
- Portable gas analyzers, commonly Portable Emissions Measurement System(PEMS): real-time as the vehicle is driven

Figure3. Lab Test Method for Emission Measurement
Source: EPA

Figure 4. Field Test Method for Emission Measurement
Source: UNECE

Vehicular Emissions Measurement Methods and Challenges

3) Emission Models

- Macroscopic (regional level): Make use of aggregated inputs, include elements like average speed and vehicle kilometers traveled (VMT)

Commonly used for calculating regional emission inventories

- Mesoscopic (corridor level): Cost-effective method for creating detailed simulations, Considers individual vehicles without addressing their interaction
- Microscopic (individual vehicle level)

Microsimulation Emission Estimation Challenges/ Gaps

- Developing most simulation models requires complex integration of traffic and external emission models.
- The process often involves extensive and error-prone data handling.
- Current approaches offer only limited ability to evaluate CO_2 emissions across different autonomous vehicle (AV) penetration scenarios.

➢ *Traffic Simulation Tool: PTV VISSIM*

- Solid graphical user interface
- Versatile Road System Modeling
- Discrete Time Step Simulation
- Behavior-Based Traffic Modeling (psychophysical car-following)
- High degree of accuracy
- Integration with Emission Models at various scales
- Customizable Lane change and Car-Following Settings

Figure5. Vissim- Bosch Integration
Source: PTV Group

➢ ***Software/Emission Simulation Model:*** *Bosch ESTM*

- **Integration and Data Transmission with VISSIM**
- **Precision Emission Measurement** (second-by-second emission statistics)
- Including CO_2 emission besides CO, NOx, HC, PM, and fuel consumption immediately after traffic simulation completion.
- **Comprehensive Vehicle Classification:** vehicle classes using 6 key elements: Emission vehicle category, class, stage, Fuel type, Size class, and Use class.
- **Real-Time Impact Assessment:** Monitor changes in vehicle emissions and air quality in VISSIM environment
- **Flexible Data Aggregation:** Aggregated data for Link Evaluation per segment or based on vehicle classes in Vehicle Network Performance Evaluation.

Figure 6. Emission Visualization in Vissim Software
Source: PTV Group, Bosch ESTM [9]

1) Establish VISSIM Network Layout

Base Map (Site of the Project)

- **Geographic Orientation:** Saratoga Springs, Utah, USA
- **Intersection:** Intersection of Redwood Road and Pioneer Crossing
- **Roads Involved:** Redwood Road (North-South) and Pioneer Crossing (East-West)
- **Road Configuration:** principal five-lane arterials

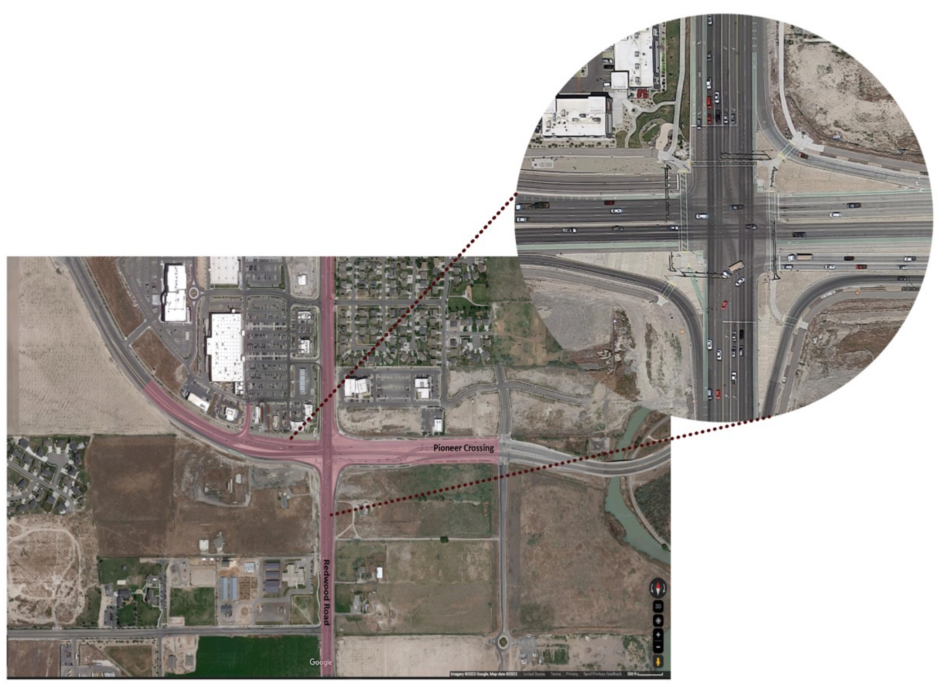


Figure7. Project Site, Saratoga Springs, UT, USA

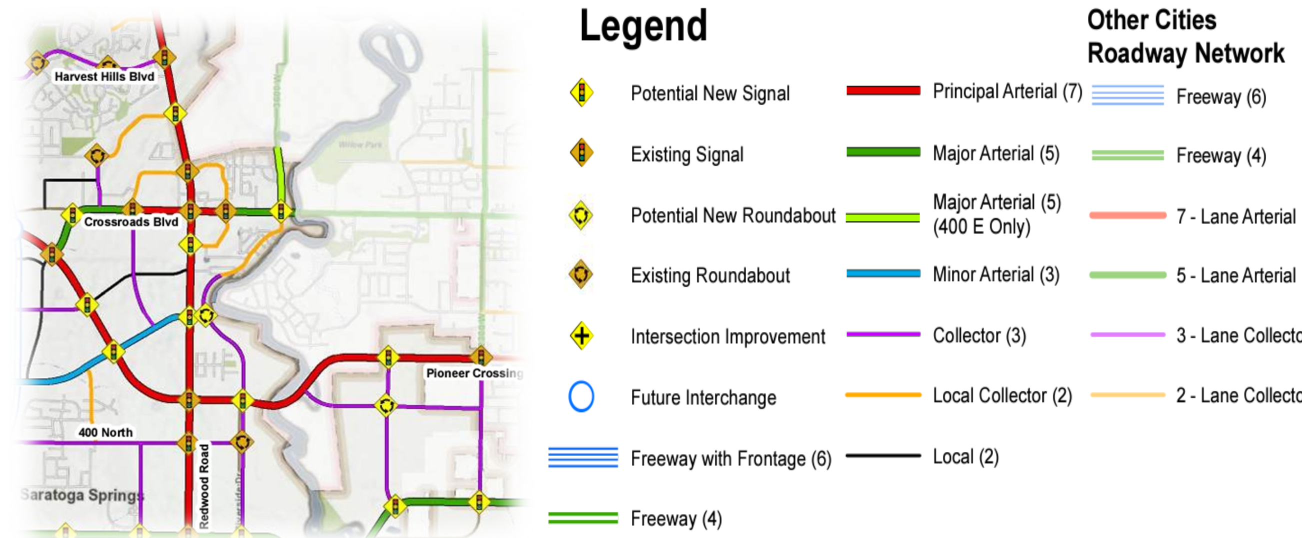


Figure 8. Part of the Saratoga Springs Master Plan Including the Project Site

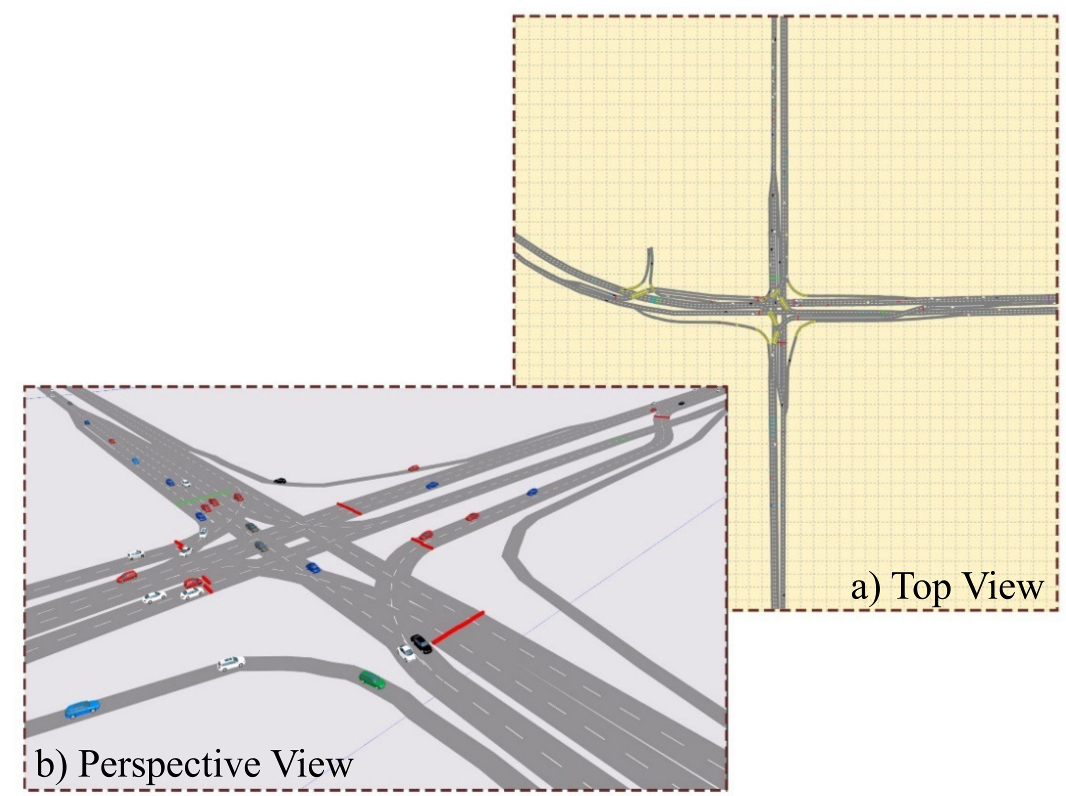


Figure 9. PTV VISSIM model for mobility and emission analysis

2) Calibration of VISSIM Model

- **Traffic Demand Input**: 1.5 hour of weekday evening peak-hour conditions (4.00-5.30 pm)

- **Vehicle Composition Input:** baseline scenario (0% AV) + 10 scenarios of mixed traffic flow of AV and Human-driven Vehicles (From 0% to 100%, in 10% increments)

- **Speed Distribution Input:** AV: deviation of only 2 km/h from the speed limit[10], Human Driven Vehicles: based on naturalistic driving data[11]

-Traffic signals: Using a ring-and-barrier structure; in accordance with the Utah DOT's traffic signal timing guidelines[12]

- **Driving Behavior Input (Table 2)**

-Number of Simulation Runs and Resolution: 10 Runs with resolution of 10 time-step

Table 2

Parameter Category	W99 Car following Parameters	Definition	Autonomous (Normal)[13]	Human-Driven[14
Thresholds for Safety Distance (Δx)	CC0 (m)	Standstill Distance	1.5	4.45
	CC1(s)	Headway Time	0.9	0.87
	CC2 (m)	Following Variation	0	5.28
	CC3 (s)	Threshold for Entering Following	-8	-7.92
Thresholds for Speed (Δv)	CC4 (m/s)	Negative Following Threshold	-0.1	-1.52
	CC5 (m/s)	Positive Following Threshold	0.1	1.52
	CC6 (-)	Speed Dependency of Oscillation	0	0.71
Acceleration Rates	CC7 (m/s^2)	Oscillation Acceleration	0.1	0.31
	CC8 (m/s^2)	Standstill Acceleration	3.5	1.03
	CC9 (m/s^2)	Acceleration at Speed of 80 km/h	1.5	0.33

3) Application of ESTM Service of Bosch

Define Emission Class Distribution :
Predefined MOVES-based 2022 profile for light-duty gas and diesel passenger vehicles, representing U.S. fleet composition from 1992–2020.

4)Simulation Process

- Within 5400s of the simulation time, a warm-up period of 900s was applied at the beginning and the end of each simulation run, in accordance with the PTV VISSIM Manual, to ensure that the results capture stabilized traffic conditions[15].

- During simulation, VISSIM generates a trajectory for each vehicle, which is then transferred to ESTM for emission calculation.

- The driving behavior element that most impacts emissions in Bosch ESTM is the dynamic profile of vehicle movement; particularly accelerations, decelerations, and stop-and-go patterns.

1) Stops

Phase 1 (0% to 10% AV penetration):

- Slight increase in the number of stops.

Phase 2 (10% to 90% AV penetration):

- Consistent and significant reduction in stops.
- Most notable reduction occurs between 40% and 80%, where traffic efficiency is significantly enhanced.

Phase 3 (90% to 100% AV penetration):

- Slight uptick in stops after reaching the lowest point at 90%.

Figure 10: Average Stops across AV Penetration Rates

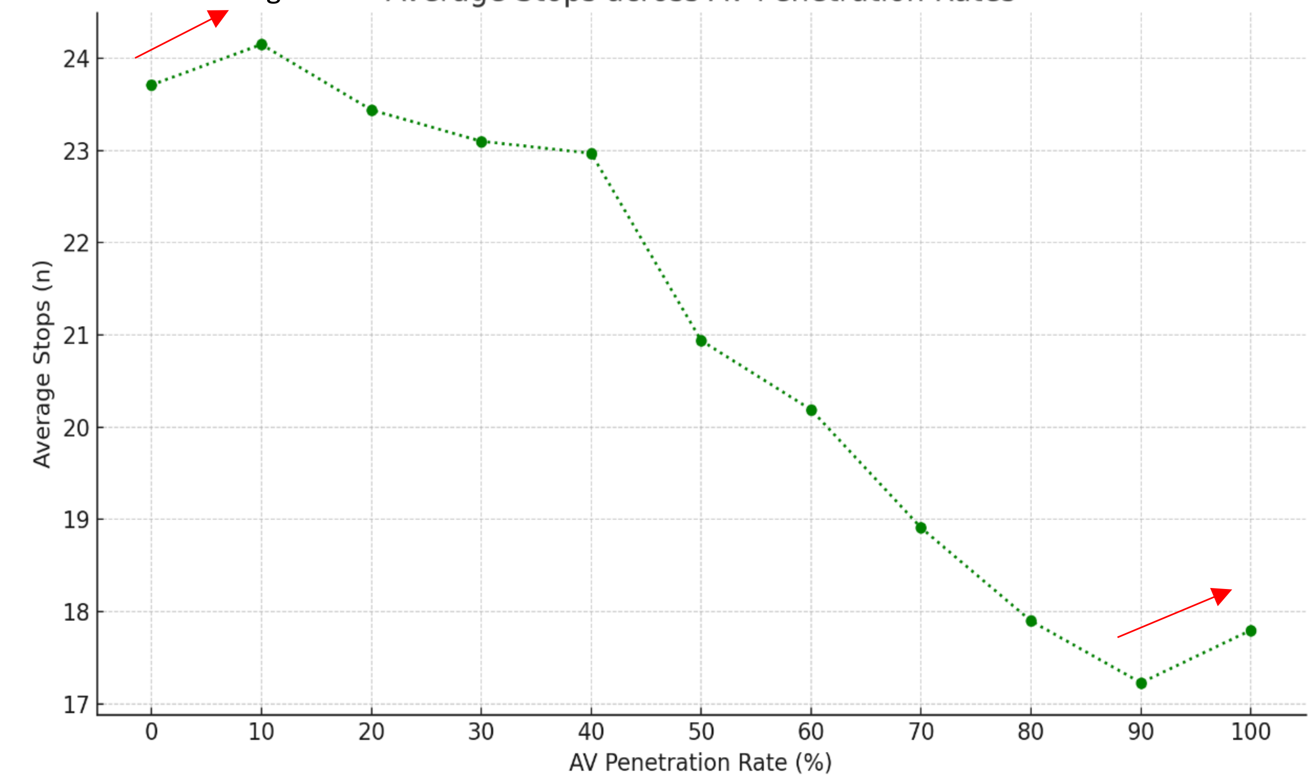
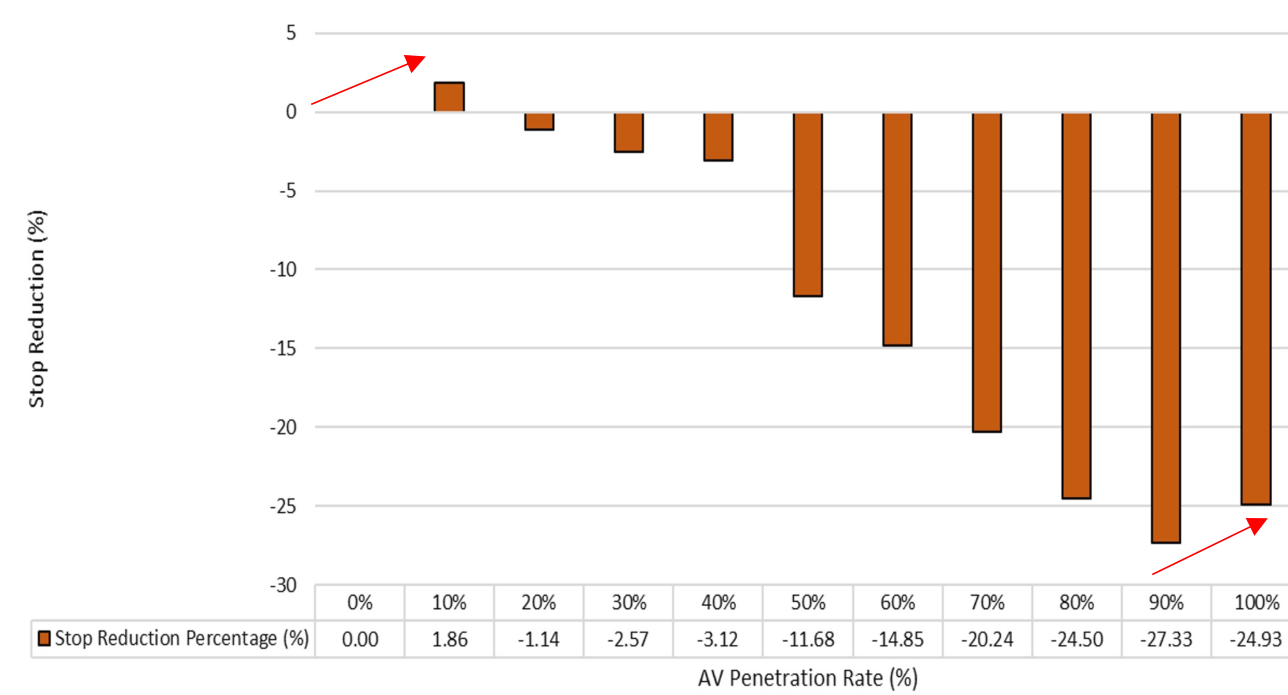


Figure 11: Stop Reduction at Different AV Penetration Rates(%)



2) Delay

Phase 1 (0% to 50% AV penetration):

- Sharp decline- Delay steadily decreases
- From 440 seconds at 0% reaching to a minimum of below 380 seconds at 50% AV penetration rate.

Phase 2 (60% to 100% AV penetration):

- Fluctuating trend
- Delay slightly increases and fluctuates, with a small peak at around 80% AV penetration, where the delay rises slightly above 384 seconds.

Overall trend: Higher AV penetration rates consistently reduce delays, with the greatest impact occurring at lower to moderate levels, then fluctuates slightly, stabilizing near 382 seconds at full penetration

- Further delay reductions may require more advanced AV capabilities and supportive infrastructure adaptations to fully realize the benefits.

Figure 12: Average Delay across AV Penetration Rates

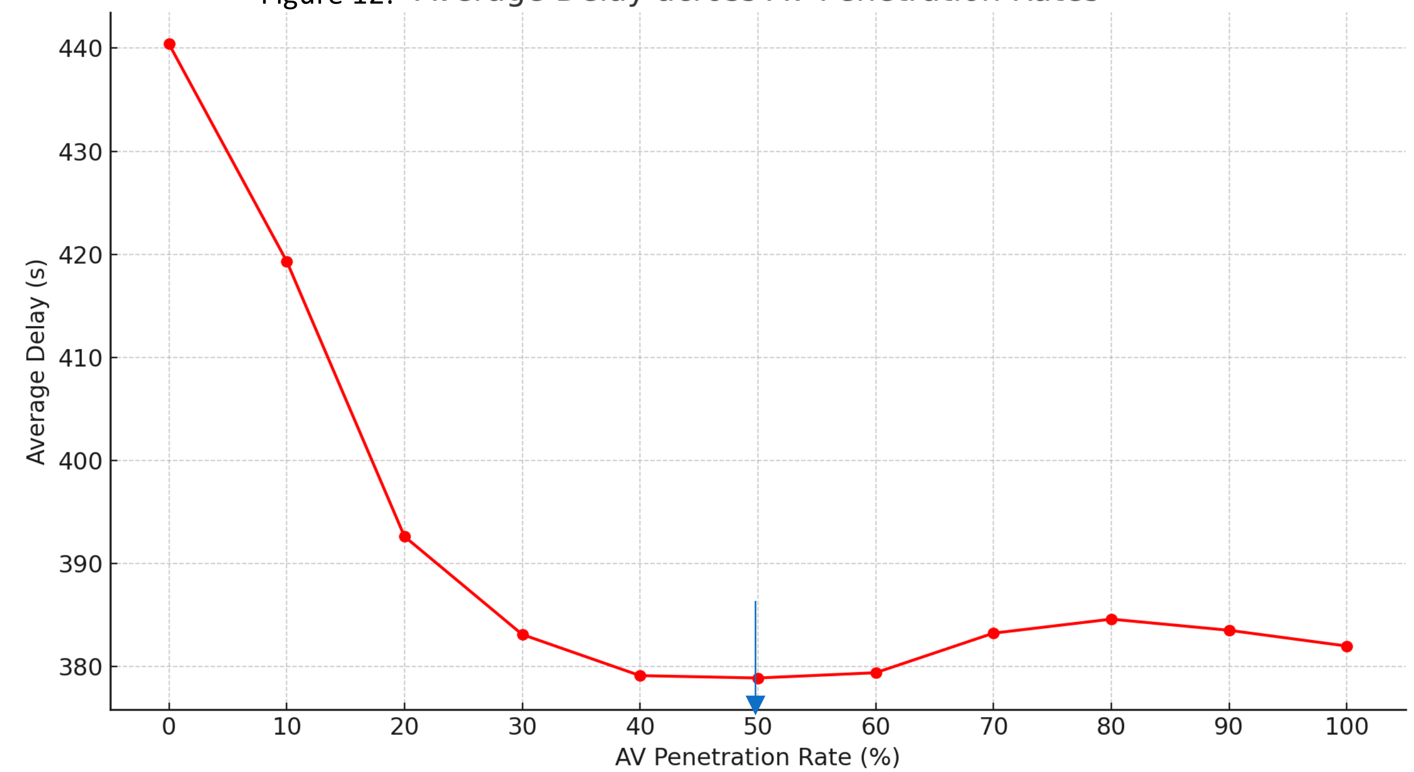
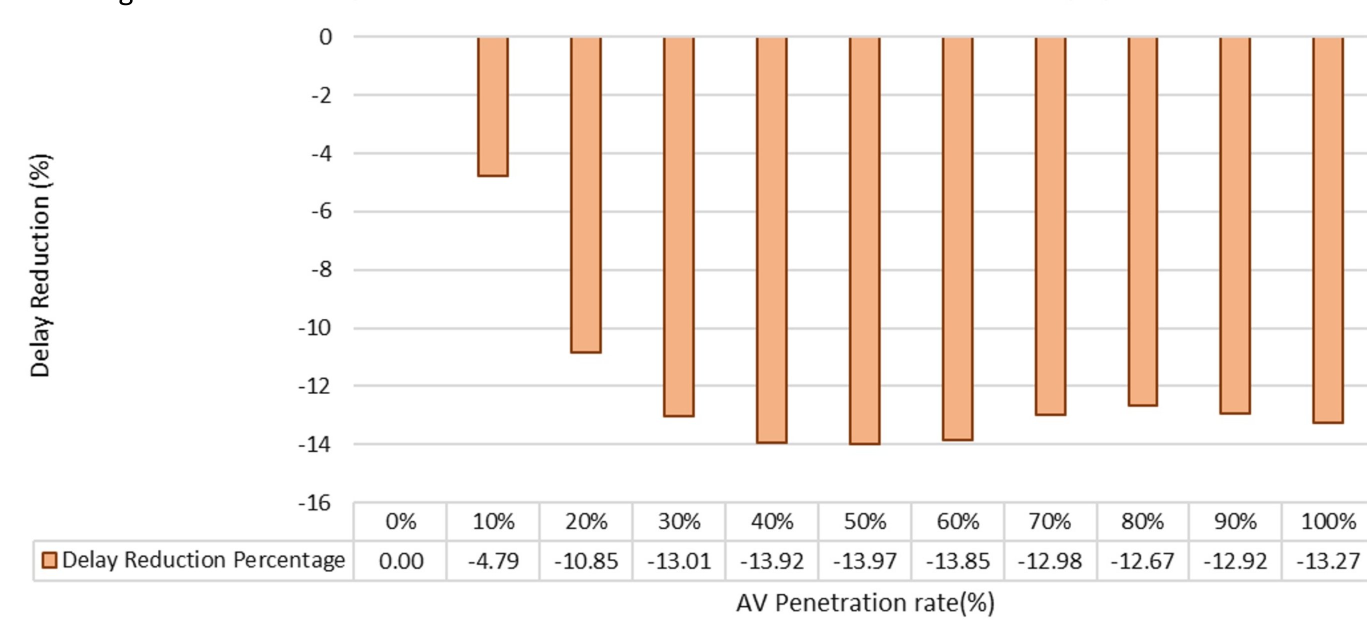


Figure 13: Delay Reduction at Different AV Penetration Rates(%)



	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Delay Reduction Percentage	0.00	-4.79	-10.85	-13.01	-13.92	-13.97	-13.85	-12.98	-12.67	-12.92	-13.27

3) Average Speed

➢ ***Phase 1 (0% to 50% AV Penetration)***

- Steady rise in average speed
- Reaches 71.81 km/h at 50% penetration
- Enhanced traffic efficiency with the introduction of AVs

➢ ***Phase 2 (50% to 100% AV Penetration)***

- Average speed continues to increase at a slower rate
- Highest recorded speed of 73.92 km/h at 100% penetration
- Fewer disruptions and improved coordination with full AV integration

Validation Note

The recorded approach speed (38 mph/61 km/h) shown in Figure 14-a, closely matched the average speed of the simulation model(Figure 14-b), (38.7 mph/62.38 km/h), yielding 97.78% accuracy.

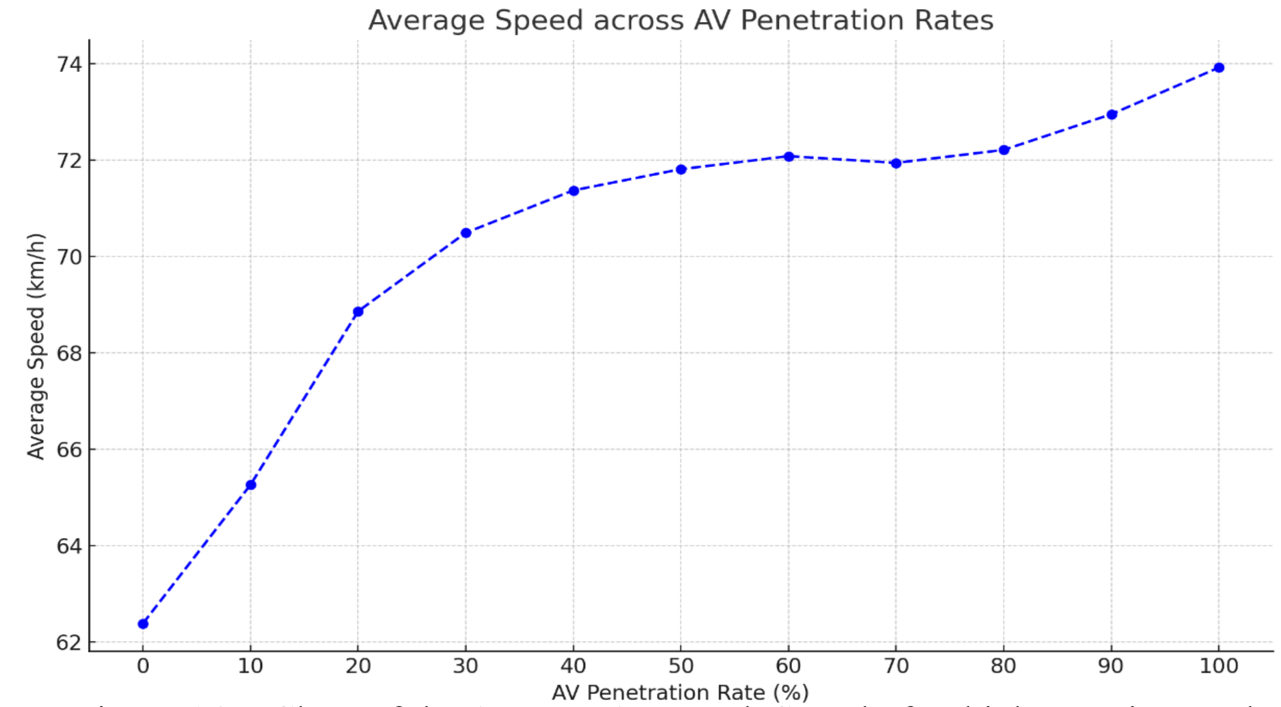


Figure 14-a:Chart of the Average Approach Speed of Vehicles During Peak Hour; Example of Westbound Through (WBT)- Utah ATSPM[25]

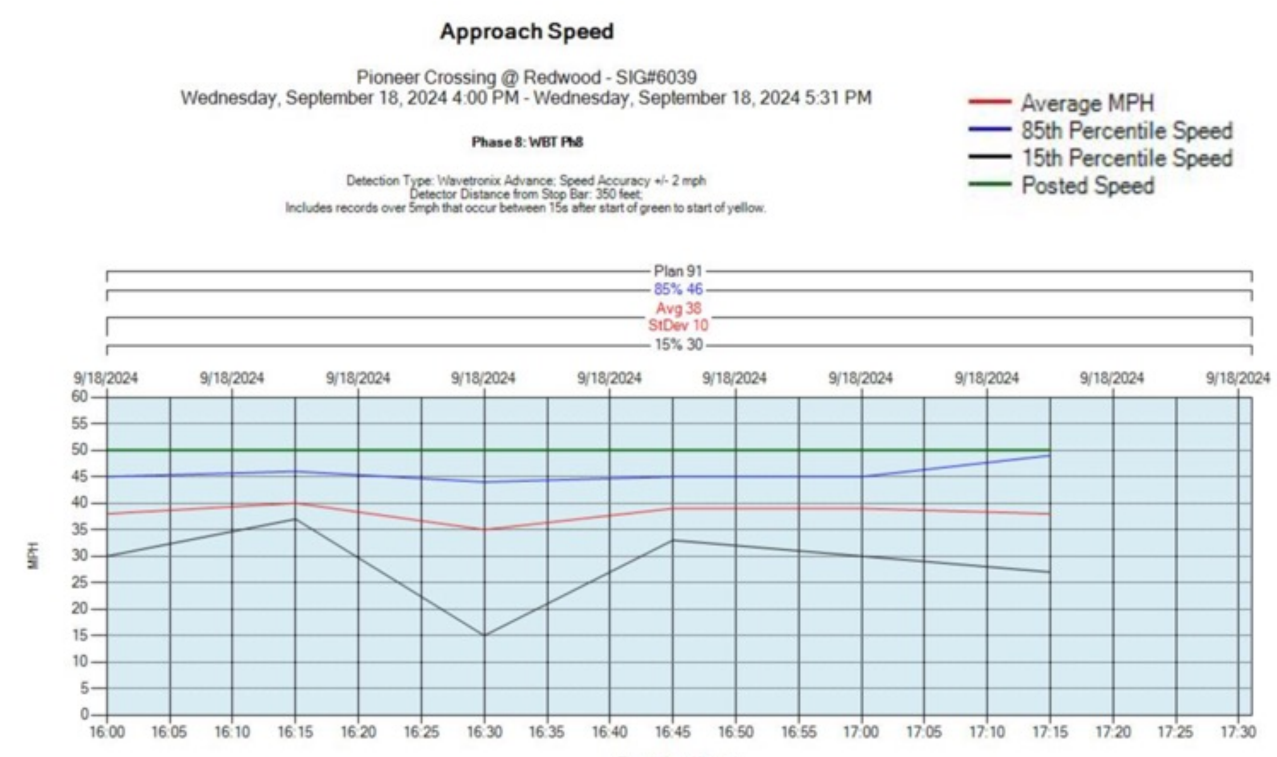


Figure 14-b

4) Air Quality Measurement

- **<u>Phase 1 (0% to 20% AV Penetration)</u>**
  - CO_2 Emissions drop by about 8%
- **<u>Phase 2 (20% to 50% AV Penetration)</u>**
  - CO_2 Emissions decline by around 12.5%
- **<u>Phase 3 (50% to 100% AV Penetration)</u>**
  - Most pronounced reduction in CO_2 emission,. about 34%

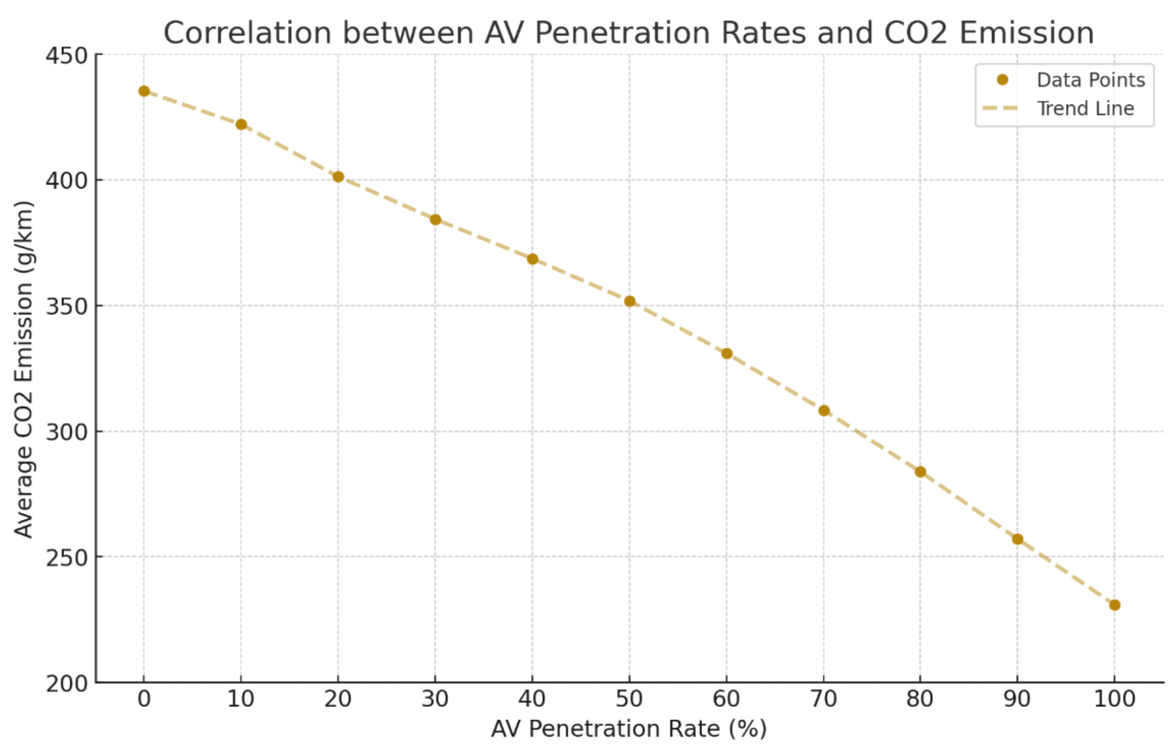
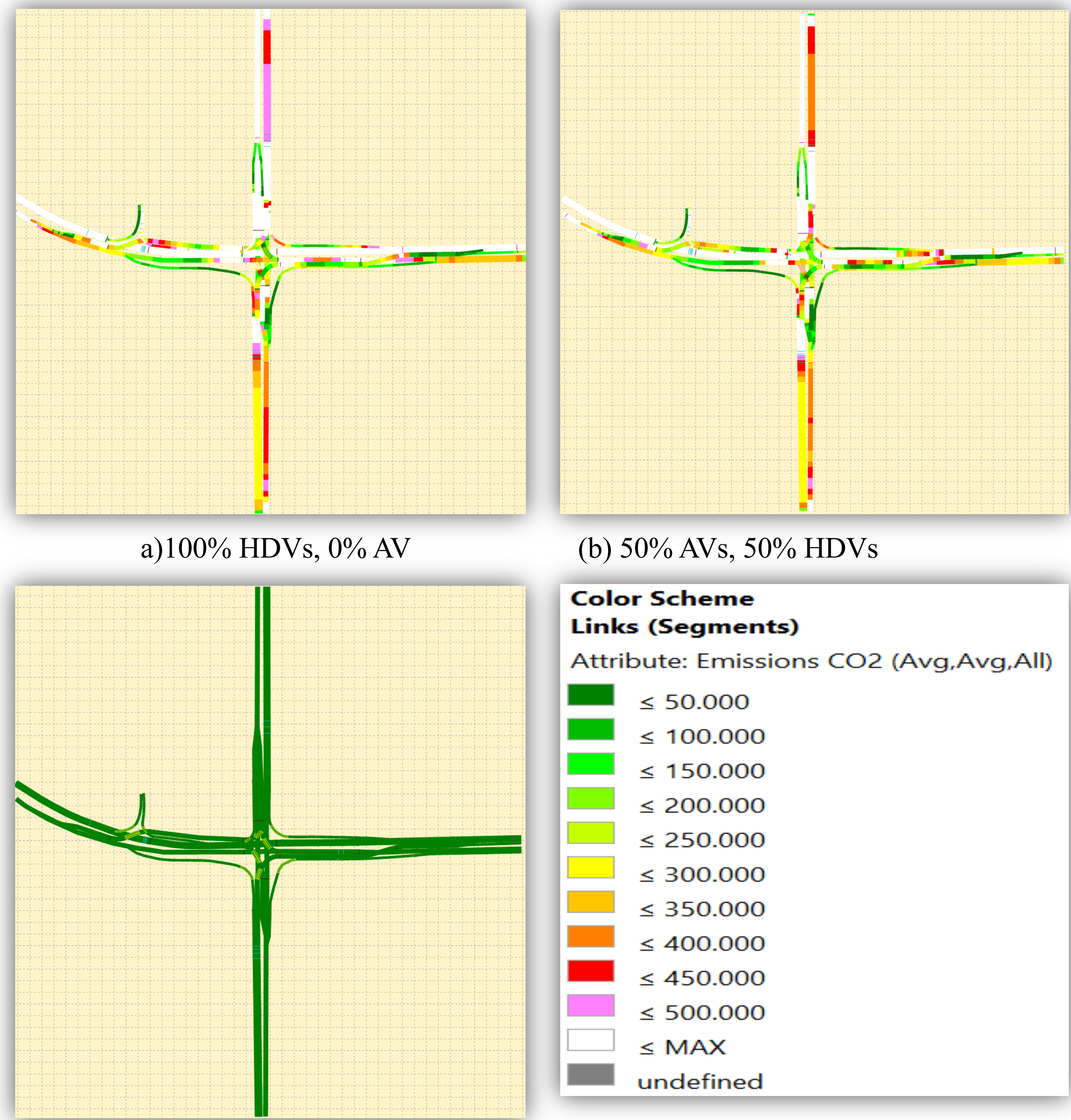


Figure 15



a)100% HDVs, 0% AV

(b) 50% AVs, 50% HDVs

(c) 100% AVs, 0% HDV

(d) Legend of CO_2 Distribution Map

Figure 16. CO_2 emission comparison for three AV Penetration Rates

Parallel Analysis of Driving Behavior, Traffic Flow and emission Outcomes

Table3

Parameters	**AVs**	**Human-Driven Vehicles**
Level of Caution (CC0 and CC1, CC2)		
Level of Perception-Reaction (CC3)		
Level of Sensitivity to the Dec/Acc (CC4, CC5)		
Level of Acceleration Oscillation (CC7)		
Level of Standstill acceleration (CC8)		
Speed Distribution Range		
Vissim Mobility Measures	**Mixed Traffic Flow**	**Traditional Network**
Average Speed (km/h)		
Average Stops (-)		
Average Delay(s)		
Bosch Emission Measures		
CO_2 Emission		
Fuel Consumption		

Conclusion

Successful Integration of VISSIM and Bosch ESTM:

- Streamlined approach to emission calculations with no need for intermediary software.
- Consistent with previous literature on emissions estimation using alternative simulation models.

Performance of AVs:

- Substantial environmental benefits, with emissions reduction of more than 50% at full AV adoption.
- Modest emission improvement at low penetration rates, while the steepest benefits occurred between 70% and 100% adoption.
- Low levels of AV integration may yield only incremental improvements, while full automation could introduce new challenges, particularly if overly cautious driving behaviors or induced demand leads to increased travel.
- Full benefits of AVs require high adoption plus supportive infrastructure, realistic driving profiles, and strong policy frameworks.
- The findings highlight the importance of coordinated planning, where technological advances in automation are integrated with traffic management strategies, upgrades to both physical and digital transportation infrastructure and built environment, and policies that prevent rebound effects.

➢ Limitations and Future work

•Broader Scope of Analysis
Extend the analysis to multiple intersections and scenarios.

•Comparative Evaluation
Compare Bosch ESTM+VISSIM with VISSIM+MOVES to provide broader insights.

•Digital Twin Development
Develop a digital twin of the modeled intersection to enhance validation.

•Passenger Comfort Assessment
Evaluate human comfort in relation to the AV calibration used in this study.

➢ Acknowledgment

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