Impede autonomous vehicles merging at on-ramps?

Christine Buisson *
University of Lyon, ENTPE, IFSTTAR, LICIT
UMR _T 9401, F-69518, LYON, France
Tel: +33 4 72 04 77 69
Email: christine.buisson@ifsttar.fr

Mehdi Keyvan-Ekbatani
University of Canterbury
Civil and Natural Resources Engineering
Private Bag 4800, Christchurch 8140, New Zealand
Email: mehdi.ekbatani@canterbury.ac.nz

Peter Wagner
Institute of Transport Systems, German Aerospace Center (DLR)
Rutherfordstrasse 2, D-12489 Berlin, Germany
Email: peter.wagner@dlr.de

* Corresponding author

Paper #18-00938 submitted for presentation at the 97th Annual Meeting Transportation Research Board, Washington D.C., January 2018

Word count: 5466 words + 6 figure(s) × 250 + 2 table(s) × 250 = 7466 words

November 16, 2017
ABSTRACT
This paper sheds some light on the macroscopic and microscopic characteristic of traffic flow on freeways in the merging areas in presence of Human-Driven Vehicles (HDV) and Connected Autonomous Vehicle (CAV) by thoroughly digging into the literature, exploiting real data and simulating simple scenarios. In particular, in the first step, an extensive literature review on merging behaviour for current and future traffic conditions (i.e. having HDV or HDV and/or CAV on the road) has been carried out. This is followed by an analysis of single vehicle data from a freeway in Lyon to illustrate current speed and headway distributions which are most likely to change with the introduction of CAV’s. Finally, some microscopic simulation results are presented which show that traffic flow typically gains from the introduction of CAV’s, but may also display negative consequences under certain circumstances. This simulation study focused mainly on the traffic characteristics at the merging area in presence of CAV. It remains for future work to map out precisely where the introduction of CAV’s improves the traffic system, and where amendments have to be made to prevent negative side-effects. It should be noted that calibrating and validating the micro-simulation tools which simulate traffic scenarios in presence of CAV’s will indeed be challenging in the future. This needs extra attention for research.

Keywords: microscopic simulation, traffic control, ramp metering, connected and automated vehicles
Traffic simulation is used to evaluate the impact of various enhancements or control measures on the performance of the traffic system at a global level. Although often the impact is analyzed via global variables (e.g. total travel time, throughput etc.), the individual behaviour (e.g. microscopic interactions) plays a vital role in the overall performance. This is mainly due to the stochastic nature of the individual driving behavior.

Diakaki et. al (1) distinguished various types of CAV depending on their impact (i.e. direct or indirect) on traffic flow. Several recent studies have shown that it is very likely that the progressive emergence of CAV will modify the traffic flow behavior (2). Figure 1 presents various possible combinations in case of a traffic share with CAV and HDVs. Classically there is only one type of interactions involved in car following: an HDV following an HDV. Note that in the rest of the paper, trucks and buses are not explicitly considered. However, they might be also automated and can be consider as vehicles with a slightly different set of parameters.

Introducing CAV to the traffic generates four types of interactions. This means that we may need up to four types of car-following behavior models. Model development in case of having a CAV following any other vehicle (CAV or HDV, i.e. interactions 3 and 4 in figure 1) is rather simple as it does not have to encompass a reproduction of human behavior. For a given type of automated car, the response to any stimuli generated by a modification of the speed of the leader will result in a given modification of the automated follower. Note that it is likely that more than one type of automated cars will be available. This generates a set of stochastic combination of behavior that must be reproduced through a large amount of replications.

Van Arem et al. (3) were among the first researchers to propose a car-following logic for CACC. Simulation of mixed (CAV and HDV) and CAV-only traffic has been the topic of several recent studies in the literature. As shown in (4), the effect of CAV on traffic is not always positive,
especially in case where there is no cooperation between them. The vast majority of the existing papers address the question of longitudinal effect of CAV by including their behavior in existing simulation tools (e.g. (3) where the tool is MIXIC, (5) applying VISSIM, and (6), (7) where the effect of connected vehicles is introduced into the MOVSIM simulation tool) but very few papers report simulation studies of merge behavior. Important to notice is the paper (8) where the authors modify the parameters of the car-following part of their model (IDM) while conserving the same lane changing procedure for adaptive cruise control (ACC) vehicles (MOBIL). Based on a simulation study, they concluded that for a three lane freeway with an on-ramp, which is congested in the reference scenario with 100 % HDV, the free flow condition might be kept by having only 25 % of ACC vehicles.

The car-following behavior of an HDV following an HDV is not supposed to be modified by the presence of other types of vehicles in the surrounding environment. Nevertheless, the presence of short time headways in the surrounding environment may lead to distance reduction for the HDVs. Interestingly, Gouy (9) conducted driving-simulator-based studies which showed HDVs following a platoon of automated vehicles, tend to reduce their time headway with their automated leader. Apart from simulator studies, on-board driving experiments might be carried out. In this type of experiments, an observer within the car films and registers any action of the driver. After the driving episode questions are asked to the driver to better understand his / her motivations to act a way or another. This type of experiment was reported in (10) and (11) for driving on a long stretch of freeway, in (12) for merges location and in (13) for the transition between ACC and manual driving.

Let us underline that the complexity generated in modelling of car-following behaviour if automated vehicles are introduced (and especially if there are more than one type of automated cars) is very little compared to the modifications of lane changing behavior (mandatory or discretionary). Indeed, in car following only the leader affects the subject vehicle behavior; in lane changing behavior, the subject vehicle driver reacts to three surrounding vehicles at least: leader in the initial lane and leader and follower of the target lane. With two types of vehicles and a set of three cars can have $2^3 = 8$ different combinations. This is in the simple case where the first potential gap in the target lane is accepted. But, if the subject drivers rejects the first gap(s) he/she analyses, then the behavior of one more or two more cars is or are involved (leading to 16 or 32 different possible combinations).

The paper (14) is one of the rare cases where a simulation tool is used to examine the impact of the modification of the merge behavior of CAV on the global throughput. This is done by the introduction of the CAV merging algorithm in CORSIM. The paper (15) reports a simulation experiment where the VISSIM simulation tool is used to test the merging control algorithm. In addition, see (16) for an extensive review of control of automated and cooperative vehicles at merges and intersection. It is noteworthy to mention that even after careful survey of the existing literature, we were not able to identify studies about the modification of the merge behavior induced by the presence of CAV on the freeway. Moreover, most part of the literature on CAV simulation is devoted to the car following part of traffic models and there is a large ignorance of the lane changing behavior.

This brief literature review shows that traffic simulation needs significant improvements before being able to evaluate the future traffic composed of human driven and connected and / or automated vehicles. Not only a careful modelling effort of the phenomena is needed in this direction, but also a calibration and validation of the resulting tool.

TRB 2018 Annual Meeting Revised paper
Earlier, generic rules of traffic simulations have been formalized by the traffic simulation tool box (17) and also within the Multitude project (18). Obviously, their recommendation of realizing careful calibration and validation studies cannot be applied in the case of Connected and Autonomous Vehicles (CAV) and/or for mix traffic conditions (Human-Driven Vehicles (HDV) and CAV). The authors believe that this must be replaced by a detailed and cautious verification of the simulation results to assess the simulation capabilities of tackling the subject at hand. Developing a common understanding of the expected behavior of the future traffic on the basis of a set of simple cases is a step in this direction. We chose here to contribute towards this direction by analyzing in details the merge behaviour on freeways. Indeed, merges are the bottlenecks causes of many freeways and they are a place where both car following and lane changing phenomenon play a crucial role and interfere. In this paper, we emphasize that some simple effects of stochasticity have not been examined on the basis of simple case studies.

The content of the paper can be summarized as follows: First, we examine the physics of merges as they currently are. Second, an extensive literature review has been carried out on the novel strategies that can be used for merges improvement. Third, applying Lyons’ real data some simple traffic analysis has been done. By means of a simulation study, we have shown that introducing CAV to the traffic might have cons or pros for the overall traffic performance. Research recommendations are discussed in the last paragraph before conclusion.

PHYSICS OF TRAFFIC FLOW AT MERGES WITH CONVENTIONAL VEHICLES AND FUTURE VEHICLES

In this work, as we have seen in the introduction, we chose to concentrate on merges when they are active bottlenecks. An active bottleneck is a stretch of a road or of a freeway where congestion is created, i.e. traffic is free flowing downstream of this location and congested upstream. Without loss of generality, we consider here only locations with an isolated merge, without interactions with other merge or diverge.

This part is mainly devoted to an analysis of the physics of the current traffic flow at various scales. We will first describe the macroscopic behavior of merges as they are now, without any connected nor autonomous vehicles, but with in some cases ramp metering. Then we will describe the behavior at merges in a microscopic way. Those two sub-parts are summarized in table 1. The last part of this paragraph is devoted to a synthetic presentation of the various modifications of those behaviors that will be introduced by connected and autonomous vehicles (CAV).

Macroscopic behaviors

Figure 2 illustrates the various behaviors observed in congestion in the different positions of vehicles alongside the merging infrastructure. When congestion occurs, in the freeway part, three zones are visible:

- Upstream zone where there is free flowing traffic. During the increasing phase of the total demand the front between freely flowing and queued traffic goes upstream, and downstream during the decrease of the total demand;
- Central zone where freeway traffic is congested and where the mandatory lane changes of merging vehicles occur;
- Downstream zone where traffic is progressively accelerating from congested regime to
<table>
<thead>
<tr>
<th>Traffic features</th>
<th>References</th>
<th>Variables</th>
<th>Measurement method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity drop</td>
<td>(19) (20) (21)</td>
<td>Stable state flows: before and after comparison</td>
<td>Loops</td>
</tr>
<tr>
<td>Capacity sharing ratio</td>
<td>(22) (23)</td>
<td>Upstream branches flows in congestion</td>
<td>Loops</td>
</tr>
<tr>
<td>Input ramp flow variability before congestion</td>
<td>-</td>
<td>Short aggregation period loops data</td>
<td>Loops</td>
</tr>
<tr>
<td>Freeway Car Following (CF) behavior</td>
<td>(24) (25)</td>
<td>Speed and headway distributions</td>
<td>Trajectory data, individual loop data</td>
</tr>
<tr>
<td>Freeway Lane Change (LC) behavior (i.e. courtesy)</td>
<td>(26)</td>
<td>Speeds and gaps</td>
<td>Trajectory data</td>
</tr>
<tr>
<td>Ramp CF Behavior</td>
<td>-</td>
<td>Initial speed value</td>
<td>Trajectory data</td>
</tr>
<tr>
<td>Ramp LC Behavior: Accepted and rejected gaps Speed profile</td>
<td>(27)</td>
<td>Gaps lengths Speeds Accelerations</td>
<td>Trajectory data</td>
</tr>
</tbody>
</table>

1 We refer to the main references when available. A “-” means that we did not succeed to find any.

free flow.

Evolution of congestion at active bottleneck merges
Consider macroscopically a merge like the one presented in the figure 2. If, at the beginning of the peak hour, merging flow and/or freeway flows increase until the total demand becomes higher than the capacity of the merge, congestion occurs. The main macroscopic features of congestion at merges are presented in figure 3, which is inspired by (28) and (29).

Capacity drop
When congestion is created, the maximal throughput observed at the downstream end of the congested area is lower than the maximal flow observed just before the breakdown. The difference between the two values is named "capacity drop". The oblique red lines of Figure 3(a) and 3(b) indicate the total capacity. Let us see how this is modified due to the congestion creation. Here, we indicate the maximal downstream capacity in congestion (dashed oblique red line) by drawing
Numerous empirical studies of the capacity drop are presented in literature, see (25) for a review. In (25) an extensive study of 16 Californian freeways is presented, which is based on a uniform methodology. They report a capacity drop variation between 16% (for two lanes) and 9% (for 5 lanes) with a linear decrease depending on the number of lanes.

Recently, in (20, 30) an analytic way of explaining the capacity in congestion was proposed. The main studied phenomena is the creation of voids in front of a car after a low speed insertion (28). Moreover, trucks and cars are taken into account and the variability of their behaviors. The equation of the effective capacity (i.e. capacity in congestion) encompasses many different parameters: wave speed, truck fraction, means and standard deviations of cars and trucks accelerations, and of their maximal densities. The article (20) presents an empirical validation of this formula on a congested merge of the M6 near Manchester, UK. They observed a global capacity drop of 26%. The lane-by-lane prediction is coherent with the observation.

**Capacity sharing ratio**

The various labeled zones of figure 3.(b) correspond to various types of congested regimes:

- In zone 1 the ramp demand is in excess and is not satisfied on the contrary to the freeway demand. Congestion is on the ramp.

- In zone 2 none of the two demands can be satisfied. The functioning point is located on the dark blue point of the figure. The capacity is shared between the two entering branches of the merge. This ratio is usually (after Daganzo (31)) named $\alpha$ ratio.

- In zone 3, the ramp flow is satisfied and the congested branch is the freeway.

The slope of the capacity sharing ratio can be observed when the two upstream branches are congested. In (22), Bar-Gera and Ahn have presented the results gathered from a comprehensive
FIGURE 3 Macroscopic behavior of a merge depending on the freeway and ramp flows (inspired from (29)).

(a) Before congestion onset. If ramp and freeway flows are above the maximal downstream capacity, congestion occurs.

(b) After congestion onset without ramp metering.

(c) With ramp metering.
Californian data-set. They show (see fig. 8 herein) a clear linear relationship between the ratio of the number of merging lanes compared to the number of downstream lanes and the capacity sharing ratio. In (23) it is shown that in some cases, the lane flow distribution must be taken as an explanatory variable of the merge ratio.

Ramp input flow short frequency oscillation
In many configurations the highway is included in an urban network and on-ramps are located downstream a traffic light. This generates group of vehicles (typically of 10 vehicles) entering the on-ramp during a short period of time (say, 20 seconds) and periods of no traffic (also during a few tens of seconds). The first period of rather high input flow may, if the highway flow is sufficiently high, create congestion on the mainline. Due to the capacity drop, the maximal output flow is immediately reduced even during the no ramp flow periods. Therefore, the congestion will not vanish before a significant decrease of the total entering demand.

Macroscopic efficiency of ramp metering
Since decades, the idea of placing traffic lights at the on-ramps of freeways to artificially limit its entering flow while maintaining free-flow conditions on the freeway itself has shown to be effective, as many authors report (32, 33, 34, 35). There are at least two complementary macroscopic explanations of ramp metering efficiency.

The first one is fluctuations of ramp entering flow with a frequency of tens of seconds. Placing a ramp metering traffic light between the surface network traffic lights and the main section splits those bunches of groups of entering traffic info small drops. Those small groups of a few vehicles (ideally groups are made of one single vehicle, if the entering flow is small enough, namely lower than 900 veh/h if the minimal cycle length is of 4 seconds) are less likely to generate disturbances in the main freeway lanes. Indeed when those disturbances are created, the capacity drops and the exiting flow is limited.

Capacity drop is the second cause of ramp metering efficiency. Indeed avoiding it maintains the best efficiency of the system. Note that when the ramp is fully congested, the metering policy usually imposes the ramp traffic light to turn to permanent green, thus, congestion is created on the freeway. But, as long as the ramp metering uniformize in time the ramp entering flow and thus permits to prevent congestion occurrence, the maximal capacity of the system is maintained. For example, imagine a freeway with an active bottleneck due to a ramp, with a main section of two lanes and a morning peak of 2 hours. Typically, the bottleneck presents a free flow capacity of 4,500 veh/h and its capacity drops to 4,000 veh/h in case of congestion. Therefore maintaining, each working day, during half an hour the ramp metering active permits to reduce the congestion duration from 2 hours to 1.5 hours. As the total wasted time is equal to the square of the congestion duration for the same input flows, this permits to gain a factor of almost two (4/2.25) of the time lost by the freeway users. This time must be compared to the time lost by ramp users, but it is usually much less than the gain of the freeway users.

The figure 3.(c) illustrates the functioning of ramp metering (29) which consists in limiting intentionally the ramp demand thus generating congestion out of the freeway. Globally, the total wasted time of ramp users when traversing this artificially created ramp congestion is lower than the total time lost by freeway users when crossing the congestion zone if there is no ramp metering. The unsatisfied ramp demand in figure 3.(c) (where the capacity in maintained at a rather high value) is lower than unsatisfied freeway demand in the previous figure (where the congestion
occupies the freeway and drops the capacity). The bigger the capacity drop value, the bigger the benefit of ramp metering.

**Microscopic vehicular behaviors at freeway merges**
The behaviors of drivers and of vehicle-drivers pairs are distributed, as was reported for example in (36) about car following and in (10) and (37) for the lane changing. Those distributions can be observed in all parts of the freeway, but they have an even stronger impact at merge locations. In this section we describe individual vehicular characteristics and how their distributions play a role in the merge global behavior with and without ramp metering (see figure 2 and table 1).

*Freeway vehicles car following behavior*
We have seen earlier that merging vehicles speeds and accelerations affect the magnitude of the disturbance caused to freeway vehicles by this insertion. Vice et versa, the characteristics of freeway insertion lane traffic impacts the capacity to merge. Vehicles characteristics encompass speed, headway and lane changing behavior.

As an example, if headway distributions have a small width and mean value, merging will be more difficult than with the same mean but a larger width. Using individual loop detector data collected on freeways permits to build lane by lane inter-vehicular headways as well as individual speeds distributions. An analysis of the headways distributions lane by lane is provided in the section 4. Some drivers of the external lane voluntary decelerate, and thus increase their distance with their leader to let the inserting drivers from the on-ramp execute their merging maneuvers safely. The only experimental way of confirming this is to analyze trajectory data.

The behavior of the drivers of the external lane of the freeway is modified by the insertion of mergers. Immediately after insertion, the distances are unsafe and the drivers modify transiently their speeds to resume safe conditions (24). Another individual freeway car following behavior (and its variability) has a strong impact on traffic flow conditions. This was put in evidence by (25), using NGSim data (38). This is the acceleration behavior at the downstream end of the congested zone.

*Freeway vehicles lane choice and lane changing behavior*
Obviously, for a given total flow, the higher the density on the right lane (the insertion lane) in comparison to the other lane(s), the more difficult the insertion will be. (23) has shown experimentally that the upstream merge lane flow distribution is specific to a given merge.

In the same vein, the lane changes occurring immediately upstream the merge will impact the size and standard deviation of gaps in which merging vehicles can insert themselves. Note that some of those lane changes are not linked with a willing of the drivers to increase their owns’ speed, but to ease the merge of other drivers. Only trajectory data and drivers’ interviews would permit to observe and quantify this behavior (for drivers’ interviews one can use the methodology used by Kondily and Elefteriadou see (39) and in the references quoted herein).

*Car-following on ramp and acceleration lane*
The microscopic modelling of this behavior has no peculiarities compared with other car-following observations. Nevertheless, the boundary conditions of CF on ramps are dictated by the upstream network. A traffic light for example pulses the entering flow and generates groups of tens of vehicles. When using a simulation tool, the boundary conditions must be carefully reproduced.
Using a mean value of one minute or more would lead to underestimating the ramp metering impact.

**Merging vehicles behavior**

The insertion behavior itself is commonly considered to be driven by the mergers’ maximization of their own safety. This implies that:

- Drivers chose safe gaps (i.e. distances between the putative leader and the putative follower) meaning that gaps above a certain threshold might be considered as acceptable.
- Drivers minimize the difference of their own speed and the one of their putative follower.

(40) reports that most of the papers presented in the literature review consider that drivers accept the first gap considered as safe. Usually, the threshold for considering a given gap as a safe one is modelled as depending on the distance with the downstream end of the acceleration lane. This paper presents the observation of individual merging trajectories data collected for two congested freeways (a Dutch and a French). The analysis focused not only of accepted but also on rejected gaps. This reveals that a significant part of the drivers first refuse safe gaps to finally accept very short ones at the downstream part of the acceleration lane.

As far as we know there was not such an exploration of the speeds differences at the insertion point. Clearly the remaining acceleration lane length and the acceleration power of the merge vehicles both play a major role in this behavior. Note that this is a key behavior as we have seen earlier that speed differences strongly impact the creation and disappearance of voids between the merger and his/her follower (41) In the same paper, as well as in (20), the acceleration after the insertion is an explaining factor of the capacity loss at merges.

**Microscopic efficiency of ramp metering**

We have above presented two main microscopic behaviors, namely car following and lane changing and the way their interactions may originate and maintain congestion at on-ramps. To the best of our knowledge the merging behavior of the vehicle passing the traffic light, leaving the on-ramp and then joining the main stream has not been correctly reproduced in microscopic simulation tools. More specifically, the speed adaptation of the merging driver to accommodate to the external lane users speed has not been taken into account.

**Modification of car-following and lane changing behavior induced by the emergence of CAV**

Table 2 presents in a comprehensive way all the emerging control methods that could be applied at merges, with the help of the analysis of a subset of recent literature. Most of the works presented here are related to car-following behavior. A complete and detailed analysis of this table would be outside of the scope of this paper. Nevertheless, we want to underline that the work presented in (41) (and in other papers of the same group of authors) is a remarkable exception. Indeed those authors had access to on-site experiments with CAV. This permitted them to realize real calibration and validation of their model. All other papers mentioned in the table 2 are based on authors’ assumption of what would be the behavior of next generation vehicles.

The next section is devoted to analyze in simulation on a simple cases that this mixing of various types of cars (HV and CAV) may significantly modify the global structure of traffic.
### TABLE 2 Main types of Connected and Automated Vehicles features that can be used at merges.

<table>
<thead>
<tr>
<th>Topic</th>
<th>Example of relevant papers</th>
<th>Content / remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 different settings for ACC</td>
<td>(8)</td>
<td>Distinction of the ACC behavioral rules depending on traffic conditions. Free flow (speed &gt; 60 km/h); congestion (speed &lt; 40 km/h); upstream jam front; downstream jam front. At bottleneck locations, the reaction time is reduced.</td>
</tr>
<tr>
<td>CACC</td>
<td>(4) (42, 43)</td>
<td>Describes the various types of CACC Report various experiments with CACC vehicles and produce models from it</td>
</tr>
<tr>
<td>ACC / CACC</td>
<td>(44, 45)</td>
<td>Solution of the control problem based on the Pontryagin’s minimum principle The second paper considers the cooperative control. A fraction of conventional vehicles is possible.</td>
</tr>
<tr>
<td>Conventional, connected, autonomous, vehicles</td>
<td>(2, 46)</td>
<td>CV CF model with 7 parameters + utility evaluation Conn.V CF: IDM. Autonomous V: (3) Realism difficult to assess because many combinations are examined and no simple verification is reported.</td>
</tr>
<tr>
<td>Downstream jam accel. (sags)</td>
<td>(47) (48)</td>
<td>Impact of reaction time decrease on a real case. Definition of an optimal strategy: deceleration acceleration deceleration acceleration.</td>
</tr>
<tr>
<td>Connected Variable speed limit</td>
<td>(6)</td>
<td>Global + cooperative VSL system, impact on consumption and pollution</td>
</tr>
<tr>
<td>AV reserved lanes</td>
<td>(49) (50)</td>
<td>Comparison of various policies of use of reserved lanes Analytic computation of capacity for any AV/CV share and platoon size; definition of optimal policies.</td>
</tr>
<tr>
<td>Merge assistance</td>
<td>(51) (14, 15, 16, 52)</td>
<td>3 strategies to use optimally the CV to ease the merge. Various approaches where CV are not really considered. Same objective: optimal merging strategies for connect / automated vehicles to increase safety</td>
</tr>
<tr>
<td>Platooning control</td>
<td>(53)</td>
<td>The idea is to split in the future the trucks platoon near ramps to ease the merging maneuvers.</td>
</tr>
<tr>
<td>Freeway LC control</td>
<td>(54, 55, 56, 57)</td>
<td>Control approaches to use optimally the capacity of each lane, upstream a (fixed or moving) bottleneck. No real study of the microscopic impact of lane changes on the receiving lane.</td>
</tr>
</tbody>
</table>
Individual observations with loop detectors: the Lyon data

The data presented in the figure 4 were collected during a typical week (21 to 28 May 2016) on three locations of the Lyon external ring road named 'C', 'B', and 'A' in the direction of travel. The presented speed distributions are from data taken during the night hours between 22 o’clock in the evening and 5 o’clock in the morning to get an approximation of the preferred speeds of the vehicles. The headway distributions have been sampled during the busiest time of the day, which is between 16 and 19 o’clock in the afternoon. Only working days have been included in the data presented in figure 4, the left panel is for the left lane, while the right panel is for the right lane. The speeds on the right lanes are typically lower than on the left lane, the headway distributions are very similar except for the one at 'B3' where extremely dense traffic is observed, which is due to the downstream divide at sites 'A'. Another important variable for the simulation below is the width of the speed distribution quantified by the coefficient of variation \( \sigma_v \) of the speed distributions. They have been estimated from the data as 0.122, 0.159, and 0.163 for the left lanes at ‘C’, ‘B’, and ‘A’, respectively, and similar values for the other lanes.

Simulation experiments with SUMO: impact of autonomous behavior distribution

Simulations have been performed with SUMO (58), an open-source microscopic traffic flow simulation. The corresponding input files are available upon request from one of the authors (PW).

The simulations implement the scenario of an on-ramp, together with four different variants of traffic (see the text below for an explanation of the three parameters):

1. fully automated and homogeneous \((T = 0.5s, \sigma_a = 0.1, \text{ and } \sigma_v = 0.15)\),
2. fully automated and heterogeneous traffic \((T = 0.5s, \sigma_a = 0.1, \text{ and } \sigma_v = 0.01)\),
3. fully human (heterogeneous), \((T = 1.1s, \sigma_a = 0.9, \text{ and } \sigma_v = 0.15)\)
4. 50% human and 50% automated \((T = 0.5s, 1.1s, \sigma_a = 0.1, 0.9, \text{ and } \sigma_v = 0.15)\).

All simulations are done with the default model of SUMO, which is a slightly modified variant of the model of Stefan Krauß (59). It has seven parameters: the minimum headway time \(T\), the acceleration noise \(\sigma_a\), its maximum acceleration \(a = 2.6m/s^2\) and deceleration \(b = 4.5m/s^2\), its length \(\ell = 4.5m\), the minimum gap (distance to the lead vehicle when standing) \(g_0 = 2.5m\), and the maximum (preferred) speed of a vehicle \(v_{pref}\). There is another important parameter that is the coefficient of variance of the preferred speeds \(\sigma_v\) which plays an important role. It is not an individual parameter of a vehicle, but describes a vehicle fleet.

Three parameters change between the different scenarios: \(T\), \(\sigma_a\), and \(\sigma_v\), the rest are left at their default values. Automated vehicles have a small headway and a small acceleration noise \(T = 0.5s\) and \(\sigma_a = 0.1\), while normal vehicles have a larger headway and a large acceleration noise, \(T = 1.1s\) and \(\sigma_a = 0.9\).

The heterogeneity of the vehicles is in \(\sigma_v\). In three scenarios, \(\sigma_v = 0.15\) is used which is in line with other empirical studies and the data from the Lyon data presented above, while for the fourth scenario all automated vehicles drove with the same speed, i.e. \(\sigma_v = 0.01\) is chosen.

This has been done since it makes a certain difference in the outcome.
FIGURE 4  Presentation of the Lyon data (external ring road, between "Bonnevay" and "Cusset"). Top: layout of the road (traffic goes from left to right). Left panel is the headway and speed distribution of the left lanes, right panel the ones of the right lanes.

The simulation’s virtual study area is organized as follows: the vehicles enter the roughly 8 km freeway with 3 lanes at edge ”in” (which is short, it decouples the insertion process from the simulation itself), then there follows a 6 km edge named ”equi” which relaxes the insertion
configuration (e.g. the headway and lane distributions) to the ”natural” one of the models, then
there follows a 300 m merging area (”merge”, which is 4 lanes), and finally a 2km edge ”down”
(not utilized here) and an edge ”out” where the vehicles are removed from the simulation. The
simulation state is sampled by three single vehicle loop detectors at 1km, 3km and 5km of the edge
”equi”, by one hour averages of all the important traffic flow variables for all the edges, and by the
time travel times of all the simulated vehicles. Each simulation is run for 10 simulated hours, with a
time-step size of 0.5 seconds which is dictated by the smallest time headway in the system (this is
a requirement of the microscopic model).

The original idea was to test the following assumption: if all the vehicles run at an headway
of $T = 0.5 s$, nobody could enter at the on-ramp. While this is a valid idea, it turns out to be correct
only under certain circumstances. The result is shown in the space-time plots in figure 5.

![Space-time plots](image-url)

**FIGURE 5** Space time diagrams of the four scenarios above. The top left is the scenario 1,
while the top right is scenario 2. Demand is very large. The bottom scenarios are with a
human part, so the demand was smaller.

More details concerning the validity and realism of the simulation can be found from the
plots of the headway distributions. The figure 6 presents the results for the scenarios 1, 3, and 4.
Compared to the real headway distributions, the simulated ones are a bit smaller.

It can be seen, that in most cases there is a sufficient share of large headway’s that allow
vehicles to enter at the on-ramp (a more detailed statistical analysis confirms this), except for the
FIGURE 6 Headway distributions for scenarios 1, 3, and 4. The left panel is for the right lanes, while the right panel is for the left lanes. Note how the distributions relax along the edge to a final outcome.

case of the homogeneous, autonomous traffic, where the insertion process the on-ramp fails. It can also be seen from a more detailed analysis, that the left lane in case of the autonomous traffic becomes very dense. The simulation seems to miss however in the human case the true width of the headway distribution as measured on the Lyon freeway, it is too small. This is a known issue of most microscopic car-following models, and it most likely is due to insufficient modeling of human drivers, or simply to an insufficient modeling of the heterogeneity of humans (36).

DISCUSSION AND RECOMMENDATIONS
The authors believe that there is an urgent need not only to design algorithms for CAV’s, but also to think about their impact on the overall transportation system. The current work has just scratched upon the surface of this topic. For instance, there are a few things about automated vehicles that are simple: the algorithms will make much less errors than human drivers (although we should be aware, that all the sensors that are needed do not work perfectly either), and they can realize much shorter reaction-times, and therefore shorter headways on a reliable basis than humans. One may even argue that most of the micro-simulation models on the market are good candidates for the mathematical description of automated vehicles, and not that much for humans. However, other
questions are much more difficult to answer at this moment; e.g.: (i) is the car-following process of
a CAV platoon stable? And much more complicated, (ii) what about the lane-changing processes?
In our view, these are a challenging issues since they are difficult to classify and to build a theory
around them. However, as the example of the simulation in this text shows, they may have a strong
effect on the performance of a transportation system. Therefore, work has to be devoted to these
questions so that one may finally came up with actual recommendations of what has to be put into
all these algorithms to make CAV’s transportation-system friendly.

Finally, we have to admit, that it is truly hard to carry out actual calibration and validation
on micro-simulation tools which are expected to simulate CAV’s. Certain steps might be taken
into this direction. First, even for purely human driven traffic, calibration should be developed so
that the parameters of the models are not just fitting parameters, but also parameters in a physical
sense – they can be measured independently of what came out of a calibration process and still
yield a reliable description of the behaviour of the modelled vehicles. Second, for mixed traffic
with a portion of (semi-)automated vehicles, we need to develop a consensus in the traffic flow
community on some simple cases where the behavior is described in details, at various scales.
To the authors opinion, this would permit to reach a certain form of verification. There are three
canonical methods: calibration, validation and verification (or CVV in short) that are recommended
by the literature (60) to warranty the quality of simulation results. In the near future, we will be
able only to propose verification for HDV /CAV traffic simulation tools. We may conclude that
one has to admit that a certain degree of uncertainty in predicting a future transportation system
which relies on automated vehicles might still remain.

CONCLUSION
This paper provides an extensive overview of the recent works carried out in the area of CAV and
its impact on the traffic flow. A through investigation of the provided literature review in this paper
confirms that despite the numerous studies in the area of CAV systems, works studying the influ-
ence of CAV on traffic flow is not yet promising. Applying Lyon’s real data, the speed and headway
distribution have been derived. Microscopic simulation tool SUMO has been implemented to sim-
ulate different scenarios in a case of having an on-ramp in order to study merging behaviour in
the presence of CAV. The simulation results presented here indicate that care has to be taken when
discussing the properties of future transportation systems which most likely have autonomous ve-
hicles in them. Although the presented case is clearly an extreme situation – might be handled by a
proper communication between the vehicles, or even by more adaptive lane-changing algorithms,
it demonstrates an example where autonomous vehicles are in fact impeding traffic flow.

Future research may deal with the definition of a set of examples situations where the
mixing of various types of vehicles challenge the existing simulation tools. Thus the community
would dispose of a common basis permitting the building of a common agreement on what will
be the behaviour of a traffic with a share between connected and automated vehicles and human
driven vehicles.

ACKNOWLEDGEMENTS
The authors want to thank Métropole de Lyon and Direction Inter-départementale des Routes
Centre-Est (Thierry Carpentier, Olivier Sené and Claude Doussot) for providing the individual
data from loops of the urban highway of Lyon-Villeurbanne.
References


