Vehicle Automation Impact on Traffic Flow and Stability: A Review of Literature

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Abstract: Vehicle automation technologies open new avenues for improving present transportation networks. It is predicted that Autonomous vehicles (AVs) and Connected Vehicles (CVs) will improve the traffic flow though increasing road capacities and reducing travel time and congestion to a great extent. According to the studies, AVs and CVs benefits will likely to more increase with their penetration rates and level of automation and cooperation. Eventually it might accelerate the expected evolution in car mobility in which the gradual transition from regular human driving to automated driving will occur. This paper summarizes the recent studies on the impact of vehicle automation in traffic flow. Although many factors are considered to affect traffic flow under the use of vehicle automation. This study has selected four main factors, these are travel behavior factor, the effect of platooning, travel time factor, and the effect of intersection control. The reviewed studies relevant to these keywords have been extensively argued and thoroughly discussed in this paper. Furthermore, the different applied models and the analytical frameworks which have been used to achieve various results and outcomes, are described in an illustrative table. Finally, all findings which have been demonstrated from this paper emphasize a great contribution of the developed vehicle automation technology to the future of our transportation system.

Keywords: autonomous vehicles; traffic flow; travel behavior; platoon formation

1 Introduction

Autonomous vehicles (AVs) are those type of vehicles which can float in traffic though the road network without the need of human decision maker to perform a comfortable driving task for the passengers. In recent years, major automobile manufacturers and technology companies have made crucial progress in the field of autonomous vehicles. Particularly, vehicle control systems have been enormously improved. For example, cruise control system which allows the vehicle to maintain the speed at specific limits was once a luxury. Now, this system is widely used and became a standard in almost all vehicles [1]. Recently, the current focus considered by car development innovations is time headway control systems [2], that provide an automatic breaking when a minimum allowable distance between two successive vehicles is reached. In addition, auto parking, object avoidance and lane keeping systems have continued the evolution of automated vehicles through conducting improvements related to safety augmentation [3]. To better classify vehicle automation development, the Society of Automotive Engineering (SAE) has defined 6 levels of automation, ranging from no automation (Level 0) represented by the regular vehicles recently existed on roadways, to fully automated (Level 5) represented by autonomous vehicles that operate without the help of human drivers. On the other hand, the term connected vehicles (CVs) refers to the vehicles that provide communication between vehicle-to-vehicle (V2V) and also vehicle-to-infrastructure (V2I) [4]. Both AVs and CVs are considered as driverless vehicles, and both use sensors to obtain information. Therefore, and due to the continuous digital development in recent decades, it is now a fact that our lives have been directly involved in the cognition of artificial intelligence through the upcoming use of cognitive mobility [5]. It is also believed that autonomous vehicles will make travel accessible to new user groups who are unable to drive a conventional vehicle or drive less than they might like. However, this might be a real reason to attract elderly persons, with the hope of achieving sustained development in terms of mobility ease and safety for the elderlies either as passengers or pedestrians [6]. In addition to the benefits provided to their users, researchers have concluded that AVs are believed to impact on traffic flow efficiency by increasing road capacity as well as reducing energy intensity, fuel consumption, travel time and congestion [7] [8]. However, increasing our efforts to attain an improved efficiency of AVs should not allow for the imperative necessity of vehicle safety to be overlooked, and a serious attention should be paid to safety enhancements of all highly-leveled automated systems [9]. Bearing in mind that the influence of AVs has a great reliability on their penetration rate into the traffic. However, low penetration rates of AVs will not influence road capacities [10]-[12], or it may initially have some negative impacts [13]. Moreover, there will be a considerable transition period to perform an alteration from human driving to automated driving in which numerous unknown traffic flow dynamics might be present. In this paper, numerous research studies have been reviewed considering the scientific relevancy to the impact of vehicle automation to traffic flow efficiency. A wide range of modeling and analysis frameworks, with different results based on the researchers' proposed assumptions has been thoroughly discussed, in the aim of filling the critical research gap in the future development of AVs on road networks.

2 Methodology

The research methodology entails a wide literature review process based on peer-reviewed journal papers. The research studies are relevant to the research objective in which a sufficient background for the systematic review has been provided. Several combinations of keywords have been used in during the initial searching which has been later widely expanded in Google and Google Scholar. Some of the keywords are: Autonomous vehicles, Adaptive Cruise Control, Cooperative Adaptive Cruise Control, Connected Vehicles and Self-Driving Vehicles. Then the search has been further extended to include the factors influencing traffic flow under the use of above-mentioned types of vehicles. These factors include First, travel behavior factors, represented by longitudinal behavior, lateral behavior, and vehicles interactions behavior. Second, travel time and congestion factor. Third, platoon formation. Fourth, the types of intersection control system. As a result, a plentiful number of research papers which have investigated the impacts of vehicle automation on traffic flow, were reviewed herein.

3 Factors Affecting Traffic Flow in Mixed Traffic

Autonomous and connected vehicles are expected to revolutionize traffic flow and increase the road capacities, mainly because of the substantial facts that reveal better reaction time for those vehicles as compared to the human drivers. Moreover, researchers addressed several factors that directly affect traffic flow, in which the theoretical analysis consider most of them as positive factors that help to enhance traffic flow efficiency. However, to achieve such gains, the whole system should work in a convenient environment, represented by the existence of optimum penetration rates, ideal connectivity between vehicles, typical road sections and active authority policy implementations. All these aspects and more will be discussed in the next subsections of the paper.

3.1 Travel Behavior

Drivers who are experiencing automation are less likely to engage in behaviors that required them to temporarily assume human control, such as overtaking. They are usually willing to abandon driving and prefer more entertainment of fully automated drive. Therefore, travel behavior for the autonomous vehicle in a mixed traffic environment is a crucial factor impacts traffic flow. It could be divided to three branches according to the direction of movement and the dynamic interactions of the vehicle.

3.1.1 Longitudinal Movement and Time Headway

The average time headway between vehicles on the road has a great influence on the traffic flow. Mathematically, it has an inverse relation to the road capacities under the use of both conventional and automated vehicles. However, although there is a variety of vehicle automation which are going to be widespread on our roads, a consensus opinion reveals that the operation of these vehicles will cause a reduction in time headway, consequently providing enhanced traffic capacity and improving traffic safety [14]. Existing research recognize the critical role played by the average time headways that belong to autonomous vehicles environment. Aria et al. [15] have investigated the effects of AV on driver's behavior and traffic performance. The study found that conventional vehicles which are driving close to a platoon of AV with short time headway, tend to reduce or maintain their time headway under the critical values. For this purpose, a microscopic traffic simulation using VISSIM was performed for both cases of 100% AV and 100% conventional vehicles scenarios. The results of simulation study indicated the positive effects of AV on roads during peak hour period. Gouy et al. [14], in the same way, have also investigated whether a 'contagion' effect from the short time headway held in platoons of vehicle equipped with automated systems would occur. Simulation has been conducted using short and long-time headway (0.3-1.4) seconds, and results showed a possibility of negative effect of short time headways on unequipped vehicle drivers in a mixed traffic. Several authors highlighted the effects of varying market penetrations of autonomous vehicles on highway capacity. Shladover et al. [16] presented a study on the impact of ACC and CACC on traffic flow, they considered the distribution of time gap settings that drivers form which represent real field data to be used in the simulation process. Although the results of the study did not show significant impact with the gradual increase of ACC penetration rate. Contrastingly, moderate to high percentages of CACC greatly increase the capacity of the road. Kesting et al. [17] disagreed with the outcomes in [16] regarding ACC effects, they suggested to maintain the time gap by accelerating or decelerating the vehicle to reach a desired speed. At the same time, rear end collision will be avoided. Due to the availability of sensors, ACC might detect and track the vehicle ahead and measuring the distance and speed difference, which will be used as inputs for the proposed car-following model used in by the researchers. The study demonstrated an increase in dynamic capacity when the penetration rate exceeds 50%. The car following model has been also used by Park et al. [18] in which the parameters set at level 4 of automation as well as a gradual increment of AVs penetration. The study adopted a microsimulation approach using VISSIM on a real road network of total distance of 4.5 km in which 13 intersections are located on. The results show an improvement in traffic flow and reduction in delay time when the network is fully saturated with AVs. Li and Wagner [12] have also selected a 5.3 km stretch on Auckland motorway to be the study case in which a simulation conducted using available traffic data. Four scenarios have been tested regarding the capacity of the motorway, these are namely, heavily congested, lightly congested, free flow traffic and future heavily expected congestion. The findings of the research work indicated insignificant impact at the initial stages of AVs deployment, while remarkable advantages have been observed when AVs penetration rate reaches 70%. Many researchers have used Intelligent Driver Model (IDM) to investigate the longitudinal driving behavior as it has many advantages over other ACC models. Péter et al. [19] have applied the stated model to examine AVs motion process by creating a relevant speed and steering angle signals in a lab setting in a manner that is consistent with the actual driving and traffic situations. Furthermore, Péter and Lakatos [20] have investigated the vehicle-dynamical properties of IDM model, represented by highest acceleration parameters set by the vehicle, the desired speed parameters of the vehicle and the distance-keeping parameters of the vehicle. Overall, the longitudinal behavior assessment based on the reviewed conducted methods by the researchers, reveal a vast desire towards shortening the time headways and gaps. Although it appears to be an advantage to get more increased capacities in light traffic, but on the other hand, jam avoiding must be seriously considered in more dense and congested traffic to avoid delay and surpass traffic breakdowns.

3.1.2 Lateral Movement and Lane Change

Although traffic flow is usually introduced by the vehicles longitudinal time headways, these are also indispensable driving situations related to the lateral movement of vehicles, including lane-change maneuvers which are directly influencing the traffic flow and capacity [13]. Studies on the lane-changing behavior stated that the main reason to entice the following drivers to proceed overtaking accrue to the slow motion of ahead vehicles. Furthermore, drivers would choose to do lane changing only if there is a sufficient gap in the destination lane which in turn resulted in a gap in the origin lane, bearing in mind that the overtaking vehicles should have higher speeds than the following vehicles in the destination lane [21] [22]. A large and growing body of literature has investigated the impact of lane-changing of automated vehicles on traffic flow characteristics. Liu et al. [23] has developed an improved Cellular Automata (CA) model to study two sets of polite and aggressive lane change behavior for a mixture of autonomous and regular vehicles. The article argued the major difference between these two types of vehicles in terms of lane changing, and considered AVs to be superior, because of the ability to communicate with another adjacent AVs in the target lanes for the possibility of conducting more flexible lane changing. In Conclusion, the study observed an increase in traffic capacity and free-flow speed of autonomous vehicles due to the lane-changing frequency between neighboring lanes which evolves with traffic density along a fundamental-diagram-like curve. Calvert et al. [13] have used Lane-change Model with Relaxation and Synchronization (LMRS) to investigate the impact of the gradual transmission from manual driving to automated driving on traffic flow dynamics. The authors conducted there simulation model through the use of empirical data which have been previously collected in [24]. These data include some ACC settings such as desired time headways and actual time gaps. As a result, low level of automation in mixed traffic might slightly have a negative effect on traffic flow, while a penetration rate of more than 70% will show noticeable improvements. Even though human error is a main factor of traffic accidents related to lane change maneuvering, many researchers focus only on the kinematic functions and how to provide an optimal trajectory for lane changing. For example, Ziegler et al. [25] proposed a local, continuous technique that is derived from a variational formulation. The solution trajectory is the constrained of an objective function that is designed to represent dynamic feasibility and comfort. In the contrary, Tehrani et al. [26] did not ignore the behavior model during challenging scenarios of merging and diverging on highway lanes. The most recent studies identified the lateral comfort of vehicle users as a major factor in lane changing decision making. It has an enormous effect on traffic efficiency and safety during automatic driving actions. Wang et al. [27] proposed a game method with Bézier curve path planning to enhance safety and comfortability of passengers. The proposed method found to be greatly met the requirements in the decision-making of lane-changing starting time, the total lane-changing time, and the lane-changing planning path, and it has been proved by using MIL simulator. The results show superior results to human drivers. On the other hand, Wang et al. [28] generate a model including both car following and lane changes to be considered as a hybrid condition. Like the study in [9], both cases of mandatory lane change and discretionary lane-change for the autonomous vehicle on the highway have been studied. However, discretionary lane-change decision process was the one that has been modeled as a game process with the following vehicle in the target lane. Eventually, it has been noticed that better comfort, traffic efficiency and stability resulted from the simulation analysis. According to the literature, it is unclear that current knowledge and model development on lane changing behavior will greatly impact traffic flow. Moreover, a complete implementation of genuine driving behavior is still lacking due to a lack of empirical ground facts and theoretical constructs. Therefore, sufficient enhancement is needed for the future traffic simulation models for the purpose of full evaluation of traffic system to acquire greater driving behavioral aspects.

3.2 Travel Time and Congestion

It is believed that the travel time for different sections of the roads will be reduced due to the spreading of autonomous vehicles more widely. Furthermore, autonomous driving is being discussed to compensate the commuters especially who spent much time for travelling high mileages, by allowing them to engage with other activities [29]-[31]. Despite the mixed results obtained from the literature, a general trend to an alleviative travel time could be noticed.

Many researchers concluded that widespread adoption of vehicle automation could lead to a positive impact on traffic flow, through the reduction of delay and average travel time. For example Ma et al. [32] and Obaid and Torok [33] have applied simulation models to different levels of automation and different penetration rates respectively, in order to alleviate traffic congestion levels. Ma et al. [32] used Origin-Destination matrix to describe vehicles movement of the whole roads network for the city of Duisburg in Germany. Afterwards Simulation of Urban Mobility (SUMO) has been used to simulate the traffic situation of the city in 2030 and 2050 considering three level of automation (non-automated, partially automated, and fully automated) vehicles. The study found an improvement traffic throughput up to 21.93% in 2030 and 22.08% in 2050 for most parts of the city which needs no expansion to road network. However, for the most congested areas traffic flow improvement has reached 67%. On the other hand, Obaid and Torok [33] conducted a macroscopic simulation of autonomous vehicle effects on traffic flow for the City of Budapest in Hungary. For this purpose, VISUM model has been used through a gradual increment of 10% for Autonomous vehicle penetration rate from (0-100)%. The results of the study show that there is a significant impact to the road network by reducing the total delay by 37.87% and increasing average speed up to 4.08%. Along the same lines, Szibma and Hartmann [30] conducted a microscopic traffic flow simulation using VISSIM on three different routes in Germany labeled as (freeway, arterial, and collector), under the consideration of two levels of automations (level 4 and level 5). The article addresses appropriate concepts to translate infrastructure capacity enhancements into travel time savings due to the operation of autonomous vehicles. Furthermore, exploiting the benefits that accrue from travel time savings to allow the commuters to conduct further activities during the trip. The study results reveal savings in travel time up to 20% due to the use of 100% penetration rate for level 4 automated vehicle, while 27% of the travel time could be saved when using level 5 automated vehicles. It is well known that commuters usually feel exhausted and frustrated when they stuck in heavy traffic conditions at peak hours. Therefore, Steck et al. [31] proposed an empirical study to provide a reduction of travel time for commuter trips using two cases of autonomous driving (a privately owned AV, and a shared autonomous vehicle SAV). The study design was based on an online questionnaire about the trip usually taken by the commuters, the respondents were asked to describe a recent trip. Moreover, they had to select one of five transportation options, these are: walk, bike, public transportation, privately owned AV, and SAV. Accordingly, the time for the trip is increased or decreased around the reference time values using suggested average speeds for each mode of transportation. However, the authors assumed excluding access and egress time for AVs and SAVs. The collected data then were analyzed using mixed logit model, and the study resulted in 31% reduction in travel time value for the privately owned autonomously driving, while the travel time spent in SAVs is showed 10% less negatively than driving manually. From the results of Zhou et al. [34], it has been observed that a gradual increase of penetration rate of

AVs, up to 25 % would cause a reduction in travel time and congestion. Safe time gaps with the value of (0.4, 0.6, 0.8, 1.0, 1.2) seconds have been used in Intelligent driver model IDM to carry out the analysis, which shows that the gaps are negatively related to the average travel time. A close to this study trend has be highlighted in the same year by Lui et al. [23], who also presented similar results in terms of vehicles automation influence in mitigating congestion levels. The study concluded that an AV has an optimum rate of 50% to lower congestion degree across the whole network. Lu et al. [35] in his study, argued mitigation of traffic congestion on urban traffic network which makes the urban commuters suffering from the long time journeys. They investigated the effect that AVs bring to macroscopic fundamental diagram (MFD) through SUMO traffic simulator both with an artificial grid road network and a real-world network in Budapest. Likewise, the aforementioned studies, there is a clear observation to capacity improvement along with AVs penetration growth. In addition, a generalized additive model (GAM) has been used to introduce an efficient modeling for MFDs with different AVs percentages. Several attempts have been made to reduce congestion through the use of lane reservation for autonomous vehicles. Talebpour et al. [36] evaluated three different strategies for reserving lanes, these include a mandatory use by AVs, an optional use and limitation the rate of AVs in the reserved lane. The study conducted on two different segments of highway in which the analysis revealed a beneficial outcome from the used policy. Especially, for the third strategy when a 50% of AV penetration rate are used in the two-lane highway segment and 30% penetration rate used in the four-lane highway segment. Carrone et al. [37] proposed a model for the congestion of single representative lane of the Copenhagen M3 motorway. Modified intelligent driver model (IIDM) has been used for a mixed traffic environment and resulted in an improved capacity utilization when the AVs penetration rate 50%. In general, the greatest portion of the studies in the literature consider the penetration rate of automated vehicles as one of the major factors influencing the travel time and congestion, thus directly affecting the traffic flow to a great extent.

3.3 Platton Formation of Automated Vehicles

The practice in which several vehicles following one another closely, resulting in mitigation to aerodynamic drag for all vehicles is referred to as Platooning. It may also reduce traffic congestion and increase road capacities. It is believed that platooning in a tight formation is risky and unsafe without automation, this is turn to the delay in the perception and reaction processes of human drivers when the vehicle ahead suddenly decreases its speed [38]. Previous studies have explored the relationships between autonomous vehicles and platooning. It has also demonstrated the impact of them together on the augmentation of traffic flow. Mena-Oreja et al. [39] focused on the parameters of desired and safe time gap as well as the maximum length of a platoon when they studied the effect of the configuration of platooning maneuvers on mixed traffic. The studied parameters are considered to greatly execute the platooning maneuvers and significantly impact the traffic flow. Other researchers like Harwood and Reed [40] and Vukadinovic et al. [41] focused on investigating the impact of using Vehicle to Vehicle communication platooning on traffic performance. The technology of road trains formation has been developed by [40], then a simulation using VISSIM has been applied and led to a proportional increase in the studied carriageway capacity. On the other hand, the study in [41] demonstrated that better traffic efficiency can be achieved by maintaining the inter-vehicle spacing at a feasible minimum. The study compared two radio technology families: IEEE 802.11p and 3GPP Cellular-V2X (C-V2X), in which the latter resulted in shorter inter-truck distances due to efficient communications performance that haven't been affected by the increasing load on the wireless channel produced by the surrounding vehicles. Yet in many cases, interference could still cause communication failures to V2V communication. Gong et al. [42] referred to the limitation for most of CACC due to the fixed information flow topology for a platoon of connected autonomous vehicles. To overcome the problem, CACC-DIFT which stand for a dynamic information flow topology is used to reduce to negative effects that of communication failure. Moreover, Next Generation Simulation (NGSIM) has been used to validate the effectiveness of the proposed CACC-DIFT, in which the results indicated remarkable surpass of CACC-DIFT design to CACC. One can observe novel contributions from Fernandes [43] study about the effect of vehicle automation on traffic flow. The study focused on maintaining the system operating at full capacity during the exit of vehicles from the main track of a platoon to an offline station, followed by an entrance of other vehicles to join the platoon at the same station. The authors proposed an algorithm to keep the spacing between platoons' leaders to avoid any negative impact on the speed of the platoons behind. Furthermore, allowing vehicles to enter the main track cooperatively to fulfil unoccupied leader's positions. Agent-based model for platoons of cooperative automated vehicles has been conducted using MATLAB/Simulink to ensure high traffic capacity and congestion avoidance. Mushtaq et al. [44] presented two level approach to achieve traffic flow improvement. The first approach includes formation of platoons to mitigate traffic congestions, and the second one, is to use V2V and V2I infrastructures to provide situations such as collision avoidance. The author used SUMO for the simulation process and the obtained results indicated significant enhancement to traffic flow. Publications that concentrate on automotive truck platooning more considerably adopt the effect of platooning on energy intensity. Since the truck speeds increased with aerodynamic losses, it is important to design a platoon formation in such a way that keeps the trucks at constant speeds, thus, providing a stable traffic flow. Tsugawa [45] has tested a platoon formation of three automated trucks moving at 80 km/h, the reduction in energy consumption reached 13% at 10 m gap when the penetration rate was 40% of heavy automated trucks. Moreover, a 25% reduction in energy consumption for the middle truck could be obtained through extrapolating the results to zero gap. Lu and Shladovar [46] have also examined a three truck platoon with 6 m spacings, The results show a plausible saving in fuel consumption by 4.3%, 10% and 14% for the first, second and third truck respectively. From these results, one can estimate an upper bound of (10%-25%) of energy savings for a large portion of fright kilometers observed on the highways. In fact, the complexity of platooning of autonomous vehicles lies in the impact of platoon maneuvering. Such as safe gaps and platoon length. Therefore, those maneuvering parameters should be carefully studied before the execution of automated platoon, so as to avoid failure, and maximize the impact of performing such mechanism in mixed traffic scenarios.

3.4 Intersection Control

In urban environments, signal timing at signalized intersection directly affects the efficiency of transportation networks. By taking the advantages of vehicle automation, the capacity of the intersections and the whole system might be significantly improved. Several studies investigated the effect of intersection control on traffic performance under the use of autonomous and connected vehicle. Guler et al. [47] defined an algorithm to gather information from connected vehicles to determine successive clearing out from the intersection. The study has tested different minimum greens and penetration rates for a mixed traffic to optimize the intersection's signal timing. Consequently, minimizing total number of stops and delay time using the proposed algorithm. Similarly, Baz et al. [48] have used a game theory based algorithm to improve the intersection efficiency during mixed traffic scenarios. A simulation model has been developed to perform the proposed algorithm and the research results indicated a significant reduction in delay time compared to a conventional control of both a roundabout and a signalized intersection by 65% and 84% respectively. On the contrary, Berktaş and Tanyel [49] have obtained negative results when they discovered that the intersection capacity decreased by increasing the rate of autonomous vehicle in unconnected traffic environment. Although the study referred to a negligible effect of AVs at low traffic volumes, remarkable changes start to vastly appear when the AVs rate reaches 40% and the traffic volume is about 1750 veh/h. At this point the calculated delay time at the intersection increased by 300% as compared to the regular situation in which no autonomous vehicles exist. In fact, the reason behind obtaining such disappointing results could be caused by the proposed assumption, in which all vehicles were considered to be passenger cars. This might affect the plausibility of acceleration and deceleration values which have been measured during the study. More significant analysis and discussion have been argued to provide better management for the autonomous vehicle at the intersections, by exploring new relevant insights and idea to the control strategies. Li et al. [50] introduced a reservation-based intersection control system named autonomous control of urban traffic (ACUTA). The operational performance characteristics using ACUTA resulted in significant improvement to the capacity and reduced the delay time at the intersection. Martin-Gasulla et al. [51] used PTV VISSIM to calibrate a microsimulation model to provide a solution for the potential reduction in throughput at low penetration rate by using new managing solution of sorting CAVs, and applying possible management to preset green-time at a two-lane intersection entry. This scenario led to a platoon formation at the intersection and mitigated the delay time by 17%. Ramezani et al. [52] on the other hand, studies four possible configurations of mixed traffic to investigate the efficiency at two lane signalized intersection. Based on the AV penetration rate, theoretical headway is validated by microsimulation data, and then estimated to derive the delay time. The delay time resulted from each lane for different penetration rates have been compared and the optimal configuration was selected. Regarding roundabouts, Cao and Zöldy [53] have studied the impact of connected vehicles on fuel consumption and vehicle emission at a selected roundabout. The study investigated the roundabout physical parameters and the vehicle driving behavior which play an important role in saving energy by achieving as smooth as accelerations and decelerations. Later, Cao and Zöldy in [54] have introduced another paper to study the path tracking of connected vehicle at a roundabout by using a model predictive control (MPC). The authors investigated the relationship between the control parameters with different curvature path which represent the road condition and thus increasing the autonomy of the vehicle. In general, the majority of the obtained results promise a reduction in delay time and provide a remarkable increment to the capacities at the intersections through the use of vehicle automation technology. This is usually occurred by applying a proper optimization to the vehicle departure sequences. However, the researchers have conducted their models and algorithms on individual intersections. Therefore, further development for the algorithms should be provided to implement coordination of multiple signalized intersection in mixed traffic environments.

4 Results and Discussion

The research papers including the authors' names, the used models and analysis frameworks and the main findings have been listed in Table 1 in chronological order. Apart of the first three listed studies in the table, all other studies have been carried out and published within the last 10 years. This emphasizes the current evolution of vehicle automation technology and reveals its important role to the transportation system which has been clearly emerged in recent scientific research. From the main findings described in Table 1, one can clearly observes that the vehicle automation penetration rate is almost the most important parameter that all the influencing factors on traffic flow might share. However, some researchers have referred to a slight effect, of low to medium penetration rates on the factors affecting traffic flow as in [17] [37] and [47]. Other few researchers concluded that low percentages of AVs have no impact like [10] [11]. On the other hand, two of the reviewed studies demonstrated that negative impact to traffic flow could be observed at low penetration rate [13] [49]. The reason behind that may turn to the loss of connectivity between the vehicles, as well as it may belongs to the uncertainty of models and assumption used in the studies (for example considering all studied vehicles as passenger cars). In Contrast, the majority of the studies have a common positive conclusion to the impact of high penetration rate of autonomous vehicles. In which higher road capacities, smoother vehicles interactions, more safety and stability of traffic and saved travel time can be demonstrated. Regarding the time headway and gaps, the researchers didn't fix a specific range for the theoretical headway. This is because of the variety of the model of simulation used for the process of validation. In addition, the existence of multiple vehicle types which lead to various dynamic characteristics results. For example, small sized vehicles maintain shorter safe gaps with the vehicle ahead and accept smaller lateral clearances to make lateral movements as compared to trucks have perform low flexibility during performing the acceleration and deceleration as well as perform lateral movement and lane change. Overall, the results obtained by the reviewed studies give an enormous contribution to the field of vehicle automation impact on traffic flow and road capacities. The improvement for both road sections and signalized intersections was introduced with a detailed process of implementation of different simulation models by the researchers.

Table 1

Papers reviewed in a chronological order

Author (Year) [Ref]	Model/ Analysis Framework	Main Findings
Arem et al. (2006) [10]	MIXIC Simulation	• CACC penetration < 40% has no effect on traffic. • CACC penetration > 60% affect traffic stability
Kesting et al. (2007) [17]	IDM Model	• Above 50% of ACC vehicles, the capacity increases faster than for lower percentages.
Shladover et al. (2012) [16]	AIMSUN Simulation	• Increasing the percentage of CACC from (0 to 100)% will lead to an increase of the capacity from (2000 to 4000) vph respectively.
Arnaout and Arnaout (2013) [11]	Agent-based Simulation	• Capacity and traffic flow performance increased. • CACC advantage appears at 40% or more, and at it will be at it's minimal for rates less than 40%
Tsugawa (2013) [45]	(CFD) Simulation	When the speed of the platoon of is 80 km/h: • 13% reduction in energy consumption at 10 m gap • 15% reduction in energy consumption at 4 m gap
Lu and Shladover (2013) [46]	DSRC Coordination	A gap of 6 m is to form a platoon of three trucks: • First truck fuel reduction is 4.3% • Second truck fuel reduction is 10%

		• Third truck fuel reduction is 14%
Li et al. (2013) [50]	ACUTA, VISSIM	• The approach capacity increased by 33% as the intersection could process additional 450 veh/h
Guler et al. (2014) [47]	Minimizing Delay	• Average delay at the intersection is significantly reduced by 60% when the penetration rate is 60%.
Ziegler et al. (2014) [25]	Optimization Model	• Design a vehicular trajectory for maneuvering fully autonomous vehicles
Fernandes (2014) [43]	MATLAB/ Simulink	• Capacity will be 7200 passenger per hour (at minimum vehicle occupancy) • Capacity will be 28000 passenger per hour (at maximum vehicle occupancy)
Gouy et al. (2014) [14]	SCANeR studio	• Negative effects of mixed traffic on unequipped vehicle by maintaining short time headways.
Harwood and Reed (2014) [40]	VISSIM Simulation	• The carriageway capacity increased by 2.1% when 50% of HGVs+5 is in road trains, and by 2.1% when 50% of HGV+8 is in road trains.
Tehrani et al. (2015) [26]	PreScan Simulation	• Evaluation of proposed automatic lane change methods for complex scenarios.
Aria et al. (2016) [15]	VISSIM Simulation	• AV scenario shows a remarkable improvement of average density by 8.09% • Enhancement for average travel speed by 8.48% • Average travel time reduced by 9.00%
Zhou et al. (2017) [34]	IDM Model	• Reduction in travel time and congestion with increasing AVs penetration rate by (0%, 5%, 15% and 25%) considering safe time gaps.
Liu et al. (2017) [23]	Cellular automaton Model	• Reduction in congestion levels reaches its optimum at 50% AVs penetration. • Traffic capacity and free-flow speed increase positively with penetration level
Calvert et al. (2017) [13]	LMRS Simulation	• Negative effect on traffic flow at low penetrations. • capacity improvements at AV rates > 70%
Ramezani et al. (2017) [52]	Delay estimation	• At 35% penetration level, the minimum delay observed in the mixed lanes. • By increasing the penetration level, the best configuration is to reserve a lane for mixed lane and another for an autonomous vehicle.
Talebpour et al. (2017) [36]	Microscopic Simulation	• Beneficial lane reservation for AVs at penetration rate of 50% for the two-lane highway and 30% for the four-lane highway.
Steck et al. (2018) [31]	Mixed logit	• Travel time reduced by 31% for private AVs. • SAV has 10% less negativity than manual driving
Mena-Oreja et al. (2018) [39]	SUMO Simulation	At AV penetration level of 100%: • Conservative gaps increase traffic flow by 9.39%

		• Neutral gaps increase traffic flow by 26.09% • Aggressive gaps increase traffic flow by 26.09%
Vukadinovic et al. (2018) [41]	C-V2X	• C-V2X resulted in shorter inter-truck distances than IEEE 802.11p and thus increasing density.
Gong et al. (2019) [42]	NGSIM Simulation	• CACC-DIFT increase noise mitigation factor, minimize spacing error, and speed tracking error, and provide string stability of the CAV platoon.
Li and Wagner (2019) [12]	SUMO Simulation	• Insignificant impact of AVs at until it reaches 70% when an enhancement to traffic flow is observed. • Improvement in total throughput, maximum volume, and travel time by 83%, 88% and 23% respectively when AV penetration rate is 100%
Martin-Gasulla et al. (2019) [51]	VISSIM Simulation	• Increment in throughput is achieved by 44% for 100% penetration rate of CAVs. • Reduction in control delay can reaches 17%
Szibma and Hartmann (2020) [30]	VISSIM Simulation	• Saving in travel time up to 20% for level 4 AVs • Saving in travel time up to 27% for level 5 AVs
Lu et al. (2020) [35]	SUMO Simulation	• Traffic capacities are 16-23% larger than that of all conventional vehicle scenario in case of 100% AVs
Baz et al. (2020) [48]	VISSIM Simulation	• AV/AV model resulted in reduction in delay time by 65% and 84% as compared to a conventional traffic control of a roundabout and four leg Int. • AV/OV model reduced delay time by 30% and 89%
Berktaş and Tanyel (2020) [49]	SIDRA Simulation	• The effect of AVs is negligible up to 1250 veh/h. • At 40% penetration when the volume is 1750 veh/h, the delay time at the intersection increased by 300% • The capacity of the intersection decreased by using autonomous vehicles without communication.
Carrone et al. (2021) [37]	IIDM Model	• Travel time savings are 9% for a 50% penetration rate of AVs and 16% for 75% AVs, while it reaches 49% at 100% penetration rate. • Throughput increases by 8% for a 50% of AVs and 14% for 75% AVs, and became 30% at 100% AVs
Ma et al. (2021) [32]	SUMO Simulation	• Reduction in travel time by 13.5% in 2030 and 16.4% in 2050. • Traffic throughput improvement by 21.93 in 2030 and 22.08 in 2050.
Wang et al. (2021) [27]	MIL Simulation	Improvement to passenger comfort achieved when maximum lateral acceleration reduced by 75.54%.
Obaid and Torok (2021) [33]	VISUM model	• Reduction in travel delay by 37.87% • Increment in average travel speed by 4.08%
Wang et al. (2021) [28]	Hybrid Condition	• Traffic efficiency: Average speed of Hybrid Condition is higher than IDM and MOBIL by 2.8%

Park et al. (2021) [18]	VISSIM Simulation	• Reduction in average delay time by 31% at full penetration rate of AVs • Increase in traffic capacity by 40% when AV penetration rate reached 100%.
Mushtaq et al. (2021) [44]	SUMO Simulation	• Significant reduction in collision rate, from 73% to 12.5% has been observed.

Conclusions

This paper has systematically reviewed a concise, state of the art, selection of studies, addressing the impact of vehicle automation, on traffic flow. It summarizes and thoroughly discusses the main findings and results achieved, by the models and analysis frameworks used by various researchers. Some of the affecting factors to road capacity improvements, under the use of automated driving have been identified from the reviewed studies, these include the travel behavior, represented by longitudinal and lateral movement behavior, travel time effect, platoon formation effect and intersection control system effect. The researchers came with a common conclusion stated that the positive benefits of autonomous and connected vehicle might be absent at low penetration rates, while a clear improvement to traffic flow start to emerge at medium to high penetration rates. Regarding travel behavior factors, it is believed that a great advantage come from a greater degree of homogeneity during the transition phase from conventional driving to automated driving. This may turn to the shorter reaction time of autonomous vehicles, which means that disturbances are promptly reacted to. Eventually, maintaining the traffic string stability due to the sufficient time headways. In contrast, the effect of lane changing may remain unclear and at minimal values due to lack of empirical ground facts and theoretical constructs. Furthermore, developing reserved lanes for autonomous vehicles can potentially increase the saved travel time and will improve the performance of both signalized intersection and the platoon. However, this technique will restrict the number of lanes available to conventional vehicles and may cause traffic congestion in urban areas. Therefore, optional use of the reserved lane is recommended by the researchers, to achieve more gains relevant to traffic flow improvement. Finally, the future specifics of the advanced technology remains unknown, especially in the area of vehicle automation and sensors technology. The reviewed papers give the “up-to-date” information on the studied topic and the outcomes provided by this work, might be valuable to both researchers, as well as policymakers. Despite the fact that these findings are not sufficiently reliable to be used to inform policy, the objectives gained are generally enough, to provide some useful insights for the direction systems may go in coming years.

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