Impact of Fog on Vehicular Emission and Fuel Consumption in a Mixed traffic Flow with Autonomous Vehicles (AVs) and Human-driven Vehicles Using Vissim Microsimulation Model

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ABSTRACT

Driving in foggy conditions poses high risks to road users due to the reduction of visibility, affecting the drivers' vision and perception, and making changes in normal driving behavior. Harsh driving, frequent aggressive accelerations, or abrupt deceleration under adverse weather conditions, could result in high amounts of fuel consumption, NOx, CO, and other exhaust emissions. (Adamidis et al. 2020) The scientific literature of the past few years indicates that the fog phenomenon has the most negative effects on driving behavior. This study analyzes the PTV VISSIM traffic microsimulation outputs for exhaust emissions and fuel consumption of vehicles simulated under adverse weather conditions. This weather-dependent simulation is developed by using the advanced psychophysical car-following model "Wiedemann's 99", to flexibly control the driving behavior parameters in various driving conditions. Results show that vehicles under foggy conditions consume more fuel and produce more emissions in comparison with clear sky conditions and other scenarios. With the gradual transition of current cities to smart sustainable cities and by introducing Automated Vehicle (AVs) to the traditional traffic network and gradually increasing their penetration rate, decrease in negative environmental impacts of driving under foggy conditions and improvements in overall mobility of a shared network of Autonomous and Human-driven is observable.

INTRODUCTION

Road transportation contributes noticeably to climate change and environmental pollution. Three key factors of vehicle-, network characteristics, and driver behavior have direct or indirect effects on the environmental impacts of road transport (Kopelias et al. 2020). Assessing the impact of driving style and operation of a vehicle on fuel consumption and exhaust emission is of significant importance. According to previous studies, fuel consumption and exhaust emission may vary depending on driving behavior and may decrease up to 40% from an aggressive driver to a calm one (Alessandrini et al. 2012)

One of the important factors that noticeably impact driving behavior, traffic flow, and safety of a traffic network is the adverse weather conditions namely snow, rain, and fog which affect sight distance and pavement conditions. According to the federal highway administration, weather-related crashes account for approximately 21% of 5,891,000 annual crashes (FHWA 2022). Fog restricts visibility as well as the visual field and causes the perspective illusion. So, it is considered the most hazardous driving condition for all drivers leading to overreaction and mishandling and contributing to numerous accidents that are usually more severe and involve more vehicles compared to those under clear weather conditions. (Musk 1991; Abdel-Aty at al. 2011).

In the technology era by the emergence of the mixed traffic flow of non-automated vehicles and automated vehicles of different automation degrees, several companies such as Waymo continuously improve radar, LiDAR, cameras, and various types of sensor technologies used for visibility and navigation purposes to compensate for their shortcomings(Vargas et al. 2021) while driving under adverse weather conditions such as foggy situations by introducing a new generation of sensors such as radars with see-through fog ability to make navigation of AVs under all driving conditions even under impaired visibility possible (Waymo 2021). Hence having a thorough understanding of the behavior of self-driving vehicles and simulating their presence of them in a state-of-the-art traffic simulation model could help ITS technology designers and traffic engineers.

The current research aimed to address the impact of aggressive driving behavior resulting from the fog on fuel consumption, NOx and CO emission and evaluate how different penetration rates of AVs in a mixed traffic flow with traditional vehicles could contribute to the enhancement of the traffic network mobility and exhaust emissions reduction under various weather conditions.

LITERATURE REVIEW

The influence of fog on visibility, headway distance, collision risk, road capacity, and vehicle speed selection, has been evaluated through various approaches in several papers. A number of previous studies have also investigated the changes in driving behavior due to foggy conditions and other adverse weather events using either driving simulators or other sophisticated microsimulations and mathematical models.

The findings of (Moore and Cooper 1972) showed that the main reason for rear-end crashes while driving in foggy weather is that drivers usually drive at a similar speed and driving pattern as their leading vehicle. Another study conducted through a multi-approach survey in Florida concluded that low visibility in foggy condition make drivers take shorter headways from the lead vehicles. (Hassan et Al). Kun Gao et.al summarized the impact of impaired visibility level due to hazy conditions in higher speed variance as well as collision risk and lower distance and headway time compared to clear weather. (Chen et al. 2019) proposed a combination of a driving simulator and Vissim traffic simulation to establish a bridge between driving behavior and traffic flow and calibrated the Wiedemann99 model for ten adverse weather. (khan et al. 2018) investigated the impact of fog on traffic performance, drivers' behavior, and speed selection using the Strategic Highway Research Program (SHRP2) Naturalistic Driving Study (NDS) dataset and reported 10% and 3% speed reduction under near fog and distant fog respectively. (Hammit et al. 2019) calibrated the Wiedemann 1999 car-following model for 1,206 SHRP2 NDS trips and then identified car-following model parameter values (CC0-CC9) for conventional vehicles under seven various weather conditions to simulate the adverse weather conditions in PTV Vissim software interface.

Most of the existing literature on Autonomous Vehicles (AVs) has addressed their potential benefits on traffic flow, travel safety, energy consumption, and emission. (Massar et al.2021) presented a review of studies investigating the reduction of GHG emissions at different levels of vehicle automation.

A few of them recommended values to simulate the driving behavior of automated vehicles in PTV Vissim software efficiently. (Zeidler et al.2019) analyzed the data from two Automated Vehicles that know two automated longitudinal control systems CACC and dCACC and recommended settings for their following behavior. (Rezaei et al. 2021) optimized human driving behavior and defined parameters for simulating AVs in Vissim software.

A handful of studies have focused on the impact of adverse weather conditions on the technology of self-driving vehicles. (Zang e al. 2019) introduced different types of sensing technologies and mentioned the impact of fog, rain, and snow on the performance of each technology.

Considering the fact that 27% of total US greenhouse gas emissions result from the transportation sector (EPA 2020) which leads to global warming and climate change, this study will help in gaining insights into how driving conditions influence the behavior of Human-driven and Self-driving vehicles and consequently the air quality and environment

METHODOLOGY

Microsimulation Software

Thanks to the traffic microsimulations, assessing the impact of different variables and driving conditions on driver behavior, the performance of a traffic network and the environment will be possible. PTV Vissim microsimulation software 2020 is utilized for this study to:

1. Model the traffic network
2. Adjust the driving behavior parameters for Traditional Vehicles (TVs) and Autonomous Vehicles (AVs) under clear sky (baseline scenario) and foggy condition
3. Simulate a mixed traffic flow of TVs with different penetration rates of AVs
4. Calculate the fuel consumption, NOx, and CO emission of Traditional Vehicles (TVs) and Autonomous Vehicles (AVs) under a clear sky and foggy condition scenarios

Vissim Model

The fundamental diagram was modeled for a real road network in Saratoga Springs, Utah, USA (fFigure.1) in Vissim and a node was defined to direct the scope of the study toward the intersection of two five-lane arterials, Redwood Road (north-south road) & Pioneer Crossing (east-west road) with the traffic volumes of above 30,000 vehicles/day and a great number of accelerations change events (Figure. 2). The highest traffic volume in Saratoga Springs happens on the southbound of redwood Road moves regional traffic through town and has a posted speed of 50 mph (80km/h). So, the desired speed for the baseline scenario was set to 80km/h and the volume of approaching vehicles was extracted from Utah Automated Traffic Signal Performance Metrics (ATSPM).

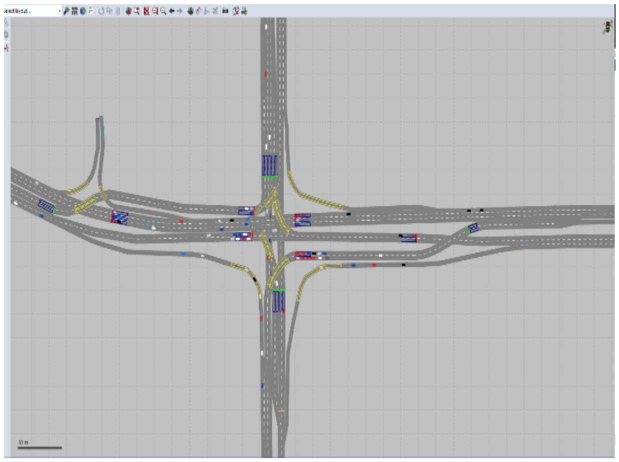


Figure. 1. Intersection Model-PTV Vissim Software

Figure. 2. Study Site (Google map)

Scenario Description

Two scenarios of Clear-Sky (baseline scenario) and Fog were defined in PTV Vissim software to compare and analyze the behavior of drivers and emitted emissions. In each of these two scenarios, the proportion of AVs increased by 30% from a completely traditional network to a network occupied 90 % by AVs (0%, 30%, 60%, 90%) intending to investigate the contribution of automated vehicles to fuel consumption- and emission reduction by changing the traditional driving pattern to Eco-Driving.

Calibration of Car-following behavior

To develop a weather-dependent microsimulation model in PTV Vissim software, the advanced psychophysical car-following model “Wiedemann’s 99”, was selected over” Wiedemann’s 74” to flexibly control the driving behavior parameters (CC0-CC9) and specifically simulate the driving condition in fog.
The behavior of Human-driven vehicles under a clear sky was simulated by using PTV Vissim default values for TVs. Also, driving under fog was modeled by calculating the ratio of optimal parameter values for the fog to the clear weather values which were proposed by (Hammit. et al. 2019) based on SHRP2 Naturalistic Driving Study data and applying these ratios to Vissim default parameters. Look ahead and look back distance for clear sky is based on Vissim suggested values and for foggy events it was extracted from visibility dataset available on Meso West website.
Table 1. illustrates parameter values used for adjusting the behavior of conventional vehicles also the definition of each parameter.

TV Model Parameter	Definition	Clear Sky	Fog
CC0	Standstill Distance(m)	1.5	1.5
CC1	Headway Time(s)	0.9	1.29
CC2	"Following” Variation(m)	4	4.06
CC3	The Threshold for Entering to “Following” Phase	-8	-7.12
CC4	Negative “Following” Threshold	-0.35	-0.35

CC5	Positive "Following" Threshold	0.35	0.43
CC6	Speed Dependency of Oscillation	11.44	14.8
CC7	Oscillation Acceleration(m/s2)	0.25	0.4
CC8	Standstill Acceleration(m/s2)	3.5	7.25
CC9	Acceleration at 80 km/h(m/s2)	1.5	3
look ahead distance	The distance that a vehicle can see forward	250	150
look back distance	The distance that a vehicle can see backwards	150	90

Table 1. Parameters for Calibration of Traditional Vehicles (TVs) in Vissim

Autonomous vehicles' behavior under a clear sky scenario was modeled by adjusting CC0-CC9 parameters based on suggested values by (Rezaei et al. 2021) and the calibration of their car-following model under fog was conducted by calculating the ratio of values for the foggy condition to clear weather from (Hammit. et al. 2019) article and applying these ratios to AVs values for a clear sky. Table 2. shows the parameters used for the calibration of self-driving vehicles.

AV Model Parameter	Definition	Clear Sky	Fog
CC0	Standstill Distance(m)	0.38	0.38
CC1	Headway Time(s)	0.45	0.64
CC2	"Following" Variation(m)	2	2.03
CC3	The Threshold for Entering to "Following" Phase	-8	-7.12
CC4	Negative "Following" Threshold	-0.35	-0.35
CC5	Positive "Following" Threshold	0.35	0.43
CC6	Speed Dependency of Oscillation	11.44	14.8
CC7	Oscillation Acceleration(m/S2)	0.25	0.4
CC8	Standstill Acceleration(m/s2)	3.5	7.25
CC9	Acceleration at 80 km/h(m/s2)	1.5	3
look ahead distance(m)	The distance that a vehicle can see forward	250	150
look back distance(m)	The distance that a vehicle can see backwards	150	90

Table 2. Parameters for Calibration of Autonomous Vehicles (AVs)

SIMULATION RESULTS AND DISCUSSION

The microsimulation model was calibrated and validated for 5400s (1h30min) from 4:00 pm to 5:30 pm; which is considered the peak hour in Utah (TomTom); with 900s (15min) warm-up time at the beginning and at the end of the simulation. The resolution of the simulation was set to 10 time-steps/simulation second and overall 8 simulation sets were run. (2 weather scenarios*4 AVs scenarios).

In terms of traffic flow, the findings of this study reveal that vehicles under foggy conditions have more stops which leads to more travel delays and longer queue lengths (Figure 3).

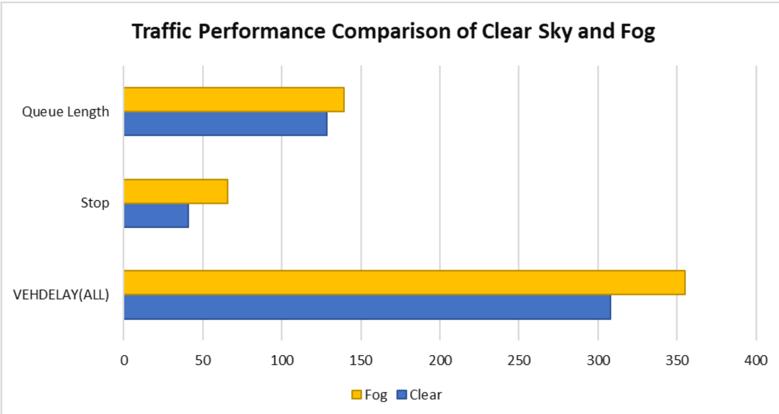


Figure 3. Comparison of traffic performance under clear and foggy weather conditions

A comparison between Vissim outputs for exhaust emissions and fuel consumption of Human-driven vehicles under limited visibility and clear sky conditions was illustrated in Figure 4. Higher amounts of vehicular emissions and fuel consumption in fog could be interpreted by aggressive driving, more stops, and severe reactions due to reduced visibility during the trip also by the overconfidence that stems from driving on the dry surface of the road.

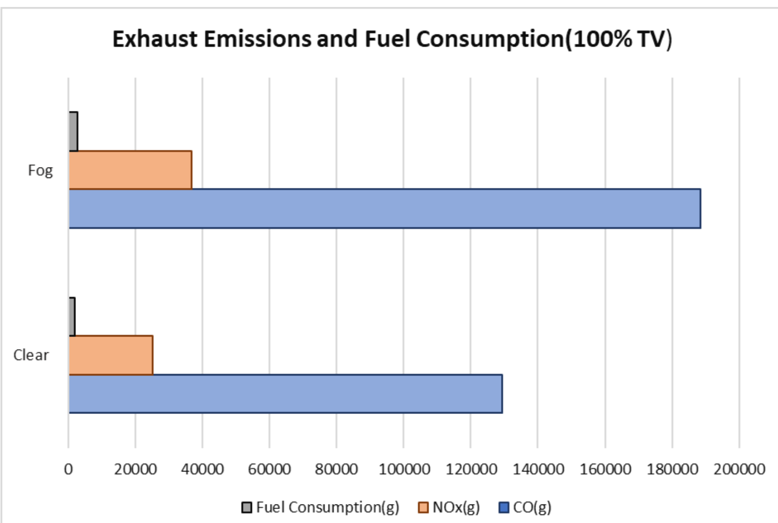
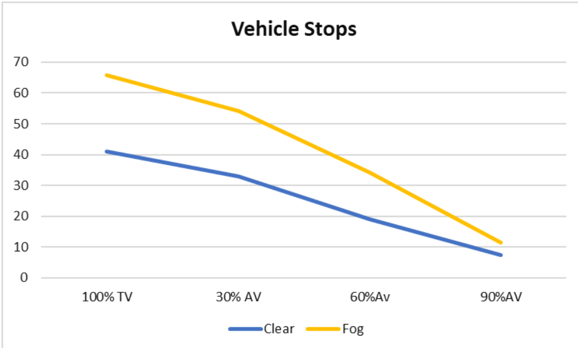


Figure 4. Comparison of CO, NOx and fuel consumption under clear and foggy weather conditions

According to Figure 5, incrementing the penetration rate of AVs by 30% from a traditional network with 0% AV and 100% TVs to a network with 90% AV and10%TV leads to an improvement in network mobility. With the presence of AVs in the modeled network, the number of stops decreased significantly (Figure. 5) and shorter queue lengths are observed (Figure. 6). To have a better understanding of how a gradual increase in the AVs' market penetration rate could result in smoother traffic flow by lowering the number of stops and queue length under adverse weather conditions it is worth mentioning that AVs with a 90% penetration rate could reduce the vehicle stops by 21% and vehicle delay 36% compared with 30% penetration level (Figure. 7).



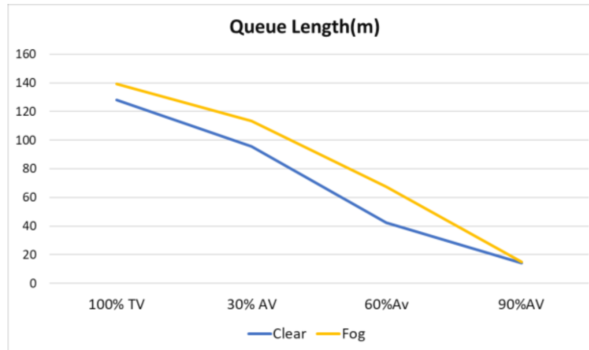
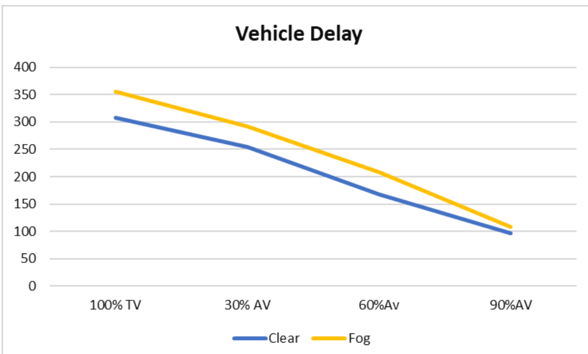


Figure 5. Vehicle Stops at different AV's PR   Figure 6. Queue length at different AV's PR



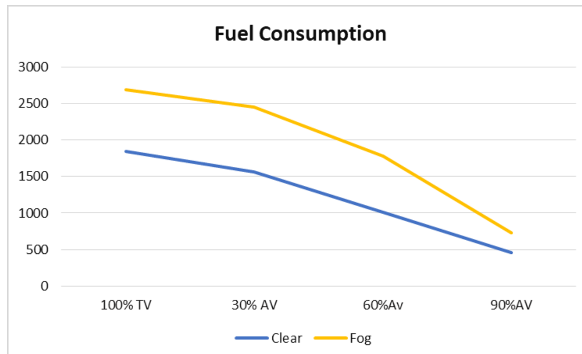
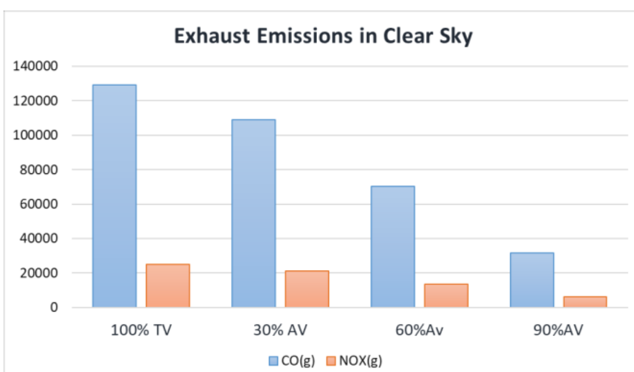


Figure 7. Vehicle Delay at different AV's PR   Figure 8. Fuel Consumption at different AV's PR

Analysis of the Vissim simulation results for emitted NOx and CO emissions in a mixed traffic flow of TVs and AVs under the baseline scenario (Figure 9) and foggy conditions (Figure 10) indicates that the increase in the proportion of AVs to TVs yields a greater decrease in vehicular emissions and more fuel saving, so that compared to a traditional traffic network (0% AV), in 90% penetration rate of autonomous vehicles 27% and 24% reduction in fuel consumption for clear sky and fog are recognized respectively.



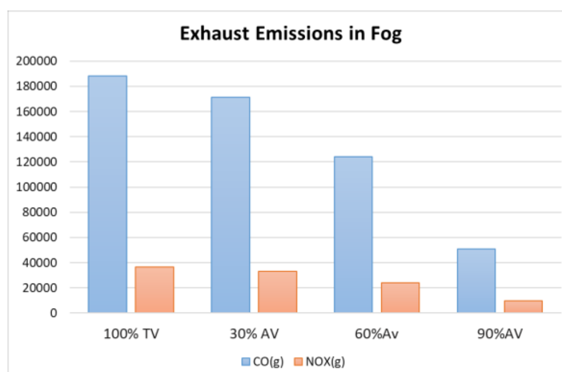


Figure 9. CO and NOx emissions under clear sky   Figure 10. CO and NOx emissions under fog

CONCLUSIONs

The present research study was undertaken to examine the impact of driving in fog on fuel consumption and exhaust emission of conventional vehicles and to investigate the potential for different penetration rates of fully- automated vehicles in reducing queue length, fuel consumption, and greenhouse gas emission under clear weather and fog scenario. A signalized intersection with a high volume of approaching vehicles in Saratoga Springs Utah was modeled as the base network of this study by defining a node in the traffic simulation software PTV Vissim, after that the traffic flow under the baseline scenario, and the fog was simulated by calibration of ten parameters of W99 car-following model, look ahead and look back distance for autonomous vehicles and traditional vehicles aligned with the related prior published studies by researchers in the transportation sector.

The negative effect of impaired visibility on driver behavior could be recognized from more vehicle delays, frequent stops, and longer average queue lengths. Higher amounts of CO, NOx emissions, and fuel consumption in the fog scenario reflect changes in driving behavior due to unpleasant driving conditions. The transition from a traditional network (100% TVs) to a 90% autonomous network through increasing the proportion of AVs by 30% in the Vissim software resulted in the overall improvement of traffic performance, fuel consumption, NOx, and CO emissions under two different scenarios, and results clearly indicate the significance of the penetration level of AVs in their operating efficiency.

This study illustrated the practice of PTV Vissim microscopic traffic simulation for the estimation of vehicular emissions at a congested intersection under two weather conditions and investigated traffic flow and air quality in the presence of autonomous vehicles, as subsystems of intelligent transportation on the road. The findings of this research validate the foggy condition as a cause of aggressive reactions in vehicles and it is aligned with the previous research works that discussed how aggressive driving behavior of vehicles on a road negatively affects safety, network efficiency, and environmental quality.

FUTURE WORK

In future research works the scope of the study on the environmental impacts of TVs and AVs will be enlarged by assessing the effects of limited visibility and slippery road surface due to snowy and rainy conditions on driving behavior and fuel consumption.

LIMITATIONS

Although traffic microsimulations have always been useful tools for conducting roadway studies under different scenarios and for predicting the traffic flow of automated and non-automated vehicles, it is of high importance to test the performance of autonomous vehicles under various real-world driving environments and conduct more research, particularly on their interaction with Human-driven vehicles and with the network under adverse driving- and weather conditions to acquire realistic data about their behavior and adjust AVs-related simulation parameters in accord with them.

Furthermore, it is worth mentioning that due to some limitations in PTV Vissim software for the simulation of autonomous vehicles' operation completely based on real-world electric self-driving vehicles, even more reductions in emissions will be expected. In other words, in the real-world AVs contribute to minimizing the emission further.

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