Influence of Drivers' Behavior on Traffic Flow at Two Roads Intersection

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Abstract. This paper presents a model to evaluate how heterogeneities in road traffic caused by different driver's profiles affect the dynamics of traffic on a road with an unsigned intersection. These driver's profiles, defined by the use of different acceleration policies, are not observed in usual measurements and can only be evaluated through computational simulations. A modified Nagel-Schreckenberg (NaSch) cellular automata model with a Probability Density Function (PDF) Beta is used to model these distinct behaviors, where each driver profile is represented by a Beta PDF. The analysis of space-time diagrams herein obtained and traditional traffic diagrams corroborate the importance of taking into account different profiles of drivers on the road.

Keywords: Traffic flow · Cellular automata · Road intersection · Driver's behavior · Computational simulations

1 Introduction

Traffic flow directly affects the quality of life of citizens in modern cities. Traffic jams and their psychological effects, besides the pollution associated with heavy traffic are some of the reasons why a better understanding of traffic flow has received so much attention in the last decades. Several solutions have been proposed to try to mitigate the effects of the increasing amount of vehicles in big centers, whether by the use of electric vehicles to minimize air pollution, or autonomous cars, in order to reduce traffic jams and reduce the number of traffic accidents. However in any situation it becomes important to know traffic dynamics and the understanding of its behavior in different situations. In order to study and to analyze traffic flow's characteristics, many mathematical models, both macroscopic and microscopic, have been employed. In the microscopic

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modeling Cellular Automata (CA) methods have been applied with good results, since the dynamics of the CA tries to closely mimic the movement of all vehicles and their interactions. Some of the main advantages of CA models are that they are easily implemented, lead to moderate computational cost and keep the basic features of the phenomenon [1–3]. As an example we can mention that there is already, in North Rhine-Westphalia [4], a CA model presenting on-line information about the freeway to guide drivers passing trough it. Recently, in all types of modeling, it has been tried to evaluate how the different drivers profiles affect the dynamics of the road traffic, in particular, the aggressive and the cautious or timid direction [5–14]. In this context, in particular, the CA models can be of great interest because it allows to describe the behavior of each driver profile that one wants to represent. Zamith et al. [12] proposes a CA model where the driver profiles, defined by the use of different acceleration policies are modeled using a non-uniform Probability Density Function (PDF), the PDF Beta. Thus, different parameters of PDF Beta will define different acceleration policies, where each driver "tries" to accelerate more aggressively or cautiously. In recent published works Leal-Toledo et al. [13] and Almeida et al. [14] used the same proposal to modify the traditional probabilistic NaSch model [15] in order to evaluate the effects of different acceleration profiles and their influence in the occurrence of dangerous situations that can lead to road accidents.

Considering the importance of the understanding of traffic flow in modeling signed or not, urban and highways crossings [16–18], in the present work we intend to show how important are the above considerations evaluating the influence of different acceleration profiles when there are a unsigned intersection in the road. For this purpose we model a intersection with a closed circuit, as proposed in Marzoug et al. [18], where two perpendicular roads cross in the middle. Marzoug et al. [18] showed that the fundamental diagram depends strongly on the probability of priority P and it exhibits four phases: free flow, the plateau, the jamming phases and a new phase occurring for any value of $P \neq 0.5$. These phases disappear gradually as one increases the probability P, and disappear completely for $P = 0.5$. In this work, we present how the different acceleration policies alter these results, as well as we evaluate the influence of braking probability on them. Different values of maximal velocities are also computed and for the purpose of comparing the influence of the acceleration policies on the results, in each analysis the same V_{max} is considered for all profiles.

The paper is structured as follows: Sect. 2 presents the modified NaSch model, with heterogeneity in acceleration and deceleration policies. In Sect. 3 we describe the intersection model used in our simulations. Next, in Sect. 4, we show some results to illustrate how different acceleration policies affect the flow traffic at two roads with an intercection. Discussions and conclusions are presented in Sect. 5.

2 Nagel-Schreckenberg Model with Driver's Behavior

Despite being a simple model, the automata cellular NaSch model [15] is able to represent traffics main characteristics such as the spontaneous occurrence of traffic jams and the relation between traffic flow and density, representing the free and congested flow [16]. It's a one-dimensional probabilistic cellular automata (CA) traffic model where space and time are discretized resulting that the lane is described by a lattice of cells that are occupied or not by vehicles and in its traditional form a vehicle occupies only one cell.

In CA models, at any instant of time t, a vehicle occupies the cell $x(i,t)$ and has the velocity $v(i,t)$, which tells how many cells it will move at that instant of time. The number of unoccupied cells in front of each vehicle, generally called as gap, is denoted by $d(i,t) = x(i+1,t) - x(i,t-1) - L$, where $L = 1$ is the vehicles' length, and the vehicle $i+1$ is considered to be in front of the vehicle i. As usual, periodic boundary condition can be considered and traditional NaSch model can be described by four simple rules applied simultaneously to all vehicles (Algorithm 1):

Table 1. Algorithm 1.

Acceleration:	$v(i,t+1) = min[v(i,t) + A, V_{max}]$
Deceleration:	$v(i,t+1) = min[v(i,t+1), d(i,t)]$
Random deceleration:	$v(i,t+1) = max[v(i,t+1) - A, 0]$, with a probability p_b
Movement:	$x(i,t+1) = x(i,t) + v(i,t+1)$

In Table 1 we have the following parameters: V_{max}, the maximum velocity that a vehicle can reach; A, the acceleration rate of the vehicles and $A = 1\,cell/s^2$ in traditional NaSch model; p_b, a stochastic parameter, modeling the uncertainty in driver behavior and representing the probability that a vehicle, randomly, do not accelerate to reach the maximum velocity or even slows down. In NaSch model typical cell length is 7.5 m and each time step corresponds to one second, resulting vehicles' speed multiples of 1 cell/s, which is equivalent to 27 km/h. In order to take into account traffic influence of driver's behavior in a modified NaSch model we considered the evaluation of how different acceleration policies influence the traffic dynamics. It was proposed that the acceleration A, which in the NaSch model is a constant, can assume different values. To do this, a more refined network discretization is used to allow the representation of these different policies. Each vehicle may then occupy more than one cell, as can be seen in Fig. 1, and each driver profile tends to accelerate in a characteristic way: abruptly (aggressive profile) or more smoothly (non-aggressive profile). A non-uniform Probability Density Function (PDF) is used to describe trends in the drivers' acceleration policy. The new acceleration parameter is stochastic and is calculated as:

$$A = int[(1-\alpha)A_{max}] \tag{1}$$

where α is a random value between 0 and 1 and *int* returns the nearest integer of its argument. Therefore, the probability p models the drivers' intention to

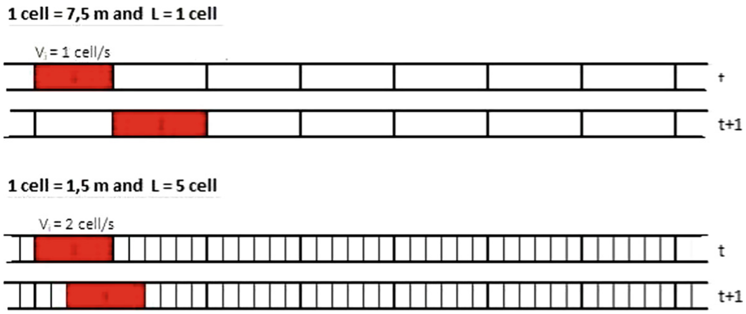


Fig. 1. Discretization scheme

accelerate while α models how they will accelerate and α is modeled by a continuous Beta Function (PDF), defined by:

$$B(a,b) = \frac{\Gamma(a+b)}{\Gamma(a)\Gamma(b)} x^{a-1}(1-x)^{b-1} \tag{2}$$

where $0 \leq x \leq 1$ and $\Gamma(n+1) = n!$, being n a positive integer. Depending on the values of the parameters a and b, the majority of α values will tend to different values between 0 and 1 and those closer to 0 will produce accelerations A closer to A_{max}, while those closer to 1 will produce accelerations A closer to 0. In fact, the α values float around the Beta mean value, which are given by $\mu = \frac{a}{a+b}$. Thus, it is possible to predict each profile acceleration trend based on the average of the Beta function used to model it. Therefore, each profile is given by a different pair (a, b) of parameters, defining one PDF Beta function, and the different mean values of these distributions model the desired acceleration tendencies as shown in Fig. 2.

3 Intersection Model

For the purpose of the present work, where we intend to evaluate the influence of different acceleration profiles at an unsigned intersection of two roads, we consider a closed circuit, as proposed in Marzoug et al. [18], where two perpendicular roads cross in the middle. In this configuration we will consider that the crossing consists of the intersection of two stretches of roads: R1 and R2. In R1 the vehicles move from top to bottom and in R2 vehicles move from left to right. In this closed circuit, the exit of R1 is the entrance of R2 and the exit of R2 is the entrance of R1, as shown in Fig. 3.

In the traditional Nasch model the road intersection is composed by one cell. Thus in our modification, the crossing is composed by the number of cells that the vehicle occupies. As in Marzoug et al. [18], we denote G1 and G2 as the distances of the vehicle to the intersection cell. When two vehicles can cross at the same time-step, the priority is given to the vehicle in R1 with probability P, and to the vehicle in R2 with probability $1 - P$. Near to the intersection the vehicle that has priority moves with its normal velocity and the vehicle that does not have priority decelerates, as described in Algorithm 1, where $d_i = G_i$ is the distance to the intersection.

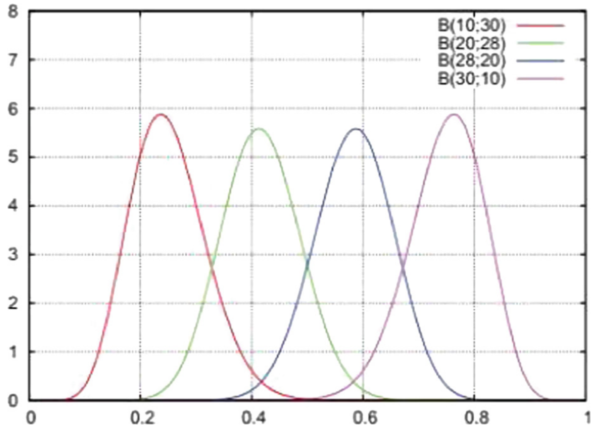


Fig. 2. PDF Beta functions

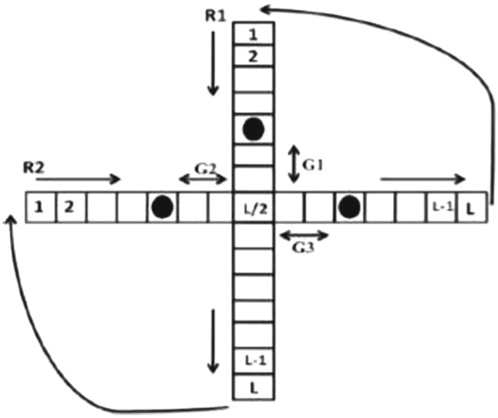


Fig. 3. Crossing scheme

4 Numerical Results and Discussion

For all results here presented the total length of the circuit is 30 km, and the results are obtained after 20,000 time steps. The first 17,000 steps were discarded since transient effects were not the target here and the density ρ is the percentage of cells occupied on the road.

To maintain analogy with the traditional NaSch model, a vehicle occupies 7.5 m, divided in n cells, where the length of cells l_c are given by $l_c = (7.5/n)\, m$, and $A_{max} = n\, cell/s^2$. For results presented here we took $n = 5$ and we called p_b the probability of braking and P the priority probability of the vehicle in $R1$ (Fig. 3). Besides the results from traditional NaSch model, we present results when $n = 5$ for four different profiles chosen to represent the different acceleration policies, with distinct averages and similar variance [14]. So, we consider in this work:

$B(10, 30)$ for the Aggressive profile, with $\mu = 4\, cell/s^2 = 6\,\mathrm{m/s^2}$;
$B(20, 28)$, for the Intermediary I, with $\mu = 3\, cell/s^2 = 4.5\,\mathrm{m/s^2}$;
$B(28, 20)$, for the Intermediary II, with $\mu = 2\, cell/s^2 = 3\,\mathrm{m/s^2}$
$B(30, 10)$, for the Cautious or Non-Aggressive profile, with $\mu = 1\, cells/s^2 = 1.5\,\mathrm{m/s^2}$.

Here μ is the average of all values of A, in Algorithm 1. In traditional NaSch model, $\mu = 1\, cells/s^2 = 7.5\,\mathrm{m/s^2}$, with A always equal n.

4.1 The Deterministic Case ($p_b = 0$)

To compare with results obtained by Marzoug et al. [18], we consider the case where $p_b = 0$ in NaSch model.

(i) *Influence of discretization*

To show the influence of discretization in this modeling, we will initially present results of the NaSch model with different discretizations. The vehicle occupies n cells and to maintain equivalence with the original model, the intersection has n cells. The vehicle moves considering both the space available for its movement and its velocity, even if the gap is not a multiple of n. Due to these factors a vehicle can occupy only part of the intersection. In this situation the intersection may be occupied by more than one instant of time by the same vehicle even if it moves. Also, the intersection can be occupied by parts of two vehicles which are in the same direction.

Figure 4 shows the fundamental diagram for $P = 0.5$, $V_{max} = (5 \times n)\, cell/s = 135\,\mathrm{km/h}$ for $n = 1$, 3 and 5. We can observe that the maximum flow in the plateau region is maintained. However, in the traffic jamming region, a new phase arises where there is no flow of vehicles. This is caused by vehicles that remain more than one instant of time at the intersection and by the priority that is given only to vehicles that can pass through the intersection at that instant of time. These situations can not be represented by the traditional NaSch model. It should be remembered that this configuration was generated in a closed circuit, and this is the reason which allows zero flow to occur, since there is no possibility of movement when parts of the road are occupied by vehicles as can be illustrated in Fig. 5.

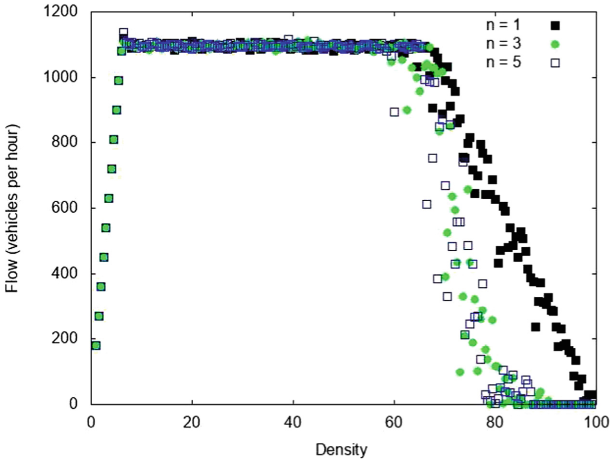
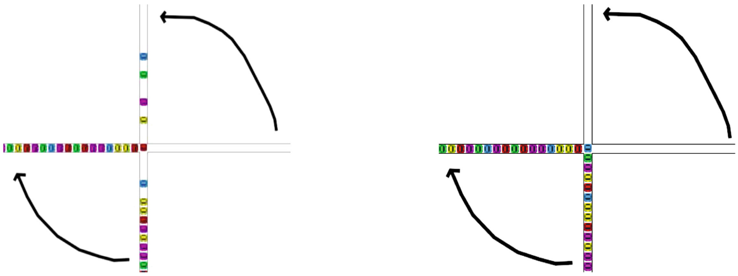


Fig. 4. Flow-density diagram ($P = 0.5$ $V_{max} = 135$ km/h)



(a) Crossing Transient Case (b) Crossing Steady state

Fig. 5. Crossing at different timesteps

(ii) *Proposed model*

It is worth noting that in the modified NaSch model $p_b = 0$ has the same meaning as in the traditional model: the probability of not accelerating or braking. This means that $p_b = 0$ makes all vehicles accelerate whenever possible. However, in our model, unlike the NaSch model, the acceleration is not constant, and is modeled by the Beta Function, making possible the definition of driver profiles based on the mean of the distribution.

To illustrate, we present in Figs. 6 and 7 comparisons for flow-density diagrams, with discretization $n = 5$, for the NaSch and NaSch modified model, for extreme behaviors which are aggressive and cautious profiles with, respectively, maximum velocities $Vmax = 15\,cell/s$ and $V_{max} = 25\,cell/s$ and priority $P = 0.5$. It can be noticed that the cautious profile presents the same flow in the region of low density, where the flow is free. However, the flow drops quickly when there is interaction between vehicles. In this phase, the flow remains practically constant, but the flow in cautious profile is much lower than the NaSch

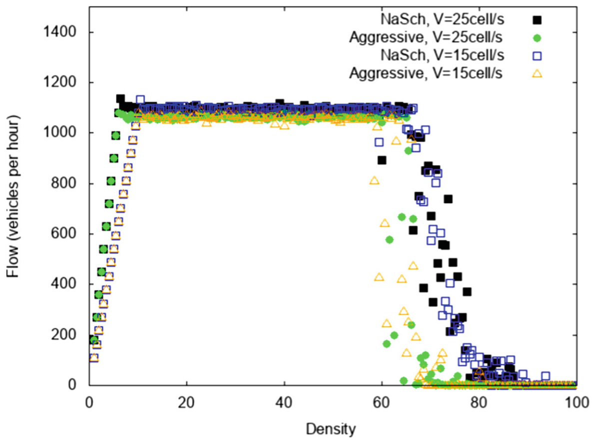


Fig. 6. Flow-density diagram: agressive drivers

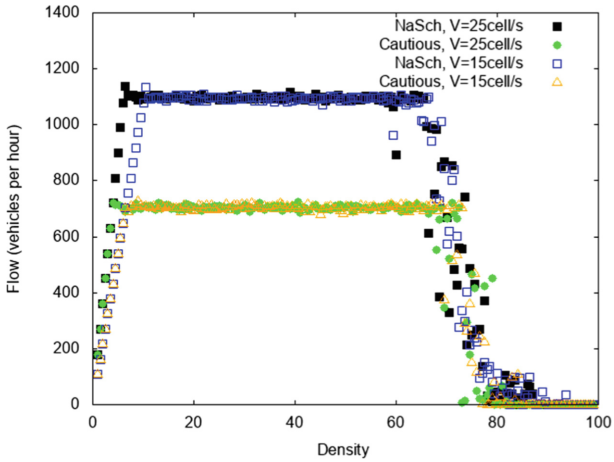


Fig. 7. Flow-density diagram: cautious drivers

model and the aggressive profile. This is because the cautious driver takes longer to resume his velocity when he needs to brake due to the approach of another vehicle. Thereafter, in a fourth step, the velocity becomes close to zero, for the reasons described in the previous example.

4.2 Probabilistic Cases ($P_b \neq 0$)

(i) *Comparing all profiles*

Figures 8 and 9 present respectively results for the flow-density and velocity-density diagrams for the NaSch model compared with the four profiles defined at the beginning of the session: aggressive, intermediate I, intermediate II and

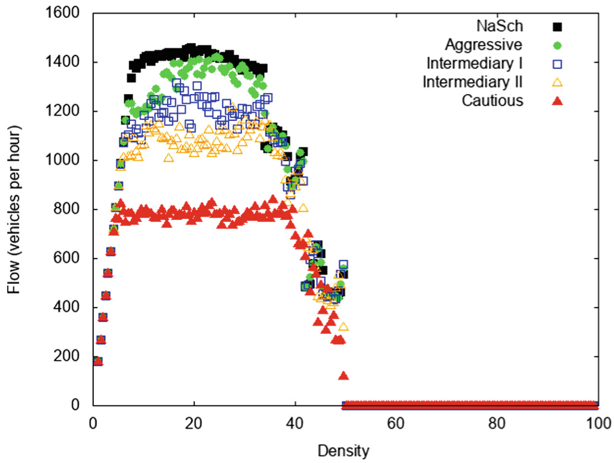


Fig. 8. Flow-density diagram: drivers' behavior comparison ($P = 1$, $p_b = 0.01$)

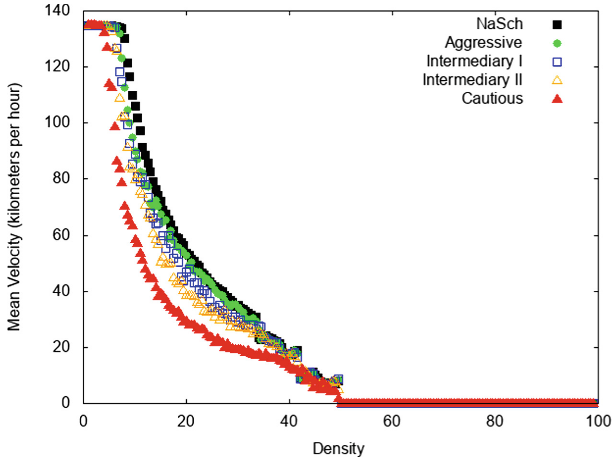


Fig. 9. Velocity-density diagram: drivers' behavior comparison ($P = 1$, $p_b = 0.01$)

cautious, for $n = 5$, $P = 1$ and $p_b = 0.01$. We can observe the existence of four phases defined by Marzoug et al. [18]. We can also observe that both, the second phase (plateau region) (Fig. 8) and the mean velocities (Fig. 9) decrease with the average acceleration of each profile, with a more pronounced difference in the cautious profile.

(ii) *Results for several priorities at the intersection*(P)

Next, Figs. 10 and 11 present flow-density and velocity-density results for the aggressive profile of the modified NaSch model with $p_b = 0.3$, for $V_{max} = 25\,cell/s$ and in Figs. 12 and 13 for $V_{max} = 15\,cell/s$, respectively, for different values of P.

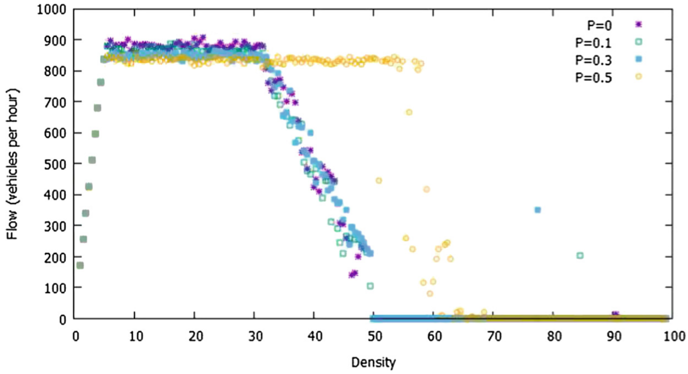


Fig. 10. Flow-density diagram with P varying: agressive driver (V = 135 km/h)

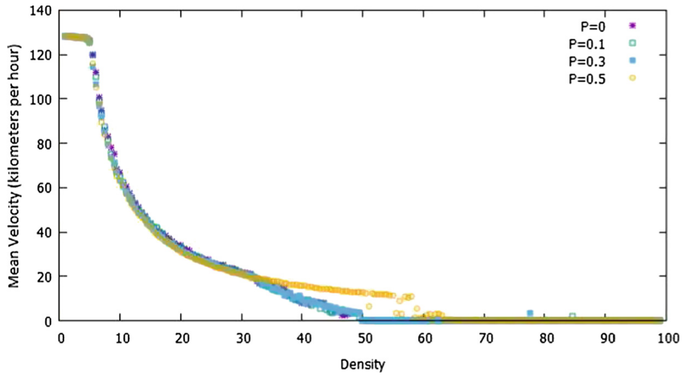


Fig. 11. Velocity-density diagram with P varying: agressive driver (V = 135 km/h)

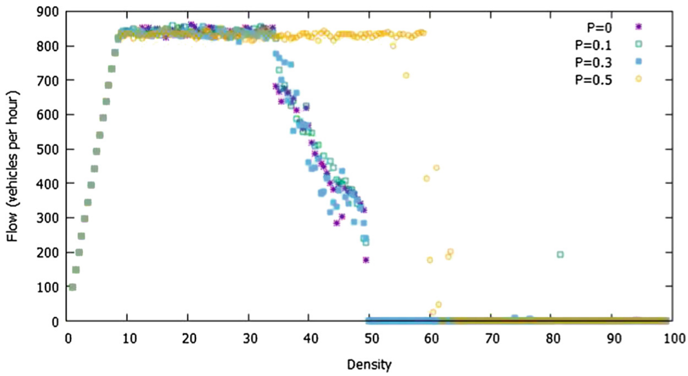


Fig. 12. Flow-density diagram with P varying: agressive driver (V = 81 km/h)

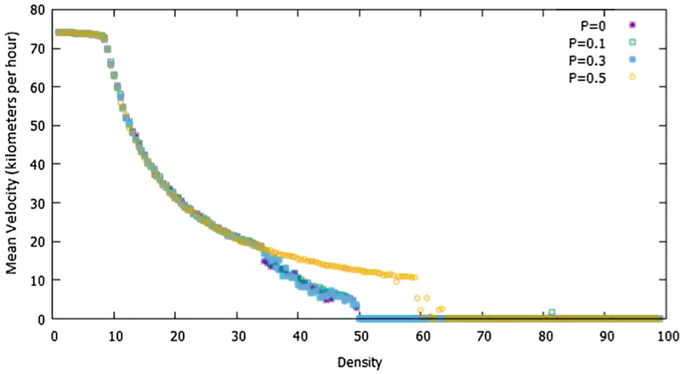


Fig. 13. Velocity-density diagram with P varying: agressive driver (V= 81 km/h)

We can observe that the results show the same discontinuity between the third and fourth phase described by Marzoug et al. [18] when the density $\rho = 50$, except when $P = 0.5$ where this discontinuity occurs when $\rho = 60$. In this case, in the results presented in Marzoug et al. [18], diagrams present only three phases, since the discretization used in the traditional NaSch model does not allow the representation of the situations described in Sect. 4.1 (i).

5 Conclusions

In this work we presented a model to evaluate how driver's behavior, defined by different accelerations policies, can affect the traffic flow on a road with an unsigned intersection. We looked for whether the way drivers speed up to reach the same maximum speed, influences the dynamics of traffic and how it influences if there is an unsigned intersection on that road. This is usually an unobservable behavior and that is why modeling the problem and performing computational simulations becomes fundamental for the understanding of traffic dynamics. To this end we modeled an intersection with a closed circuit, as proposed for Marzoug et al. [18], where we have two transversal roads crossing in their middle, leading to an eight shape (Fig. 3).

We used a modified version of the NaSch model that includes heterogeneities due to different acceleration policies for vehicles under the same velocity limit, using a continuous probability density function, the Beta function, to model it. The usage of functions with different mean values made possible the consideration of drivers with different steering behaviours, given by their acceleration profile.

From the results we conclude that the proposed model represents the four phases of the flow, as described by Marzoug et al. [18] for the same configuration of the road: free flow, the plateau, the jamming phase and the intermediate phase, where flow decreases. However, we have verified that the most refined discretization allows the representation of situations not representable by the traditional model, with a vehicle partially occupying the intersection or having parts of two vehicles in the same direction, occupying the intersection. It is also noticed that the representation of the different acceleration profiles decisively interfere in the modeling of the problem, since more cautious profiles significantly alter the flow-density and velocity-density diagrams. These factors lead us to conclude that this type of modeling is necessary when analyzing more complex topologies, with the existence of more crossings, roundabout, traffic signals among others.

With the approach here considered, driver's behaviors besides being able to be described by different maximum velocity, can also estimate if the way these drivers reaches this velocity influences the dynamics of traffic and how it influences. This is an unobservable behavior in usual measurements and thus usually disregarded in traffic flow analysis.

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