Impact of Urban Arterial Traffic LOS on the Vehicle Density of Different Lanes of the Arterial in Proximity of an Unsignalized Intersection for Autonomous Vehicle vs. Conventional Vehicle Environments

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ABSTRACT

Traffic congestion is known as one of the serious global problems the transportation systems face due to the rapid urbanization in large cities. Traffic congestion is undesirable as it imposes a major cost on the users and economy and causes significant reductions in traffic flow. The congestion problem is even more serious on urban arterials especially near driveways and unsignalized intersections' locations where vehicle movements are subject to drivers' judgment. Application of active traffic management (ATM) strategies is the common way to overcome the operational and safety challenges associated with congested urban arterials. Yet, the rapid increase in people movements to urban areas is becoming beyond the management capabilities of traditional ATM strategies. The emerging Autonomous Vehicle (AV) technology offers ample opportunities to overcome the ever growing congestion problem, hence supplement and/or replace traditional ATM strategies. This study investigates the benefits of AVs for congestion management at driveway locations on urban arterials. The impact of AVs on the traffic density of each lane of an urban arterial in close proximity of a driveway is assessed in this study. The Highway Capacity Manual (HCM) defined Level of Service (LOS) measure is used as a boundary to assess the impact of AVs under different traffic congestion levels. Eight separate traffic simulation models are developed for two scenarios (conventional vehicle environment and AV environment). The results indicated that AVs have a superior capability in relieving traffic congestion significantly in the vicinity of a driveway in moderate LOS. This performance is achieved by the AVs capability to distribute vehicles evenly across lanes which helps redistribute gaps along the arterial section, hence allows vehicles from the driveway to merge more smoothly to the arterial. These findings indicate that transforming into an AV network can provide an optimal access point management and allow a better accessibility to adjacent land-uses and facilities.

KEYWORDS: Density; Driveway; Volume; Automated Vehicle; Access Management; Gap Distribution

INTRODUCTION

Traffic congestion is a monotonically increasing problem due to the rapid urbanization, motorization, and population growth. Traffic congestion leads to a significant increase in travel time, fuel consumption, air pollution, stop delay, and economic losses, in addition to users fatigue and frustration (Access Management Manual 2014; Al-Kadi et al. 2014; Tyagi et al. 2012). Generally, Traffic congestion could be attributed to various factors, such as limited road capacity, sudden increase in demand levels, adverse weather conditions, and traffic incidents (Al-Kadi et al. 2014). Among the leading causes of traffic congestion is the poorly designed roads, in addition to the drivers' behavior, which could lead to an uneven distribution of traffic across lanes and intensifies traffic congestion (Barrachina et al. 2015). For instance, urban arterials that are characterized by high traffic volume and closely spaced signalized and unsignalized intersections are more prone to formation of traffic congestion due to the high traffic demand for either entering or exiting adjacent land uses (Federal Highway Administration 2010; Khan et al. 2017). This high demand causes aggregation of traffic volume and result in high traffic densities in the proximity of access points.

Due to the adverse effects of traffic congestion, public agencies constantly work to alleviate the traffic pressure (Barrachina et al. 2015). A traditional solution to mitigate traffic congestion has been through capacity expansion. However, this is very often no longer a feasible option because of the lack of space or the associated high cost of such a solution (Ajitha et al. 2013). Additionally, capacity expansion is a paradoxical solution as it may induce more demand and traffic congestion such that even a major network capacity expansion may not eventually lead to density reduction (Graham et al. 2014). Recently, the state-of-practice focuses on operational tools to improve the performance of the existing infrastructure, instead of expanding the infrastructure. Application of Intelligent Transportation System (ITS) and Active Traffic Management (ATM) is acknowledged as an efficient means of managing the transportation system that relies on provision of real-time traffic data, such as traffic congestion, to assist road users through choice of speed, route, or departure time (Ajitha et al. 2013). Vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications are two forms of ITS that can help provide information to road users about the surrounding environment. Combination of both V2V and V2I, also known as V2X, is capable of providing real-time data about the traffic conditions to predict travel time and improve transportation mobility and safety (Liu et al. 2007; Ma et al. 2009; Ma et al. 2012).

Urban arterials play a fundamental role in serving and connecting the urban activity centers and carrying high traffic volumes. Generally, urban arterials are characterized by high traffic demands and closely spaced signalized and unsignalized intersections to provide access to the adjacent land-uses. This operational scheme lead to more traffic congestion, conflicts, and operational and safety concerns (AASHTO 2011; Federal Highway Administration 2010; Khan et al. 2017). While V2X offer several benefits that may improve the operational characteristics of such arterial locations, they may suffer from compliance issues that may limit these benefits. Autonomous Vehicles (AVs) on the other hand have the potential to overcome the driver compliance issue and eliminate drivers' judgement from the equation. Thus, the focus of this study is to evaluate the operational benefits of AVs in urban arterials near unsignalized intersections. In doing so, a simulation model is developed to evaluate the performance of fully automated systems compared to conventional vehicle environments in different levels of service.

LITERATURE REVIEW

The literature is rich of various studies focusing on the benefits of access management and ATM strategies at different demand levels. Evaluation of management strategies such as direct left turn (DLT) and right-turn followed by U-turn (RTUT) showed that the efficiency of access management is very location and traffic condition specific (Chowdhury et al. 2005; Liu et al. 2007). For instance, on multilane divided arterials, DLT is advantageous over RTUT and reduces the network delay when the arterial volume is less than 650 pc/hr/lane (Chowdhury et al. 2005). On the other hand, Liu et al. (2017) proved that increasing the volume of both through traffic (1000-6000 pc/hr) and left-turns from driveways (50-150 pc/hr) improve the performance of the RTUT. Assessing different scenarios under the connected vehicle (CV)-supported dynamic access control showed an improvement in operation while implementing right-in-right-out instead of fully open driveways (Khan et al. 2018).

Yang et al. (2016) evaluated the delay of an isolated signalized intersection under various traffic conditions. The study evaluated the effect of conventional, connected, and automated vehicles on the operation of an isolated signalized intersection. Different total flows, demand ratios, and market penetration rates were simulated, and the operational performance was compared for an actuated signal control algorithm and a proposed algorithm for connected vehicles. The results indicated that proposed algorithm improved the operational characteristics of the intersection. Sun et al. (2017) proposed an intersection operation algorithm, called maximum capacity intersection operation scheme with signals, in which the intersection capacity is to be maximized by using all the available lanes simultaneously in addition to optimizing signal green time dynamically. The results indicated that this approach could double the capacity of an intersection.

In a recent study, the benefits of AVs were evaluated in comparison with conventional vehicles in terms of network operation. The results revealed the positive effect of AVs on the network, especially when the network is congested, e.g., peak period. Moreover, the capacity, speed, and travel time of the network improved when AVs were implemented (Aria et al. 2016). Hoogendoorn et al. (2014) analyzed the effect of automation on traffic flow efficiency and indicated that even though AVs can positively influence traffic flow in the future, the impact of roadway users should not be neglected. Depending on the level of automation, the effect of AVs' drivers and also the behavior of drivers of conventional vehicles in the vicinity of AVs impact the performance of AVS and as a consequence traffic flow.

Although AVs are known to be beneficial and influence daily travel significantly, many studies believe that the system-level effects at low market penetration rate will be minimal. Talebpour et al. (2017) explored the outcomes of reserving a lane for autonomous vehicles on travel time reliability and traffic flow dynamics. Evaluation of three different scenarios including a. Mandatory use of the reserved lane by AVs; b. Arbitrary use of the reserved lane by AVs; and c. Limiting AVs to operate autonomously in the reserved lane indicated that the optional use of the reserved lane for AVs without imposing any limitation could improve the operation of the network and reduces traffic congestion.

To improve the operation of automated vehicles at freeway merging areas, Letter and Elefteriadou (2017) developed an algorithm to search for the best and optimized route for AVs to perform the merging maneuver. The results of evaluating a simulated merging segment indicated that the algorithm enhances traffic, compared to conventional vehicles, by reducing travel time and increasing travel speed for AVs. Also, it provides safe merging of the vehicles under the congested condition. A study evaluated the effect of vehicle automation on the capacity of the freeways. The results indicated a substantial improvement through implementing automated platooning could occur, compared to 1800-2200 vphpl for manually driven vehicles (Karaaslan et al. 1991). Vanderwerf et al. (2004) also studied the effect of automation on the capacity of freeways and showed a considerable improvement in capacity from 2100 vphpl to 2900 vphpl by implementing 20% Adaptive Cruise Control (ACC), 60% Cooperative ACC (CACC), besides 20% manual driven vehicles.

METHODOLOGY

The purpose of this study is to explore the impact of AVs on the operational characteristics of urban arterials near driveway locations under various traffic levels of service (LOS). A micro-simulation model was developed using VISSIM for a three-lane urban arterial with a one-lane driveway perpendicular as shown in Figure 1.

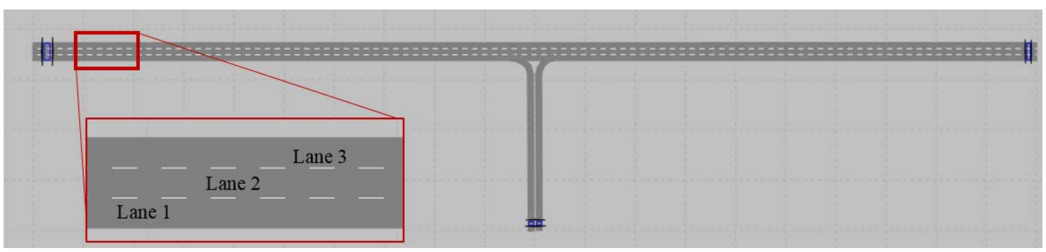

Figure 1. Simulated Roadway Network and Lane Numbers.

Four different LOS (A, B, C, and D) were implemented to assess the impact of AVs under various levels of traffic congestion. The traffic volume of the arterial was altered in each simulation run according to the predefined volumes for each LOS, given in Table 1, to represent each LOS. However, the volume of the driveway remained constant at 240 pc/hr/ln across all LOS scenarios and represent the maximum number of vehicles that could merge to the arterial from the most congested scenario, which was the conventional vehicle environment with LOS D. Table 1 depicts the traffic volumes associated with each LOS for both the arterial and driveway. Since the simulation was run for 10 minutes only, the traffic volumes shown in the table are adjusted to account for that.

Each LOS was simulated under two AV market penetration rates of 0% and 100%; examining the effects of different penetration rates for the AVs was beyond the scope of the study. The 0% AV MPR is the base scenario and represents a fully conventional vehicle environment. To develop the AV network, the VISSIM protocols and manual were used to obtain the associated AV characteristics such as headway, lane changing models, etc. (PTV VISSIM, 2018). Each scenario was run for 10 minutes considering the first minute as a warm-up period (given the speed limit of 45 mph and arterial length of 2000 ft.). Eventually, the evaluation results of the simulation runs were stored for every 50 ft section of the simulated segment and 0.1 seconds time interval. The 50 ft is selected as it is the required storage to accommodate two passenger cars and the spacing in between.

Table 1. Traffic Volume for Multilane Highways for Different LOS.

LOS	Maximum Service Flow Rate (pcphpl) (City/County Association of Governments of San Mateo County 2005)	Input Volume for the Major Road for 10 Minutes (pcpl)	Input Volume for Driveway for 10 Minutes (pcpl)
A	600	100	40
B	1,000	167	40
C	1,400	233	40
D	1,670	278	40

RESULTS AND DISCUSSION

The results of the microsimulation models were used to analyze the impact of AVs on the traffic density across lanes of the arterial under four different LOS, from A to D. The arterial was split into three equal segment lengths to represent upstream of the driveway, at the driveway, and downstream of the driveway segments.

Table 2 compares the traffic density of each lane of the conventional vehicle environment with its corresponding lane in the AV environment under LOS A. The table shows the percent of the times that the vehicle density exceeds 34 pc/mi/ln, which imply LOS E and LOS F (City/County Association of Governments of San Mateo County 2005).

Table 2. Percentage of the Times with Traffic Density Greater than 34 pc/mi/ln for LOS A for Conventional Vehicle and AV Environments.

Lane	**Upstream Segment**		**Driveway Segment**		**Downstream Segment**	
	Conventional Vehicle	AV	Conventional Vehicle	AV	Conventional Vehicle	AV
1	0.1	1.9	2.1	3.2	0.1	1.1
2	0.3	1.1	1.5	1.1	0.0	0.0
3	0.0	1.1	0.3	0.9	0.3	0.6

Based on the given table, even though the average density of most of the lanes and sections of the AV environment is higher than the conventional vehicle environment, the maximum percent of the times that the density exceeds 34 pc/mi/ln is not large enough to interfere with the operation of the network. Also, based on Table 3, the statistical analysis confirms that there is no significant difference between the density of the AV and conventional environments at 95% confidence interval.

Table 3. Statistical Analysis of AV vs. Conventional Vehicle Environments under LOS A.

Variable	**Value**	**Variable**	**Value**
Difference	0.25063	Confidence	0.95
Std Err Dif	0.13515	t Ratio	1.854384
Upper CL Dif	0.51554	DF	15733.62
Lower CL Dif	-0.01429	Prob > |t|	0.0637

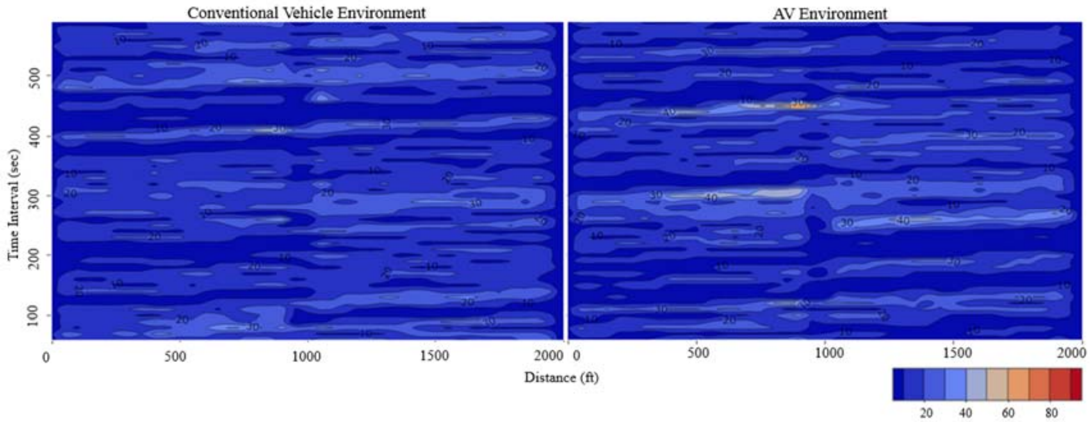

Figure 2. Vehicle Density for Lane One under LOS A.

Therefore, in low traffic volume condition, the conventional vehicles and AVs perform similarly. This is supported by the graphical representation of traffic density in Figure 2. The figure depicts the traffic density for lane one, which is the closest lane to the driveway, under LOS A in both fully conventional vehicle and AV environments.

Table 4 and Figure 3 display the performance of the AVs under LOS B. For the LOS B, as in LOS A, however the traffic density in the AV environment is often higher compared to the conventional vehicle environment, there is not a significant difference between each lane and segment of the conventional vehicle environment and its corresponding lane and segment in the AV network at 95% confidence interval, Table 5.

Table 4. Percentage of the Times with Traffic Density Greater than 34 pc/mi/ln for LOS B for Conventional Vehicle and AV Environments.

Lane	**Upstream Segment**		**Driveway Segment**		**Downstream Segment**	
	Conventional Vehicle	AV	Conventional Vehicle	AV	Conventional Vehicle	AV
1	6.3	7.3	10.3	12.6	5.6	6.8
2	6.0	7.0	7.8	11.6	4.6	9.0
3	3.7	5.4	9.9	5.3	9.7	5.8

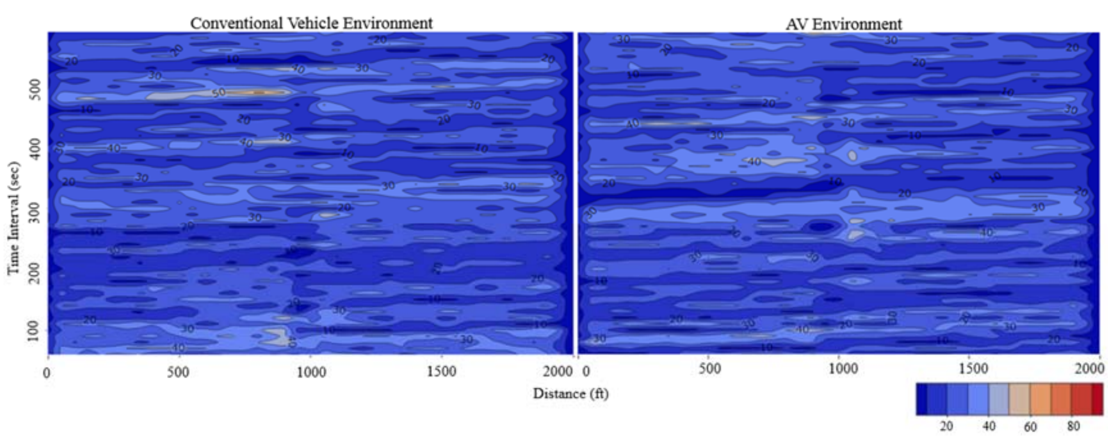

Figure 3. Vehicle Density for Lane One under LOS B.

Table 5. Statistical Analysis of AV vs. Conventional Vehicle Environments under LOS B.

Variable	Value	Variable	Value
Difference	0.01897	Confidence	0.95
Std Err Dif	0.18273	t Ratio	0.103824
Upper CL Dif	0.37715	DF	15597.55
Lower CL Dif	-0.33921	Prob > |t|	0.9173

Therefore, the pattern of the traffic density for the different lanes in low traffic volume conditions, LOS A and LOS B, is relatively the same and low for both the AVs and conventional vehicles. This similarity in the traffic density distribution in both scenarios is due to the presence of adequate gaps for the vehicles to perform their merging and lane changing maneuvers conveniently without interfering with the operation of the surrounding vehicles of the arterial.

When more vehicles are injected into the traffic stream, as in LOS C, different results can be observed. Table 6 shows the overall traffic density numerically for the conventional vehicle and AV networks. Based on the results, the conventional vehicle environment experienced more congestion compared to the AV environment. These results show improvements over all the lanes for the driveway segment and the downstream segment. However, the traffic density of the lanes of the conventional vehicle environment for the upstream segment is lower compared to the AV network. However, the density over the entire lane in various segments indicate 2.2%, 1.4%, and 2.6% reduction in the traffic density in the AV network over the lanes of 1, 2, and 3, respectively.

Table 6. Percentage of the Times with Density Greater than 34 pc/mi/ln for LOS C for AV and Conventional Vehicle Environments.

Lane	Upstream Segment		Driveway Segment		Downstream Segment	
	Conventional Vehicle	AV	Conventional Vehicle	AV	Conventional Vehicle	AV
1	35.3	35.2	47.9	44.3	31.2	28.3
2	31.2	31.9	46.0	42.0	36.6	35.6
3	28.6	31.1	38.0	32.9	34.2	29.1

Figure 4 depicts the traffic density of each lane for the AV MPRs of 0% and 100% under LOS C. Based on the figure, the vehicle density in the conventional vehicle environment increases significantly in the close vicinity of the driveway for all the three lanes and reaches up to 170 pc/mi/ln for the middle lane. However, in the AV environment, the vehicles are distributed more evenly across all the lanes and segments. Hence, the AVs perform better and provide a smoother traffic flow and operation, compared to the conventional vehicles, in the moderate traffic volume.

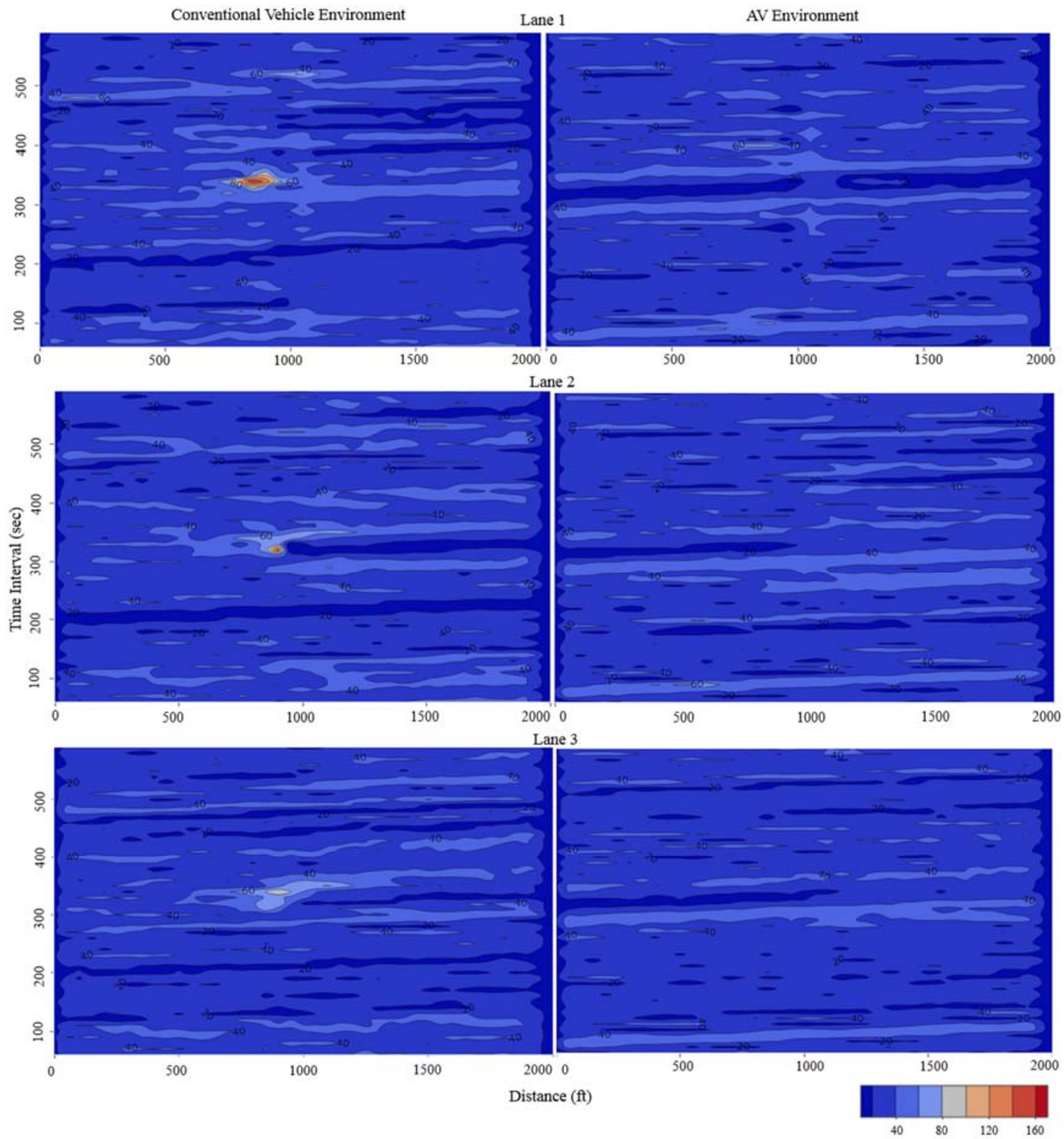

Figure 4. Vehicle Density under LOS C for Different Lanes along the Major Road.

Similar results are obtained for LOS D. Table 7 represents the percent of the times that the traffic congestion interferes with the smooth operation of the network.

Table 7. Percentage of the Times with Density Greater than 34 pc/mi/ln for LOS D for AV and Conventional Vehicle Environments.

Lane	Upstream Segment		Driveway Segment		Downstream Segment	
	Conventional Vehicle	AV	Conventional Vehicle	AV	Conventional Vehicle	AV
1	59.5	60.3	72.6	69.0	45.7	50.0
2	57.3	58.3	71.0	67.6	56.7	54.8
3	57.4	55.8	70.8	59.3	57.7	50.4

Figure 5 also depicts the traffic density variation over time for each lane of both conventional vehicle and AV roadway networks, graphically, for LOS D.

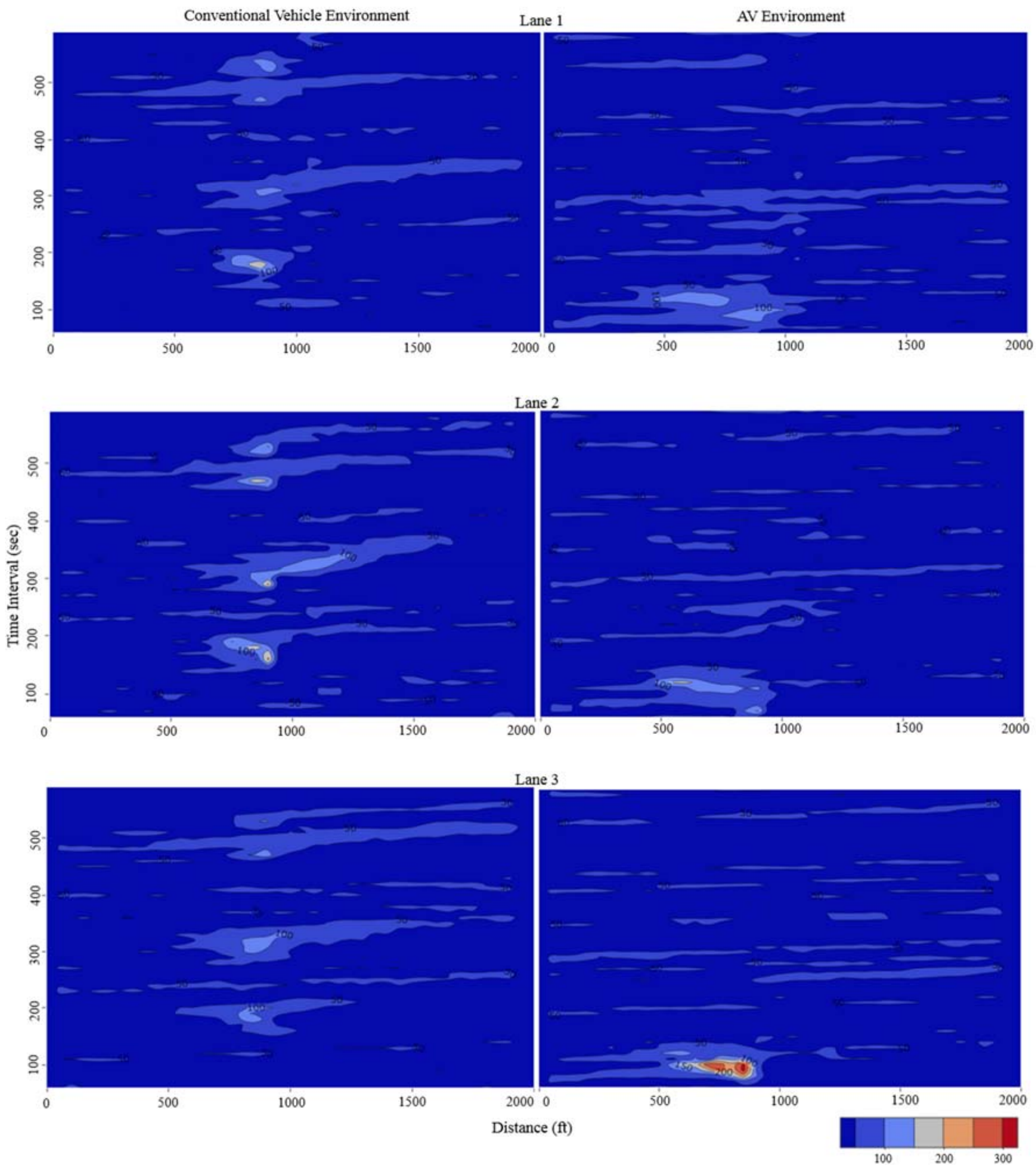

Figure 5. Vehicle Density under LOS D for Different Lanes along the Major Road.

The results of the LOS D display that the vehicle density for all the lanes for both conventional vehicle and AV scenarios is higher in the proximity of the driveway, compared to the other sections of the roadway. The higher spot density nearby the driveway is due to the high volume of the traffic on the arterial that prevents the driveway vehicles to enter and exit the driveway conveniently. In other words, unavailability of adequate spacing and acceptable gaps from the arterial hinders the vehicles from merging, diverging or even changing lane to avoid driving in the congested lane. Hence, the traffic interruptions occur, especially nearby the driveway. It is notable that there is no communication and cooperation between AVs to call for a gap to change lane and merge to the major road. Although the density around the driveway is higher in all the lanes for both scenarios, an improvement can be observed for the overall performance of the AVs, compared to the conventional vehicle network.

Figure 6 presents a summary of the performance of the conventional vehicles vs. AVs under LOS C and LOS D. As shown, the density of the driveway segment in the AV environment is lower for all the lanes and both LOS.

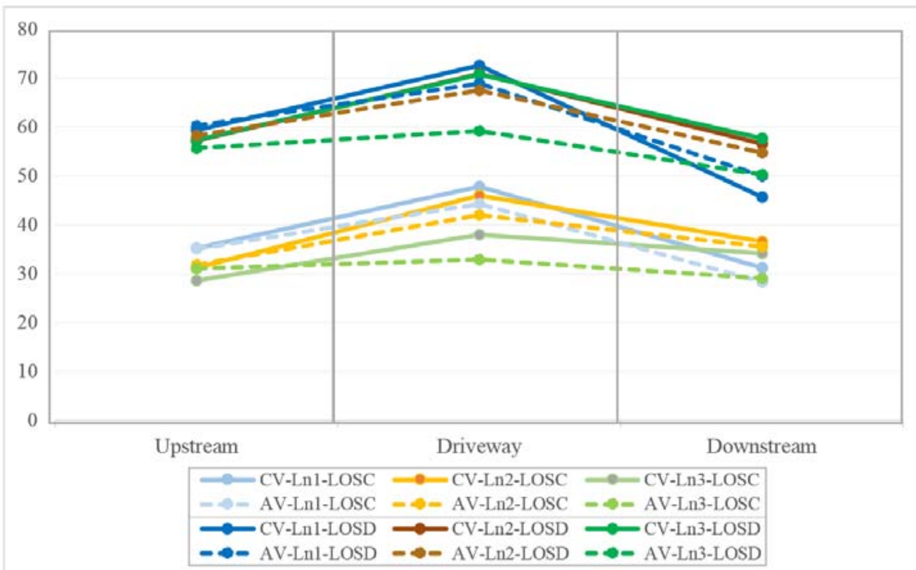

Figure 6. Percent of the Times with Traffic Blockage under LOS C and LOS D for in the Conventional Vehicle Environment vs. AV Environment.

CONCLUSIONS

Traffic congestion is a serious global problem in large cities and has been increasing due to the rapid urbanization. Traffic congestion leads to flow reduction and imposes a cost on the users and economy by increasing travel time, fuel consumption, air pollution, users fatigue, users' frustration, and stop delay. Urban arterials that are characterized by high driveway density and traffic volume are locations that are prone to safety and operational concerns. Therefore, this study investigated the effect of autonomous vehicles on the operational performance of the arterials in the proximity of the driveways by comparing the results to the base scenario of a fully conventional vehicle environment.

To this aim, a simulation model was developed and run under various traffic LOS conditions, from A to D, for two AV MPRs of 0% and 100%. The results of the study indicated that the AVs improve the traffic operation by decreasing the traffic density over all the lanes of the segment nearby of the driveway in moderate traffic volume environments, LOS C and LOS D. Also, by smoothing the traffic flow and operation, traffic safety can be promoted simultaneously (Kala & Stach 2006). Even though the traffic density for the upstream and downstream segments of the driveway had fluctuations over lanes, the AV environment resulted in overall improvements compared to the conventional vehicle environment.

This study addresses one of the fundamental issues in the access management that is the spacing and density of the driveways (Gluck & King, 2003). In conclusion, as in the AV environment, the vehicles distribute more evenly between and along the lanes, the traffic density of the arterial does not increase significantly in close proximity of the driveway. Moreover, the traffic density at the driveway is lower in the AV environment for all the available lanes for the moderate traffic congestion that represents urban arterials. Therefore, the driveway density could be increased in an AV environment to provide better accessibility to the roadways and adjacent land-uses without interrupting the smooth traffic operation.

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