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ABSTRACT

Recent developments in autonomous vehicle (AV) or connected AVs (CAVs) technology have led to predictions that fully self-driven vehicles could completely change the transportation network over the next decades. However, at this stage, AVs and CAVs are still in the development stage which requires various trails in the field and machine learning through autonomous driving miles on real road networks. Until the complete market adoption of autonomous technology, a long transition period of coexistence between conventional and autonomous cars would exist. It is important to study and develop the expected driving behavior of future autonomous cars and the traffic simulation platforms provide an opportunity for researchers and technology developers to implement and assess the different behaviors of self-driving vehicle technology before launching it to the actual ground. This study utilizes PTV VISSIM microsimulation platform to evaluate the mobility performance of unmanned vehicles at a 4-way signalized traffic intersection. The software contains three different AV-ready driving logics such as AV-cautious, AV-normal, and AV-aggressive which were tested against the performance of the conventional vehicles, and the results of the study revealed that the overall network operational performance improves with the progressive introduction of AVs using AV-normal, and AV-aggressive driving behaviors while the AV-cautious driving behavior stays conservative and deteriorates the traffic performance.

Keywords: autonomous vehicles, micro-simulation, traffic-intersection, intelligent transportation system

1. INTRODUCTION

In recent decades, heavy traffic congestions in the major cities have become serious economic and environmental challenge around the world with a prediction that global urbanization is expected to encompass approximately 70% of the world population by 2050 [1]. Only in 2017, traffic-jam caused urban Americans to travel an extra 8.8 billion hours and purchase extra 3.3 billion gallons of fuel [2]. Recently, an INRIX global traffic scorecard report estimated that traffic congestion in 2021 cost the drivers almost $564 billion, an increase of $168 billion from 2020 in the USA only [3]. Hence, this implies that mobility convenience and improved traffic operations are major concerns for the existing transportation systems.

Over the past few years, the automobile and technology industries have been researching on producing autonomous vehicles (AVs) that have the potential to alter transportation systems by increasing road capacity, saving fuel, averting deadly crashes, and lowering emissions [4]. Several automobile companies have already started producing partial self-driven vehicles with features such as adaptive cruise control (ACC), lane departure warnings, collision avoidance, parking assistance, and on-board navigation [5]. However, at this stage, AVs are still in the process of development which requires various trails in the field and machine learning through autonomous driving miles on real road networks [6]. Until the complete penetration of unmanned vehicles, a long transition period of coexistence between conventional and automatic cars would exist. It is important to study and develop the expected driving behavior of future autonomous cars.

The microscopic traffic simulation platforms provide an opportunity for researchers and technology developers to implement and assess different ideas in a controlled setting without disrupting traffic conditions on the road [7]. Therefore, in this study, we have adopted the PTV VISSIM 2020 microscopic traffic simulation platform to analyze the impact of the

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expected driving behaviors of autonomous vehicles and their interaction with the conventional vehicles in the traffic network. The remainder of this paper is organized into three sections. Section 2 consists of the modeling of AV and test study setup into the VISSIM microsimulation platform. The discussion on the evaluation results is provided in section 3. Lastly, section 4 contains the conclusion of the study and recommendations for future research.

2. MODELING

The PTV VISSIM 2020 software models human driving behavior using a psychophysical car-following model which was first developed by Wiedemann in 1974 [8] and further enhanced in 1992 by Wiedemann and Reiter which is now called Wiedemann 99 (W99) car-following model [9]. The Wiedemann model decides how the following vehicle behaves based on the distance and difference of speed to the vehicle ahead. The model uses numerous random numbers, statistical distributions, and stochastic variations that ensure each car has different behavior in each time step [10]. The driving behavior of humans is naturally distributed which essentially means that each driver has different driving capabilities for perception, reaction, and estimation of the surrounding traffic environment, safety needs, desired speed, and aggressiveness towards maximum acceleration/ deceleration values [9]. Similarly, the same principle applies to the vehicle's ability in exercising basic features such as maximum speed and maximum acceleration/ deceleration. The VISSIM 2020 version contains several tools that can be used to model the expected driving behavior of AVs that are developed under the CoEXist study [11]. The CoEXist is a European Commission funded project which prepares the concerned authorities for a transition phase during which both the automated vehicles and the conventional vehicles will co-exist on the roadways, and this project has simulated real examples of AVs in four European cities such as Milton Keynes-UK, Stuttgart-Germany, Gothenburg-Sweden, and Helmond-Netherland [12].

In order to model the behavior of AVs into VISSIM software, the spread of values for individual vehicles is reduced for several functions such as desired acceleration, desired deceleration, maximum acceleration, maximum deceleration, and speed distribution since it is expected that AVs will have deterministic behavior unlike the stochastic behavior of human drivers [13]. Figure 1 shows that the human-driven vehicles have a large spread of values for the maximum acceleration and AVs have a linear distribution of values and the same consideration can be made for the desired speed, acceleration, and deceleration. Additionally, the VISSIM 2020 lets a user set different desired safety distances (i.e. CC0 and CC1 for Wiedemann 99) for each vehicle class of the leading vehicle so that AVs will follow each other with closer safety distance unlike an AV would follow a conventional vehicle with higher safety distance [14].

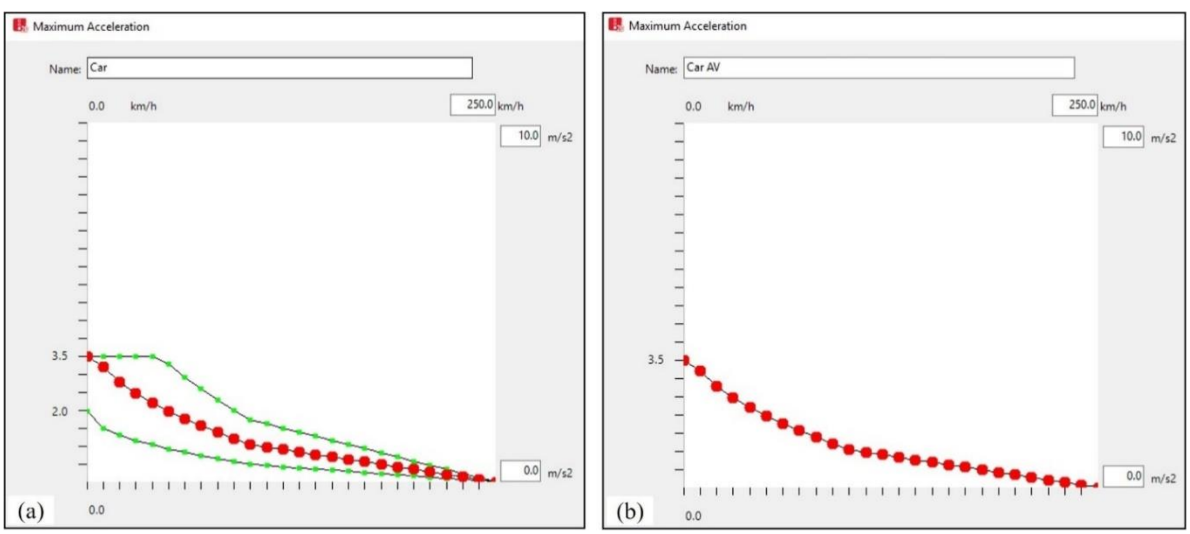

Figure 1. Maximum acceleration function (a) human-driven vehicles (b) autonomous vehicles

The CoEXist project also introduces three AV-ready driving logics in VISSIM 2020 under driving behaviors such as cautious, normal, and aggressive. Each driving logic uses different parameters for the W99 car-following model, lane-change, and following behaviors. The cautious driving vehicle maneuvers in a safe manner at all times and maintains larger headways as compared to the default driving behavior. The normal driving vehicle behaves similar to the default driving behavior; however, it can sense the vehicle's distance to other vehicles in the range and their real-time speed. The aggressive driving vehicle is "all-knowing" of the entire traffic situation, equipped with traffic situation prognosis, and maintains a minimum gap to other vehicles [15]. The description of significant driving parameters of the VISSIM default human-driving behavior and the three built-in AV driving logics are provided in Table 1. The complete details and guidelines for each of the W99 driving parameters are provided in the PTV VISSIM 2020 user manual [14].

Table 1. VISSIM driving parameter for conventional and autonomous vehicles.

VISSIM Parameters	**Default**	**AV-cautious**	**AV-normal**	**AV-aggressive**
a) Following behavior				
Max. look ahead distance (m)	250.0	250.0	250.0	300.0
Number of interaction objects	4	2	2	10
Number of interaction vehicles	99	1	1	8
b) Car-following (Wiedemann 99)				
CC0 (Standstill Distance)	1.5	1.5	1.5	1.0
CC1 (Headway Time)	0.9	1.5	0.9	0.5
CC3 (Threshold for Entering Following)	-8.0	-8.0	-8.0	-6.0
CC8 (Standstill Acceleration)	3.5	3.0	3.5	4.0
CC9 (Acceleration at 80 km/h)	1.5	1.2	1.5	2.0
c) Lane-change				
Necessary lane change - max. deceleration (m/s^2) for own vehicle	-4.0	3.5	-4.0	-4.0
Necessary lane change - max. deceleration (m/s^2) for trailing vehicle	-3.0	-2.5	-3.0	-4.0
Necessary lane change - 1 m/s^2 per distance (m)	100.0	80.0	100.0	100.0
Necessary lane change - accepted deceleration (m/s^2) for own vehicle	-1.0	-1.0	-1.0	-1.0
Necessary lane change - accepted deceleration (m/s^2) for trailing vehicle	-1.0	-1.0	-1.0	-1.5
Safety distance reduction factor	0.6	1.0	0.6	0.8
Max. deceleration for cooperative braking (m/s^2)	-3.0	-2.5	-3.0	-6.0
Cooperative merging	No	No	Yes	Yes
d) Autonomous driving				
Enforce absolute braking distance	No	Yes	No	No

2.1 Network setup

The VISSIM network consists of a 4-way intersection in an urban area that serves as a major connection between Albertville and St. Michael cities in the state of Minnesota, USA. It is a signalized intersection consisting of two through lanes, one dedicated left-turn lane, and one dedicated right-turn lane in the northbound and southbound directions and one through lane, one dedicated left-turn lane, and one dedicated right-turn lane in the eastbound and westbound directions near the traffic intersection. For the mobility performance evaluation of the network, we introduced two network objects including a "node" at the intersection, and "queue counters" at the stop line near the traffic intersection on each traffic approach to record vehicle delays and queue lengths at the traffic intersection as shown in Figure 2.

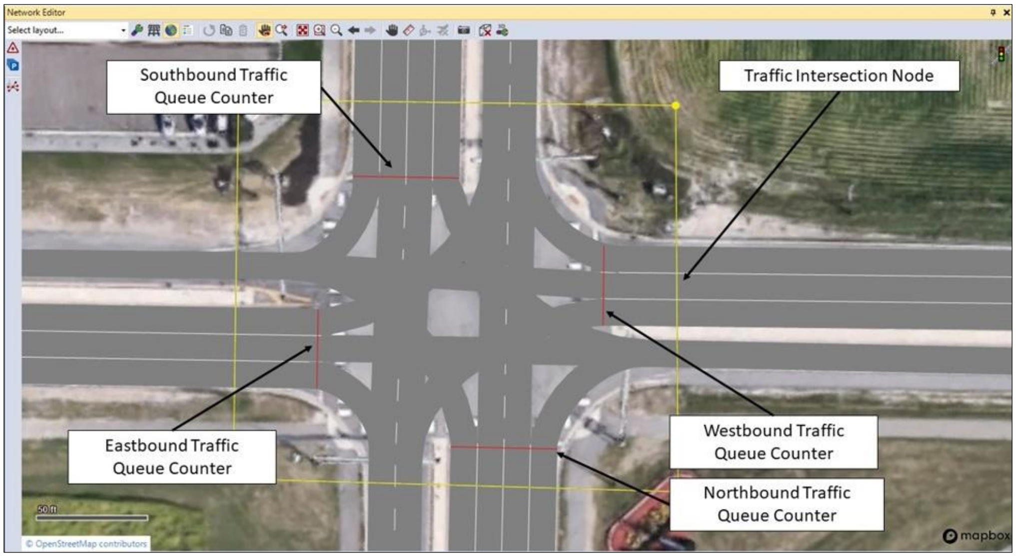

Figure 2. VISSIM model with traffic intersection node and queue counters.

The traffic signal control strategy at the intersection consists of a four-phase signalized intersection control with two through phases and two protected left-turn phases. The right-turning vehicles were provided during permitted phases such that right-turn vehicles must yield to the right-of-way of the through traffic streams. The priority rules for the conflicting movements and the reduced speed areas were also defined in the model to more accurately reflect actual vehicle movements. The posted speed limits on each traffic approach were used in the model for defining the speed of conventional and autonomous vehicles. On each traffic approach, 800 passenger cars/hour/lane was used as vehicle input volume. Further description and breakdown of vehicle input volume/hour are presented in Figure 3.

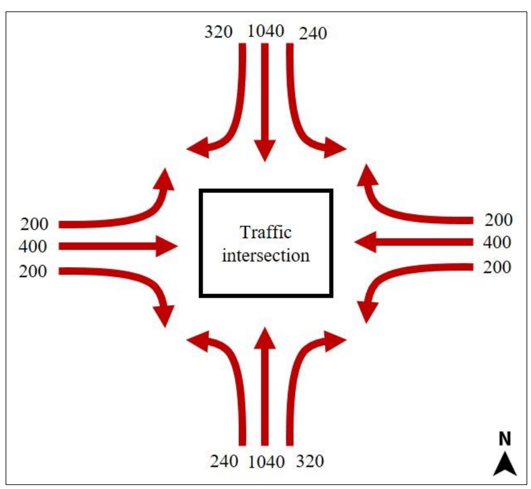

Figure 3. Hourly vehicular volume breakdown for the selected 4-way traffic intersection.

2.2 Simulation configuration for evaluation

The settings of VISSIM simulation parameters have a great influence on the simulation results. Different sets of values create variation in the output results and hence generate stochastic distributions. For mobility performance evaluation, a simulation period of 5400 s is selected in which the initial warm-up period of 900 s and final cooling-down period of 900 s are excluded from simulation evaluation. The warm-up and cooling-down periods are excluded from the simulation considering that at the start of a simulation, the network is empty which may lead to faulty results because of no congestion and hence providing a warm-up period would allow vehicles to occupy the network in advance before conducting the actual simulation analysis and similarly a cooling down period would help in eliminating the remaining queues or bottleneck in the network [16]. This simulation setting is incorporated by running 10 simulations for each sensitivity test as the minimum requirement defined by the Oregon Department of Transportation (ODOT) [17].

2.3 Sensitivity test setup

In this study, the sensitivity of the VISSIM default driving behavior using the Wiedemann 99 model was analyzed as a reference for comparison. To evaluate the mobility performances of the CoEXist project driving behaviors, nineteen simulation tests were performed. Among the nineteen sensitivity tests, one of the analysis cases was performed using only conventional vehicles, six analysis cases consist of conventional and AV-cautious vehicles, six cases consist of conventional and AV-normal vehicles, and six cases consist of conventional and AV-aggressive vehicles. Further description of each sensitivity test is provided in Table 2.

Table 2. List of all sensitivity tests

S No.	Vehicle Composition	Description of Tests	No. of Sensitivity Tests
1	Conventional Vehicles	It consists of 100% conventional vehicles.	1
2	Conventional Vehicles + AV-cautious Vehicles	It consists of AV-cautious and conventional vehicles with a market penetration rate of AV-cautious vehicles ranging from 15% - 90% at an interval of 15%.	6
3	Conventional Vehicles + AV-normal Vehicles	It consists of AV-normal and conventional vehicles with a market penetration rate of AV-normal ranging from 15% - 90% at an interval of 15%.	6
4	Conventional Vehicles + AV-aggressive Vehicles	It consists of AV-aggressive and conventional vehicles with a market penetration rate of AV-aggressive vehicles ranging from 15% - 90% at an interval of 15%.	6

3. RESULTS & DISCUSSIONS

VISSIM provides several parametric results after each successive simulation run for evaluating the performance of a network. This study reports average vehicle delay at the intersection and average vehicle queue lengths on each traffic approach for operational performance analysis of the signalized intersection [18]. Vehicular delays at the traffic intersection gradually decreased with the increasing penetration rate of autonomous vehicles using the AV-normal and AV-aggressive driving behaviors, resulting in operational performance improvement of approximately 14 % for AV-aggressive and approximately 6 % for AV-normal driving behaviors at 90 % market penetration rate as shown in Figure 4. The AV-cautious driving behavior is conservative as compared to the W99 model, hence resulting in higher traffic delays for the increasing market penetration rates.

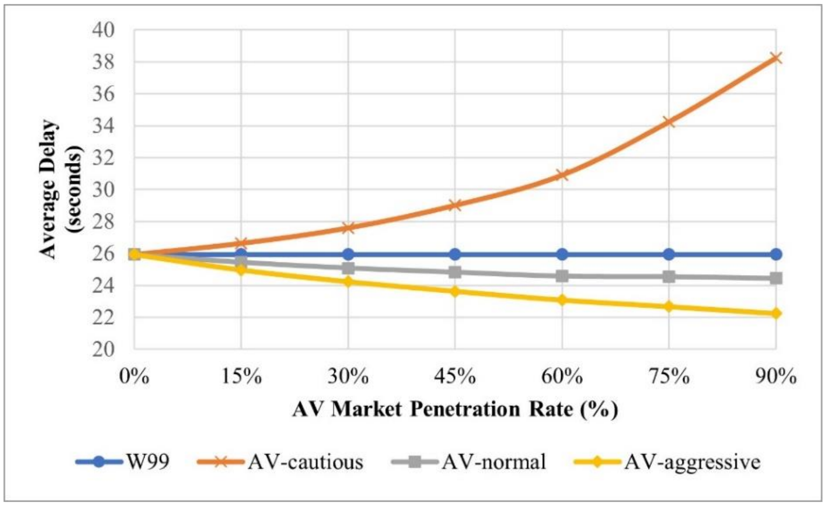

Figure 4. Sensitivity results of average vehicle delay at the traffic intersection

The results of the 190 simulation runs conducted for the queue length evaluation along the major (northbound and southbound) and the minor (eastbound and westbound) directional traffic showed a continuous decrease in average queue lengths with the progressive introduction of AV-aggressive and AV-normal vehicles into the mixed traffic as shown in Figure 5. The AV-normal behavior is modeled similar to the W99 model but due to its deterministic nature, the vehicular queue length started to decrease with as little as 15% AV market penetration reaching a maximum of 8.5% for major direction and 6.6% for lesser traffic minor direction at 90% AV market penetration rate. Due to the more aggressive driving behavior of AV-aggressive vehicles, considering smaller headway and reduced following distance, the queue length results were further improved to approximately 28% in the northbound and southbound traffic direction and approximately 18% in the eastbound and westbound direction at 90% market penetration rate. The network performance deteriorated with the introduction of AV-cautious vehicles, the average queue lengths increased between 2.4% to 11% for major direction and between 2.4% to 60% for minor direction at 15% to 90% penetration rates respectively. This is due to the conservative behavior of the AV-cautious vehicles as explained in the previous section.

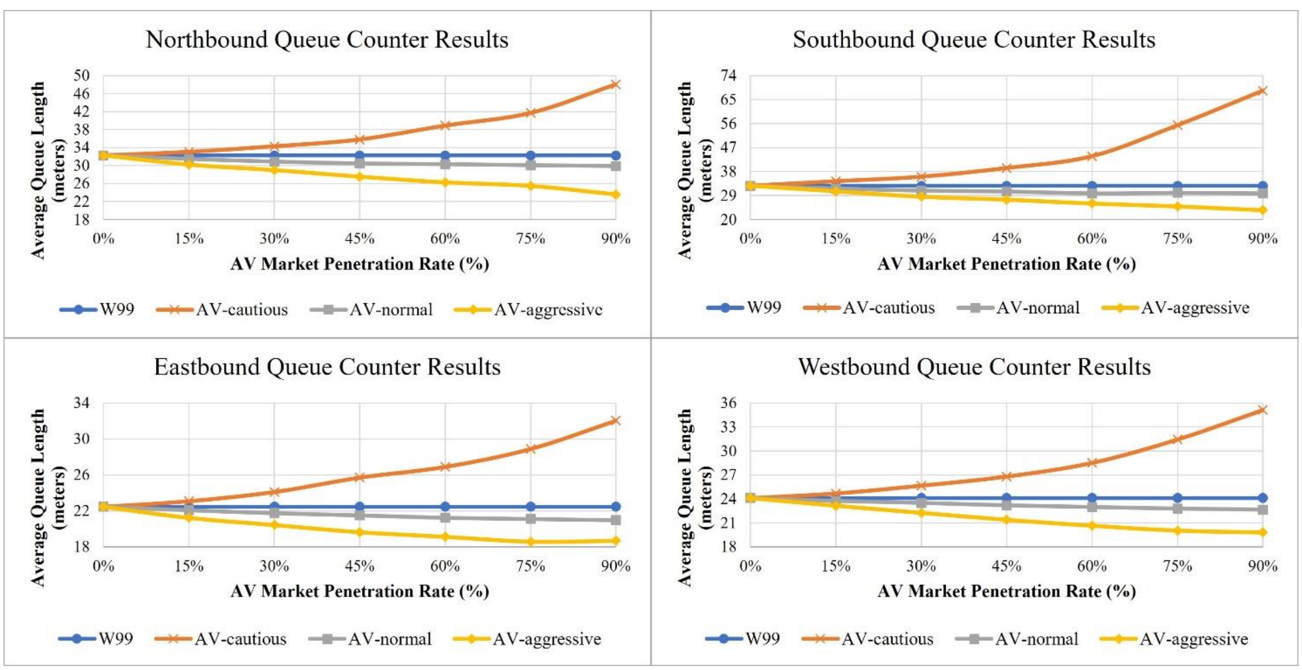

Figure 5. Sensitivity results of average queue lengths at the traffic intersection

4. CONCLUSION & RECOMMENDATIONS

This study evaluated the operational performance of autonomous vehicles at a signalized traffic intersection in a mixed traffic environment. Since it is uncertain what features and driving capabilities future self-driven vehicles will contain, it is necessary to analyze different potential driving behaviors of connected and autonomous vehicles. In this essence, the VISSIM microsimulation platform was utilized to compare the impact of three AV-ready driving behaviors i.e. AV-cautious, AV-normal, and AV-aggressive on traffic mobility. The results of the study revealed that the progressive introduction of unmanned vehicles using a normal or aggressive driving behavior consisting of shorter headway and smaller following distance will significantly improve signalized traffic intersection operational capacity. However, the network performance deteriorates when cautious driving behavior is penetrated into the traffic stream resulting in increased vehicle delays and longer queue lengths. This is expected since the cautious vehicle maintains a larger safety gap as compared to the conventional human-driven vehicle and when the penetration rate increases, the desired safety gap between vehicles creates a reduction in the network capacity.

This study recommends the use of connected and autonomous vehicles for improving the mobility performance of the vehicular transportation systems. This approach is a potential tool for solving the existing problems of traffic delays, travel costs, driver's stress, and traffic accidents. The benefits of self-driven vehicle technology are possible when higher market penetrations of AVs are available into the traffic stream. Hence, early investing in this technology would enable safe and convenient mobility options. The simulation platforms provide an opportunity for researchers and technology developers to implement and assess the idea before launching it to the actual ground. Therefore, the use of a simulation platform such as VISSIM is highly recommended at the initial period where the concept is in the evaluation stage.

This study has implemented the autonomous vehicle logics that exist within the VISSIM software for a basic urban traffic intersection. However, other control conditions such as merge, diverge, weaving, and ramp control are not considered. The implementation of the proposed logic requires further sensitivity studies to investigate a larger road network consisting of multiple traffic intersections and several road segments to achieve better results for introducing autonomous vehicles in higher penetration in the traffic. Additionally, the traffic is composed of private vehicles only with no heavy vehicles so the inclusion of trucks and other heavy goods vehicles in the network would have an impact on the mobility performance of the proposed logic.

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