Impact of Connected and Automated Vehicles on Capacity of single lane road based on macroscopic fundamental diagram

Amirhosein Karbasi
Master Student, Tarbiat Modares University
Amirhosein.karbasi98@gmail.com

Behzad Bamdad Mehrabani
Ph.D. Candidate, Université catholique de Louvain
behzad.bamdad@uclouvain.be

Mahmoud Saffarzadeh
Full Professor, Tarbiat Modares University
saffar_m@modares.ac.ir

Abstract

Shortly, Automated Vehicles (AV) will be used in urban streets in many countries. On the other hand, many countries are faced with congested problems and are looking for some way to solve congestion problems. Therefore, it is necessary to find the impact of these vehicles on different aspects of transportation planning. In recent years many researchers have been encouraged to investigate the impact of Connected and Automated Vehicles (CAV) on the capacity of transportation networks. In this paper, we have a specific goal, and the goal is to show how CAVs can influence roads' capacity. In this research, we choose the SUMO simulator to reach our goal. Besides, we use Krauss car-following model to specify the following vehicle behavior and also choose the speed-density relationship and macroscopic fundamental diagram (MFD) to determine the density and capacity of our network. In the last part, we show the result of a simulation-based on data collected from the SUMO simulator. Based on results, CAVs have great potential to improve transportation networks' situation from a capacity perspective.

Keywords: Connected and automated vehicles, Fundamental diagram, SUMO, Capacity.

Introduction

Nowadays CAVs have become a solution to reduce congestion and a lot of researchers work on the impact of this kind of vehicle on the capacity of roads (Xiao et al. 2018). One of the import aspects of automated vehicles is a different level of automation. There is a classification about the automation level that specifies a definition for every automation level. This definition is published by the Society of Automotive Engineers (SAE) (Parkhurst 2016). Table 1 shows the definition of different levels of automation and the meaning of automation in this article is level 5 of automation.

The other aspect of CAVs is connectivity. Connected vehicles are able to connect to other vehicles (is known Vehicle to Vehicle communication (V2V)) or they can connect to specific infrastructure (is known Vehicle to Infrastructure communication (V2I)) (Atkins Ltd. 2016).

The concept of this study is related to importance of emerging vehicle automation and connection aspect of this vehicle. In this study we tried to show the impact of CAVs on the capacity of a single road.

Table 1. definition of different level of automation defined in SAE J3016 definition(Parkhurst 2016)

Level of Automation	Definition
Level 0 No automation	The full-time performance by the human driver of all aspects of the dynamic driving task, even when enhanced by warning or intervention systems
Level 1 Driver Assistance	The driving mode-specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the human driver performs all remaining aspects of the dynamic driving task.
Level 2 Partial Automation	The driving mode-specific execution by one or more driver assistance systems of both steering and acceleration/deceleration using information about the driving environment and with the expectation that the human driver performs all remaining aspects of the dynamic driving task.
Level 3 Conditional Automation	The driving mode-specific performance by an automated driving system of all aspects of the dynamic driving task with the expectation that the human drivers respond appropriately to a request to intervene.
Level 4 High Automation	The driving mode-specific performance by an automated driving system of all aspects of the dynamic driving task, even if a human driver does not respond appropriately to a request to intervene.
Level 5 Full Automation	The full-time performance by an automated driving system of all aspects of the dynamic driving task under all roadway and environmental conditions that can be managed by a human driver.

Literature Review

There are some studies about the impact of vehicle automation on the capacity of transportation networks. Lu et al. (2019), exanimated impact of automated vehicles on the capacity of 36 intersections and a part of the urban road using speed density formula and macroscopic fundamental diagram and they concluded that AVs can improve the capacity of intersections. In another study Hartmann et al. (2017) investigated the impact of autonomous vehicles on the German freeways using microsimulation. Also, Atkins Ltd. (2016), determined the impact of CAVs using microsimulation for different types of urban networks include intersection, freeway, roundabout, and complex networks. Olia et al. (2017) used Fritzsche car-following model to find the impact of automated vehicles and cooperative automated vehicles on the capacity of the merge section. Friedrich (2016), use some formula to find the impact of autonomous vehicles on the capacity of transportation networks. Also, in this paper impact of autonomous vehicles on stability is investigated. Tilg et al. (2018) determined impact of automated vehicles on the weaving section using a multiclass hybrid model and they considered lane changing and reaction time in the simulation.

Method

This study has a specific goal, and the goal is to determine the capacity of a single lane road in the presence of CAVs. To achieve this goal, we consider different scenarios that are shown in table 2 and these scenarios are based on penetration rates of CAVs and regular vehicles in mixed traffic. Also, we consider some phases. In the first phase, the data (including speed and density) is obtained using the SUMO simulator. SUMO is a software that is open source, and it provides this possibility to implements traffic simulation (Behrisch et al. 2011).in this phase we used car following model to define drivers' behavior in mixed traffic and information about car following model will be discussed in the next section In the second phase, the data is aggregated in 1-minute intervals. The third phase is using Papageorgiou speed-density relationship and macroscopic fundamental relationship to find capacity and density that divided flow into a free-flow branch and congested flow branch. The equations (1) and (2) show the speed-density relationship and macroscopic fundamental diagram relationship, respectively (Lu et al. 2019; Krishna et al., .2019).in the first equation we tried to specify the relationship between speed and density and specify the parameters and then we substituted equation (1) in equation (2) to obtain flow for different time intervals. In Equation (1), Vf shows free-flow speed; Km is critical density; k is density, and a is equation parameter. In Equation (2) Q shows the flow (veh/hr) of a network; p determine density in (veh/km); and V means mean speed (km/hr).

$$V = v_f \exp\left[-\frac{1}{a}\left(\frac{k}{k_m}\right)^a\right] \tag{1}$$

$$Q = p.V \tag{2}$$

Table 2. Scenarios for simulations

Scenario	CAV penetration rate	Regular vehicle penetration rate
Scenario 1	0	100
Scenario 2	20	80
Scenario 3	40	60
Scenario 4	60	40
Scenario 5	80	20
Scenario 6	100	0

Car following model

For implementing traffic, simulation is necessary to determine the car following parameters. In this study, we choose Krauss car-following model that is a default SUMO car-following model. For regular vehicles, car-following models are taken from Lu et al. (2019), and for CAVs acceleration, tau (minimum time headway) and minimum gap were taken from Atkins Ltd. (2016). To comply with safety requirements deceleration, emergency deceleration for CAVs is equal to regular vehicles. (Lu et al. 2019). Sigma (driver imperfection) for CAVs was taken from Lücken et al. (2019). Table 3 shows the parameters for the car-following model for regular vehicles and CAVs.
In the car following model the parameters are defined as follows: Mingap is defined the offset to the leading vehicle or Empty space after leader (in m). Acceleration is the acceleration ability of vehicles (in m/s2). Deceleration is the deceleration ability of vehicles (in m/s2). Emergency Deceleration is the maximum physically deceleration ability of vehicles (in m/s2). Sigma is The drtver imperfection .Tau is the driver's minimum time headway (in s) (Lu and Tettamanti, 2018).

Table 3. Car following models parameter

Parameters	Regular vehicle	CAVs
Acceleration (m/s^2)	3.5	3.8
Deceleration (m/s^2)	4.5	4.5
Emergency Deceleration (m/s^2)	8	8
sigma	0.5	0
Tau	0.9	0.5
Mingap	1.5	0.5

Network and simulation setup

To determine the impact of CAVs on the transportation networks' capacity, it is necessary to define the network. In this paper, we choose a single lane urban road. Figure 1 shows the network. In figure1 blue vehicles demonstrate the CAVs and red vehicles show the regular vehicles.

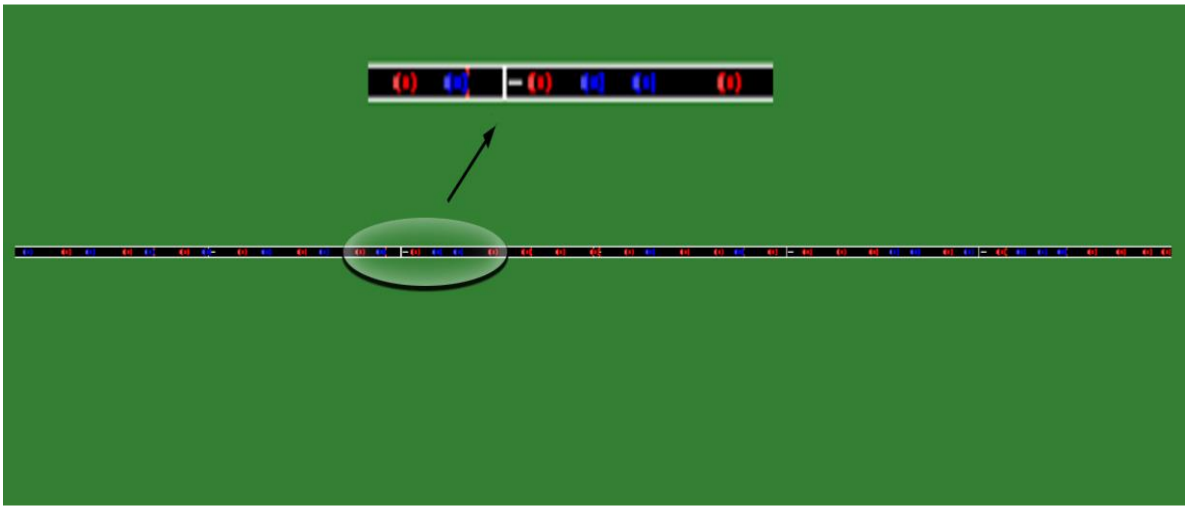

Figure1. Network in simulation environment

For this simulation we have 2 different branch as shown in figure 2.In the figure 2 there are two different branch .The first branch is known as free flow branch that is starts from zero vehicles in the network and continue until the network reaches its capacity and automatically can be built in SUMO. The second branch is known as congested flow branch that is begin from capacity to jam density. SUMO can't create jam density by default. So there are some way to create jam density in SUMO. Figure 1 shows a jam density. The way that we choose for this simulation is using variable speed sign (VSS). In this method in some period of time the speed of network was reduced to create jam density.
For implementation the simulation the speed of vehicles should be specified. In this simulation we set the speed of vehicles equal to 50 km/hr because the area of simulation is urban area the speed has a logical value. In addition, the length of vehicles is 5 meters. Also, the length of simulation network is set to 1 km.

Result

The simulation data were collected, and using equation (1) critical density (Km) and (a) were obtained. Then, with the help of equation (2), the maximum flow for every scenario was determined. Table 4 shows the different values for different scenarios. From equation (2), the flow density relationship can be determined, and the diagram based on this relationship can help us understand the free-flow branch and congested flow branch. The flow density diagrams are shown in figure 3 for each scenario.

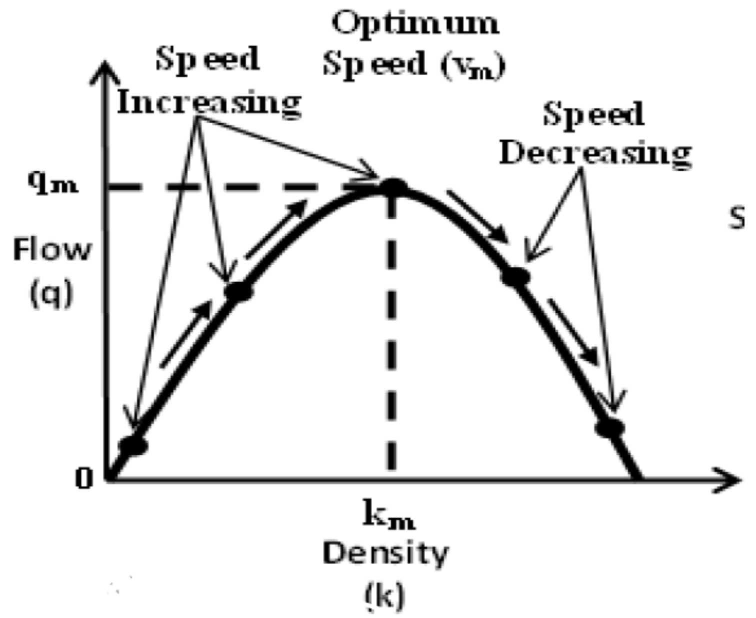

Figure2. Greenshield's Fundamental Diagrams(Zaidi et al. 2014)

Table 4. Simulation result

Scenario	a	K_m(critical density)	Flow	Flow changes (%)	K_m changes (%)
1	3.447	63.566	2243	0	0
2	3.529	68.617	2426	8.16	7.94
3	3.605	74.538	2642	17.78	17.26
4	3.926	79.936	2897	29.11	25.75
5	4.255	86.869	3216	43.32	36.65
6	4.651	94.632	3603	60.57	48.87

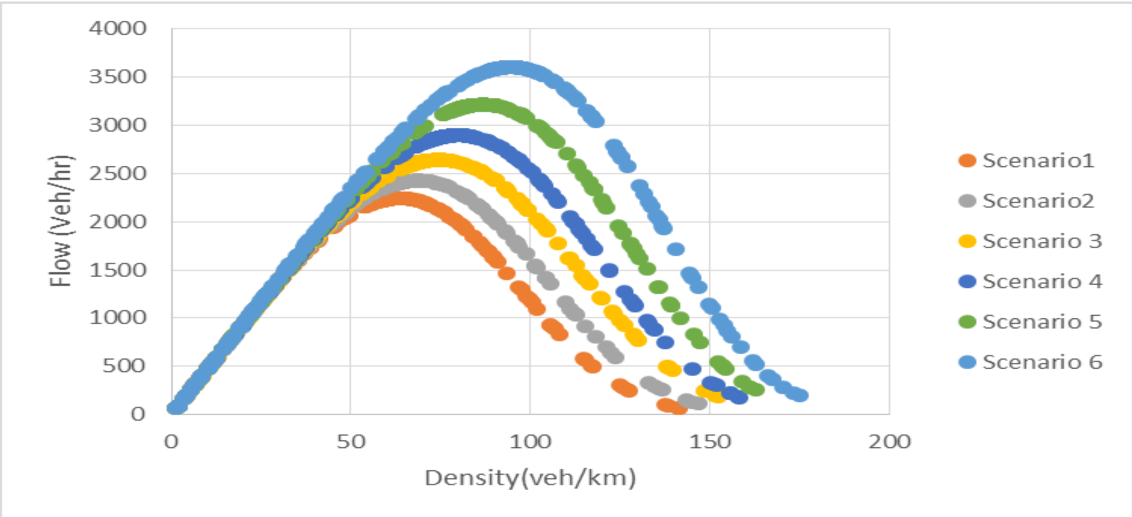

Figure3. Flow density diagram

As shown in table 4 and figure 3, there are some changes in critical density and flow for each scenario.in the figure 3 there are flow density relationships for every scenarios that are obtained from equation (2). Critical density experienced a change from 63.563 to 94.632 that from this change can we realized that CAVs could improve critical density substantially and this change also can be realized from the figure 3.in addition, flow went up from 2243 to 3603 that we can realize that CAVs play a

vital role in improving the capacity of the road and redacting congested transportation networks. Figures 4 and 5 respectively show changes in flow and density compared to percentage changes in CAV.
On the other hand, there are interesting changes in density and flow changing. Table 1 shows that as the penetration of CAVs increases, the percentage of changes in density and flow also increases. Also, there is a comparison between changes in flow and changes in density compared with the change in penetration rate in CAVs shown in figure 6. Figure 6 shows there is a similar change in density and flow when the penetration rate of CAV is under 40 %. In contrast, after a 40% penetration rate, changes in flow are higher than changes in density. At last, figure 7 shows the 3D plot of fundamental diagrams and the percentage of CAVs.

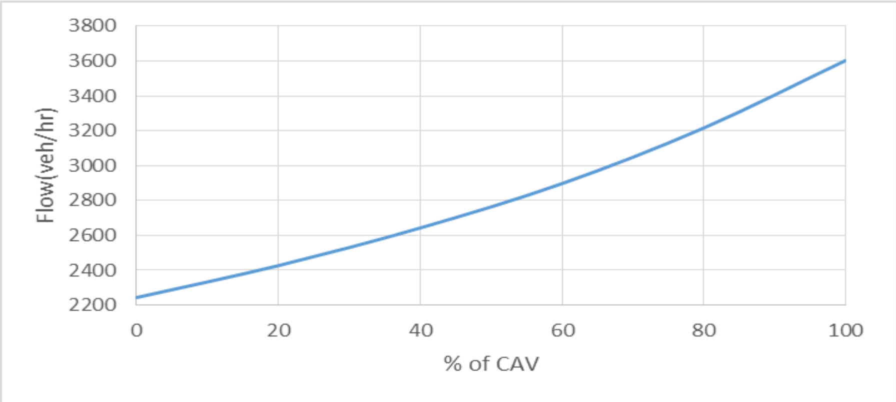

Figure4. Flow change compared to percentage change in CAV

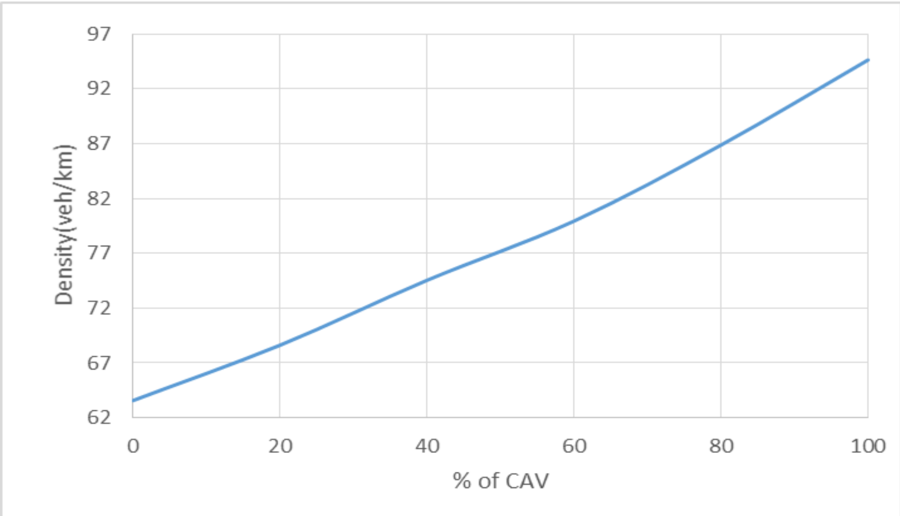

Figure5. Density change compared to percentage change in CAV

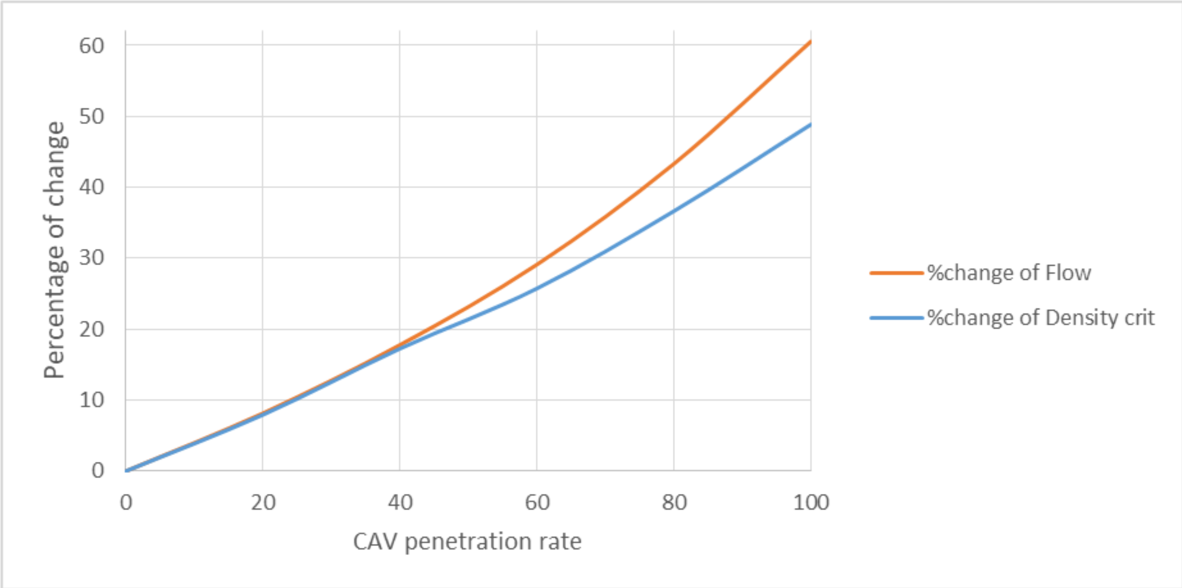

Figure6. Percentage change in critical density and flow compared to percentage change in CAV

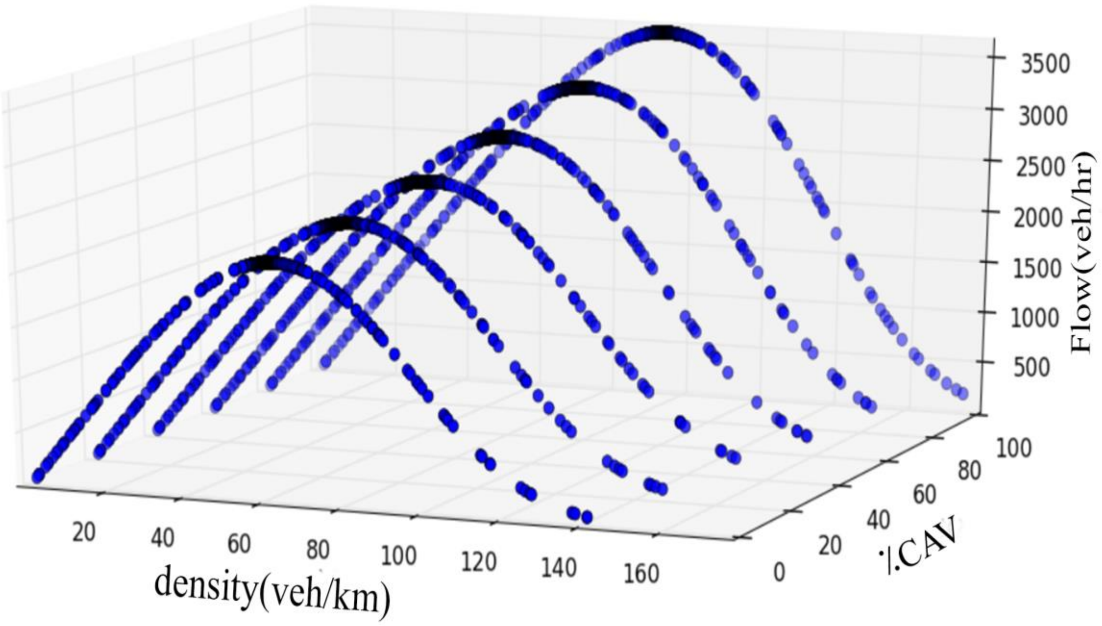

Figure7. 3D plot of flow density diagram and percentage of CAV

Conclusion

The impact of CAVs on the capacity of a single road using macroscopic fundamental diagrams have been investigated in this study. Results show that CAVs have provided a great opportunity to increase the capacity of the road; therefore, these kinds of vehicles can be a solution to the congested problem in the transportation network. Also, results show that CAVs can improve the density that divided fundamental diagram to free-flow branch and congested flow branch that is known as critical density.

References

Atkins Ltd. (2016). "Research on the Impacts of Connected and Autonomous Vehicles (CAVs) on Traffic Flow." (May). Technical Report. Department for Transport.

Behrisch, Michael, Laura Bieker, Jakob Erdmann, and Daniel Krajzewicz. (2011). "SUMO – Simulation of Urban MObility."

Friedrich B. (2016) the Effect of Autonomous Vehicles on Traffic. In: Maurer M., Gerdes J., Lenz B., Winner H. (eds) Autonomous Driving. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-662-48847-8_16

Hartmann, Martin. (2017). "Impact of Automated Vehicles on Capacity of the German Freeway Network Impact of Automated Vehicles on Capacity of the German Freeway Network." (October).

Krishna, Hari and Gaddam K. Ramachandra. (2019). "Speed – Density Functional Relationship for Heterogeneous Traffic Data : A Statistical and Theoretical Investigation." *Journal of Modern Transportation* 27(1):61–74.

Lu, Qiong and Tamás Tettamanti. (2018). "Impacts of Autonomous Vehicles on the Urban Fundamental Diagram ImPACTS Of AuTONOmOuS VehiCleS ON The URbAN FuNdAmeNTAl DiAgRAm." (May).

Lu, Qiong, Tamás Tettamanti, Dániel Hörcher, István Varga, and Qiong Lu. (2019). "The Impact of Autonomous Vehicles on Urban Traffic Network Capacity : An Experimental Analysis by Microscopic Traffic Simulation Experimental Analysis by Microscopic Tra Ffi c Simulation." *Transportation Letters* 00(00):1–10.

Lücken, Leonhard, Evangelos Mintsis, Kallirroi N. Porfyri, Yun-pang Flötteröd, and Dimitris Koutras.(2019). "From Automated to Manual - Modeling Control Transitions with SUMO."

Olia, Arash, Saiedeh Razavi, Baher Abdulhai, and Hossam Abdelgawad. (2017). "Traffic Capacity Implications of Automated Vehicles Mixed with Regular Vehicles." 2450(January 2018).

Parkhurst, Graham Peter. (2016). "The Mobility of Older People , and the Future Role of Connnected Autonomous Vehicles A Literature Review . Sept 2016." (September).

Tilg, Gabriel, Kaidi Yang, and Monica Menendez. (2018). "Evaluating the e Ff Ects of Automated Vehicle Technology on the Capacity of Freeway Weaving Sections." *Transportation Research Part C* 96(September):3–21.

Xiao, Lin, Lin Xiao, Meng Wang, Wouter Schakel, and Bart Van Arem. (2018). "Unravelling Effects of Cooperative Adaptive Cruise Control Deactivation on Traffic Flow Characteristics at Merging Bottlenecks Transportation Research Part C Unravelling Effects of Cooperative Adaptive Cruise Control Deactivation on Traffic Flow Characteristics at Merging Bottlenecks." *Transportation Research Part C* 96(November 2018):380–97.

Zaidi, Kamran, Milos Milojevic, Veselin Rakocevic, and Muttukrishnan Rajarajan. (2014). "Data Centric Rogue Node Detection in VANETs." (December 2015).