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1 **Impede autonomous vehicles merging at on-ramps?**

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1 **ABSTRACT**

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

17 *Keywords:* microscopic simulation, traffic control, ramp metering, connected and automated vehi-
18 cles

1 INTRODUCTION

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

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

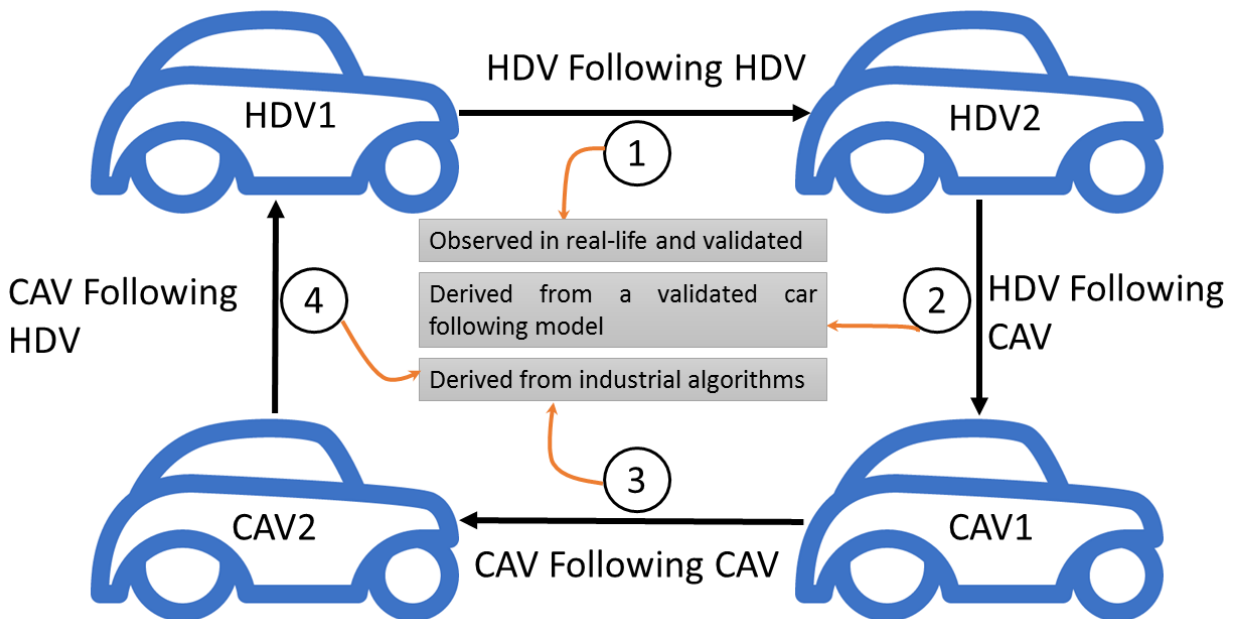


FIGURE 1 Illustration of the various types of car-following in case of sharing of regular and connected or automated vehicles (HDV and CAV, respectively).

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

22 Van Arem et al. (3) were among the first researchers to propose a car-following logic for
 23 CACC. Simulation of mixed (CAV and HDV) and CAV-only traffic has been the topic of several
 24 recent studies in the literature. As shown in (4), the effect of CAV on traffic is not always positive,

1 especially in case where there is no cooperation between them. The vast majority of the existing
2 papers address the question of longitudinal effect of CAV by including their behavior in existing
3 simulation tools (e.g. (3) where the tool is MIXIC, (5) applying VISSIM, and (6), (7) where
4 the effect of connected vehicles is introduced into the MOVSIM simulation tool) but very few
5 papers report simulation studies of merge behavior. Important to notice is the paper (8) where the
6 authors modify the parameters of the car-following part of their model (IDM) while conserving
7 the same lane changing procedure for adaptive cruise control (ACC) vehicles (MOBIL). Based on a
8 simulation study, they concluded that for a three lane freeway with an on-ramp, which is congested
9 in the reference scenario with 100 % HDV, the free flow condition might be kept by having only
10 25 % of ACC vehicles.

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

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

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

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

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

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

19 **PHYSICS OF TRAFFIC FLOW AT MERGES WITH CONVENTIONAL VEHICLES AND** 20 **FUTURE VEHICLES**

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

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

32 **Macroscopic behaviors**

33 Figure 2 illustrates the various behaviors observed in congestion in the different positions of ve-
34 hicles alongside the merging infrastructure. When congestion occurs, in the freeway part, three
35 zones are visible:

- 36 • Upstream zone where there is free flowing traffic. During the increasing phase of the
37 total demand the front between freely flowing and queued traffic goes upstream, and
38 downstream during the decrease of the total demand;
- 39 • Central zone where freeway traffic is congested and where the mandatory lane changes
40 of merging vehicles occur;
- 41 • Downstream zone where traffic is progressively accelerating from congested regime to

TABLE 1 Macroscopic and microscopic types of behaviors, main references¹ about experimental observations and relevant data and variables.

	Traffic features	References ¹	Variables	Measurement method
MA CRO SCO	Capacity drop	(19) (20) (21)	Stable state flows: before and after comparison	Loops
PIC	Capacity sharing ratio	(22) (23)	Upstream branches flows in congestion	Loops
	Input ramp flow variability before congestion	-	Short aggregation period loops data	Loops
MI CRO SCO	Freeway Car Following (CF) behavior	(24) (25)	Speed and headway distributions	Trajectory data, individual loop data
PIC	Freeway Lane Change (LC) behavior (i.e. courtesy)	(26)	Speeds and gaps	Trajectory data
	Ramp CF Behavior	-	Initial speed value	Trajectory data
	Ramp LC Behavior: Accepted and rejected gaps Speed profile	(27)	Gaps lengths Speeds Accelerations	Trajectory data

1 free flow.

2 *Evolution of congestion at active bottleneck merges*

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

7 *Capacity drop*

8 When congestion is created, the maximal throughput observed at the downstream end of the con-
9 gested area is lower than the maximal flow observed just before the breakdown. The difference
10 between the two values is named "capacity drop". The oblique red lines of Figure 3(a) and 3(b)
11 indicate the total capacity. Let us see how this is modified due to the congestion creation. Here,
12 we indicate the maximal downstream capacity in congestion (dashed oblique red line) by drawing

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

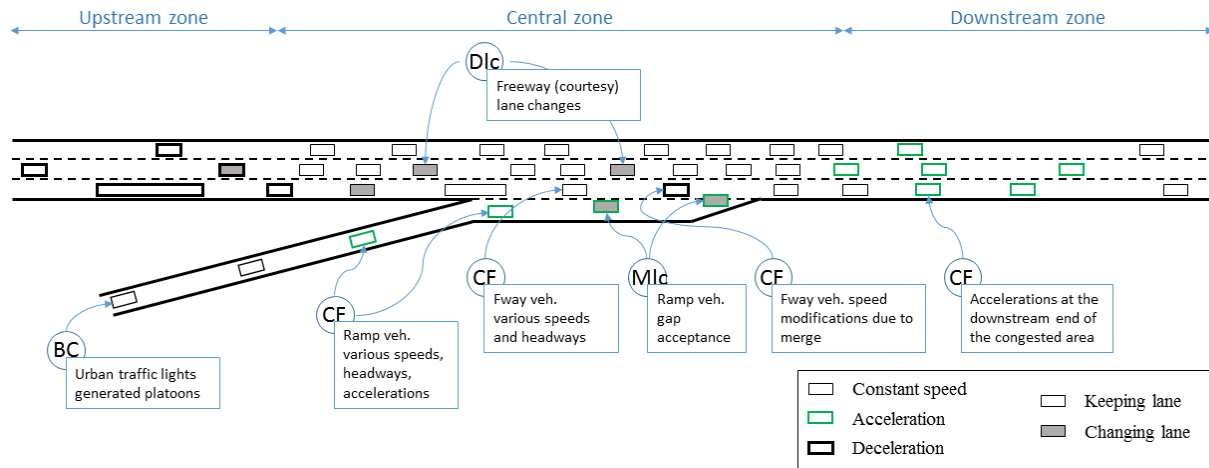


FIGURE 2 illustration of the various microscopic behaviors occurring at a merge. CF: car-following, BC: boundary conditions, DLC: discretionary lane change, MLC: Mandatory lane change.

1 a line parallel to the one corresponding to the capacity in free flow.

2 Numerous empirical studies of the capacity drop are presented in literature, see (25) for a
 3 review. In (25) an extensive study of 16 Californian freeways is presented, which is based on a
 4 uniform methodology. They report a capacity drop variation between 16% (for two lanes) and 9%
 5 (for 5 lanes) with a linear decrease depending on the number of lanes.

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

14 *Capacity sharing ratio*

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

- 16 • In zone 1 the ramp demand is in excess and is not satisfied on the contrary to the freeway
 17 demand. Congestion is on the ramp.
- 18 • In zone 2 none of the two demands can be satisfied. The functioning point is located
 19 on the dark blue point of the figure. The capacity is shared between the two entering
 20 branches of the merge. This ratio is usually (after Daganzo (31)) named α ratio.
- 21 • In zone 3, the ramp flow is satisfied and the congested branch is the freeway.

22 The slope of the capacity sharing ratio can be observed when the two upstream branches are
 23 congested. In (22), Bar-Gera and Ahn have presented the results gathered from a comprehensive

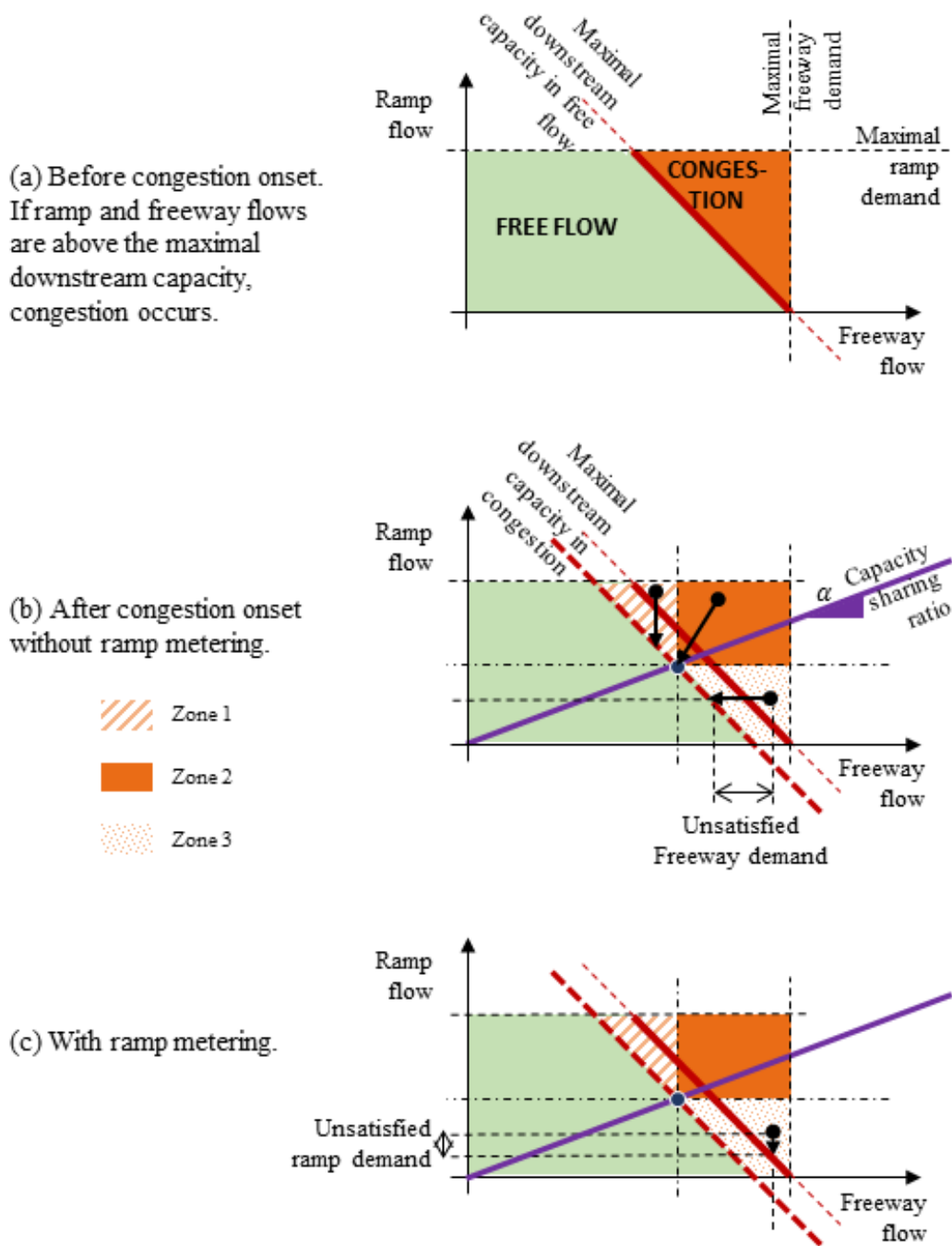


FIGURE 3 Macroscopic behavior of a merge depending on the freeway and ramp flows (inspired from (29)).

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

5 *Ramp input flow short frequency oscillation*

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

13 *Macroscopic efficiency of ramp metering*

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

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

25 Capacity drop is the second cause of ramp metering efficiency. Indeed avoiding it maintains
26 the best efficiency of the system. Note that when the ramp is fully congested, the metering policy
27 usually imposes the ramp traffic light to turn to permanent green, thus, congestion is created on
28 the freeway. But, as long as the ramp metering uniformize in time the ramp entering flow and thus
29 permits to prevent congestion occurrence, the maximal capacity of the system is maintained. For
30 example, imagine a freeway with an active bottleneck due to a ramp, with a main section of two
31 lanes and a morning peak of 2 hours. Typically, the bottleneck presents a free flow capacity of
32 4,500 veh/h and its capacity drops to 4,000 veh/h in case of congestion. Therefore maintaining,
33 each working day, during half an hour the ramp metering active permits to reduce the congestion
34 duration from 2 hours to 1,5 hours. As the total wasted time is equal to the square of the congestion
35 duration for the same input flows, this permits to gain a factor of almost two ($4/2.25$) of the time
36 lost by the freeway users. This time must be compared to the time lost by ramp users, but it is
37 usually much less than the gain of the freeway users.

38 The figure 3.(c) illustrates the functioning of ramp metering (29) which consists in limiting
39 intentionally the ramp demand thus generating congestion out of the freeway. Globally, the total
40 wasted time of ramp users when traversing this artificially created ramp congestion is lower than
41 the total time lost by freeway users when crossing the congestion zone if there is no ramp me-
42 tering. The unsatisfied ramp demand in figure 3.(c) (where the capacity is maintained at a rather
43 high value) is lower than unsatisfied freeway demand in the previous figure (where the congestion

1 occupies the freeway and drops the capacity). The bigger the capacity drop value, the bigger the
2 benefit of ramp metering.

3 **Microscopic vehicular behaviors at freeway merges**

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

9 *Freeway vehicles car following behavior*

10 We have seen earlier that merging vehicles speeds and accelerations affect the magnitude of the
11 disturbance caused to freeway vehicles by this insertion. Vice et versa, the characteristics of free-
12 way insertion lane traffic impacts the capacity to merge. Vehicles characteristics encompass speed,
13 headway and lane changing behavior.

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

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

27 *Freeway vehicles lane choice and lane changing behavior*

28 Obviously, for a given total flow, the higher the density on the right lane (the insertion lane) in com-
29 parison to the other lane(s), the more difficult the insertion will be. (23) has shown experimentally
30 that the upstream merge lane flow distribution is specific to a given merge.

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

37 *Car-following on ramp and acceleration lane*

38 The microscopic modelling of this behavior has no peculiarities compared with other car-following
39 observations. Nevertheless, the boundary conditions of CF on ramps are dictated by the upstream
40 network. A traffic light for example pulses the entering flow and generates groups of tens of
41 vehicles. When using a simulation tool, the boundary conditions must be carefully reproduced.

1 Using a mean value of one minute or more would lead to underestimating the ramp metering
2 impact.

3 *Merging vehicles behavior*

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

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

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

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

22 *Microscopic efficiency of ramp metering*

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

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

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

38 The next section is devoted to analyze in simulation on a simple cases that this mixing of
39 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.

Topic	Example of relevant papers	Content / remarks
5 different settings for ACC	(8)	Distinction of the ACC behavioral rules depending on traffic conditions. Free flow (speed > 60 km/h); congestion (speed < 40 km/h); upstream jam front; downstream jam front. At bottleneck locations, the reaction time is reduced.
CACC	(4) (42, 43)	Describes the various types of CACC Report various experiments with CACC vehicles and produce models from it
ACC / CACC	(44, 45)	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.
Conventional, connected, autonomous, vehicles	(2, 46)	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.
Downstream jam accel. (sags)	(47) (48)	Impact of reaction time decrease on a real case. Definition of an optimal strategy: deceleration acceleration deceleration acceleration.
Connected Variable speed limit	(6)	Global + cooperative VSL system, impact on consumption and pollution
AV reserved lanes	(49) (50)	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.
Merge assistance	(51) (14, 15, 16, 52)	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
Platooning control	(53)	The idea is to split in the future the trucks platoon near ramps to ease the merging maneuvers.
Freeway LC control	(54, 55, 56, 57)	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.

1 IMPACT OF STOCHASTICITY ON THE GLOBAL BEHAVIOR: ANALYSIS OF REAL 2 DATA AND MIXED TRAFFIC SIMULATION

3 Individual observations with loop detectors: the Lyon data

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

17 Simulation experiments with SUMO: impact of autonomous behavior distribution

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

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

- 22 1 fully automated and homogeneous ($T = 0.5s$, $\sigma_a = 0.1$, and $\sigma_v = 0.15$),
- 23 2 fully automated and heterogeneous traffic ($T = 0.5s$, $\sigma_a = 0.1$, and $\sigma_v = 0.01$),
- 24 3 fully human (heterogeneous), ($T = 1.1s$, $\sigma_a = 0.9$, and $\sigma_v = 0.15$)
- 25 4 50% human and 50% automated ($T = 0.5s$, $1.1s$, $\sigma_a = 0.1$, 0.9 , and $\sigma_v = 0.15$).

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

33 Three parameters change between the different scenarios: T , σ_a , and σ_v , the rest are left
34 at their default values. Automated vehicles have a small headway and a small acceleration noise
35 $T = 0.5s$ and $\sigma_a = 0.1$, while normal vehicles have a larger headway and a large acceleration noise,
36 $T = 1.1s$ and $\sigma_a = 0.9$.

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

40 This has been done since it makes a certain difference in the outcome.

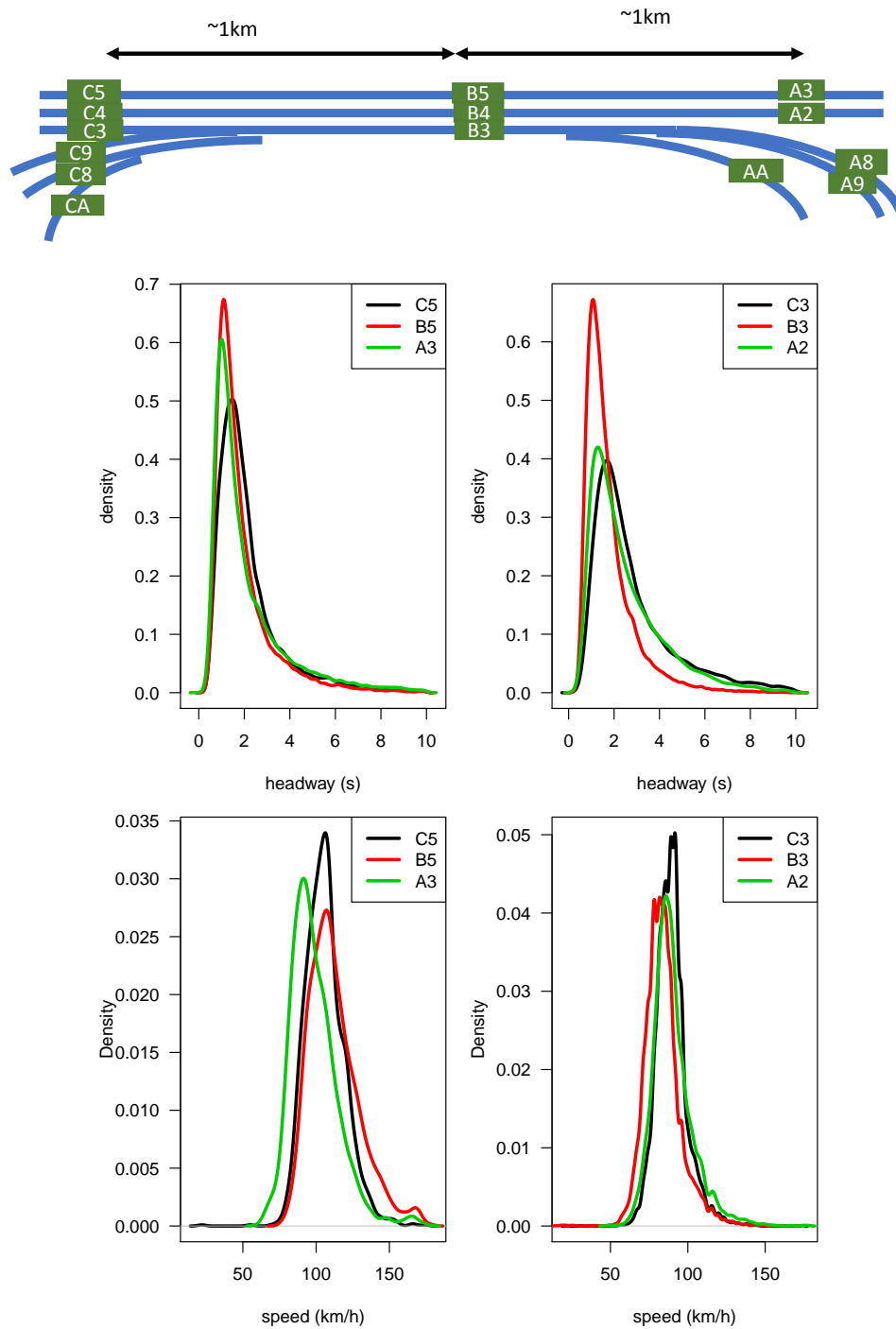


FIGURE 4 Presentation of the Lyon data (external ring road, between "Bonnevay" and "Cusset"). Top: layout of the road (traffic goes from left to right). Left panel is the headway and speed distribution of the left lanes, right panel the ones of the right lanes.

1 The simulation's virtual study area is organized as follows: the vehicles enter the roughly
 2 8 km freeway with 3 lanes at edge "in" (which is short, it decouples the insertion process from
 3 the simulation itself), then there follows a 6 km edge named "equi" which relaxes the insertion

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

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

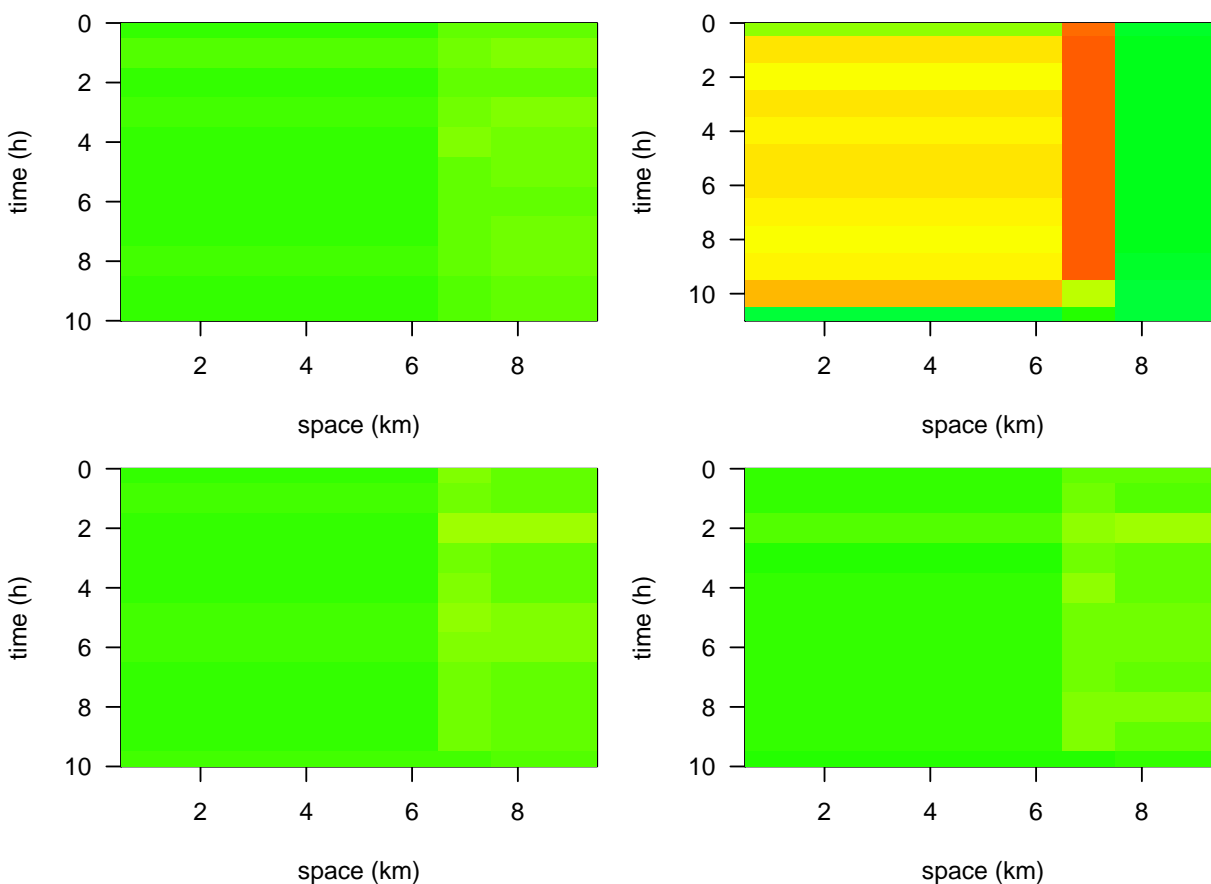


FIGURE 5 Space time diagrams of the four scenarios above. The top left is the scenario 1, while the top right is scenario 2. Demand is very large. The bottom scenarios are with a human part, so the demand was smaller.

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

15 It can be seen, that in most cases there is a sufficient share of large headway's that allow
 16 vehicles to enter at the on-ramp (a more detailed statistical analysis confirms this), except for the

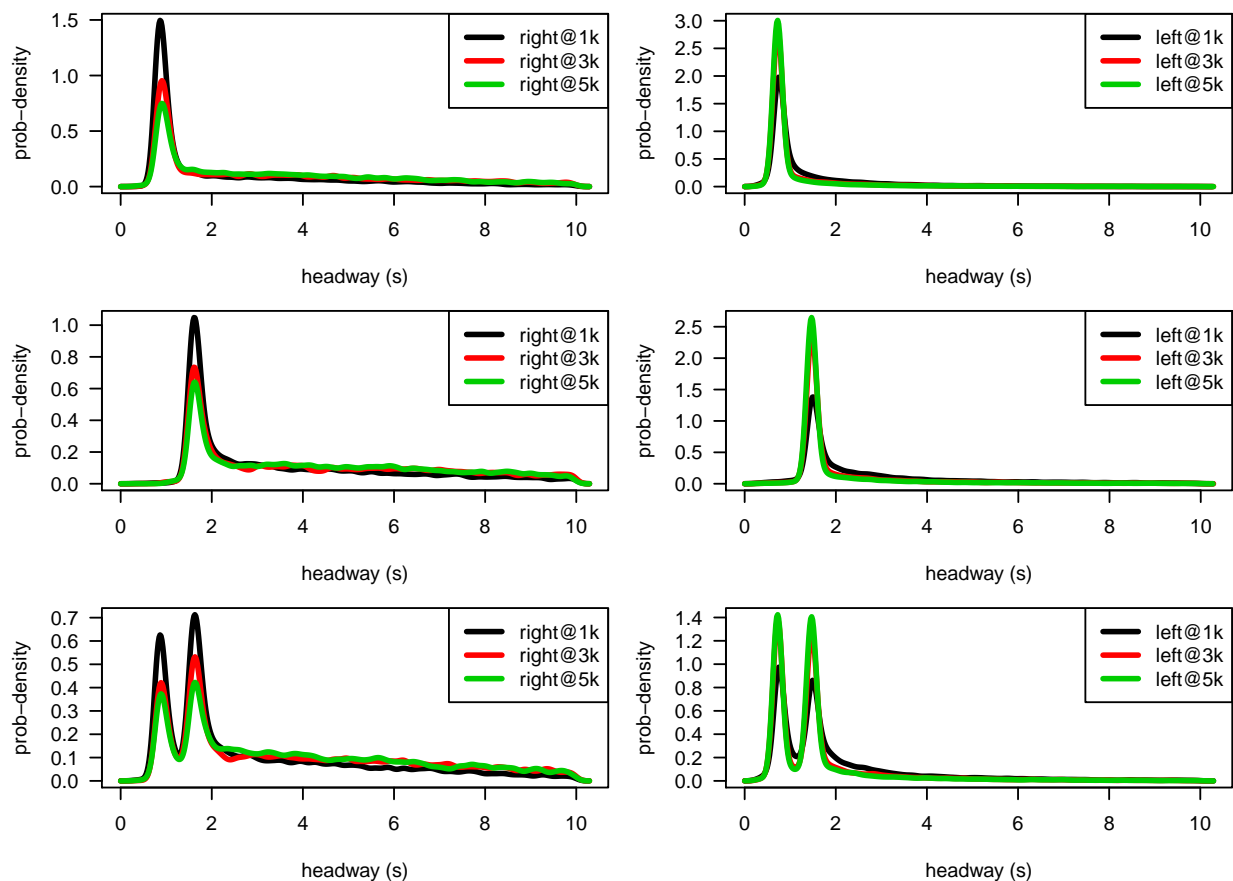


FIGURE 6 Headway distributions for scenarios 1, 3, and 4. The left panel is for the right lanes, while the right panel is for the left lanes. note how the distributions relax along the edge to a final outcome.

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

7 DISCUSSION AND RECOMMENDATIONS

8 The authors believe that there is an urgent need not only to design algorithms for CAV's, but also to
 9 think about their impact on the overall transportation system. The current work has just scratched
 10 upon the surface of this topic. For instance, there are a few things about automated vehicles that
 11 are simple: the algorithms will make much less errors than human drivers (although we should be
 12 aware, that all the sensors that are needed do not work perfectly either), and they can realize much
 13 shorter reaction-times, and therefore shorter headways on a reliable basis than humans. One may
 14 even argue that most of the micro-simulation models on the market are good candidates for the
 15 mathematical description of automated vehicles, and not that much for humans. However, other

1 questions are much more difficult to answer at this moment; e.g.: (i) is the car-following process of
2 a CAV platoon stable? And much more complicated, (ii) what about the lane-changing processes?
3 In our view, these are a challenging issues since they are difficult to classify and to build a theory
4 around them. However, as the example of the simulation in this text shows, they may have a strong
5 effect on the performance of a transportation system. Therefore, work has to be devoted to these
6 questions so that one may finally came up with actual recommendations of what has to be put into
7 all these algorithms to make CAV's transportation-system friendly.

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

22 CONCLUSION

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

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

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