A cellular automaton model of traffic flow taking into account velocity anticipation is introduced. The strength of anticipation can be varied which allows to describe different driving schemes. We find phase separation into a free-flow regime and a so-called v-platoon in an intermediate density regime. In a v-platoon all cars move with velocity v and have vanishing headway. The velocity v of a platoon only depends on the strength of anticipation. At high densities, a congested state characterized by the coexistence of a 0-platoon with several v-platoons is reached. The results are not only relevant for automated highway systems, but also help to elucidate the effects of anticipation that play an essential role in realistic traffic models. From a physics point of view the model is interesting because it exhibits phase separation with a condensed phase in which particles move coherently with finite velocity coexisting with either a non-condensed (free-flow) phase or another condensed phase that is non-moving.

PACS numbers: 45.70.Vn, 02.50.Ey, 05.40.-a
anticipatory driving parameter is relevant for Automated Highway Systems (AHS) \[19, 20\].

According to simulation results from our proposed model, the relations derived from the density vs. velocity and density vs. flow curves are in agreement with the fundamental diagrams that describe these relations in real non-automated traffic. In addition, simulation results from our model in the case of high anticipation (like automation) describe one of the interesting phenomena in traffic flow, formation of platoons. We will show that, in contrast to models without anticipation, dense platoons can be formed where all cars move coherently with some finite velocity \( v > 0 \). The mechanism for platoon formation is not only of great importance for AHS to increase highway capacity in a much safer way \[21\], but also helps to understand the essential role of anticipation effects in realistic traffic models. By varying the anticipatory driving parameter three different regimes, characterized by different slopes of the fundamental diagrams, can be observed. Apart from a free-flow and a congested phase, an additional regime where platoons of cars moving with the same velocity \( v < v_{max} \) exist.

The paper is organized as follows. In Section III, we present a modified NaSch model to consider different driving strategies. In this way, we introduce a new parameter to determine a velocity-dependent braking distance. In Section III, we present the results of our investigations. We show results for the fundamental diagram and different values of the anticipation parameter. A comparison with those for other models and real non-automated traffic is presented. Phase separation into a free-flow regime and so-called \( v \)-platoon is observed in a certain intermediate density regime. For large densities, in the congested state phase separation into a dense jam (0-platoon) and \( v \)-platoons is observed. The flow structure determined by the existence of dense platoons with velocity \( v \) is calculated. Dependence of an optimal anticipation level on the density is found. Analytical results are in excellent agreement with results from computer simulations. In the concluding Section IV, we summarize our results and discuss the relevance of our results for traffic models and real traffic.

II. DEFINITION OF THE MODEL

In this section we introduce the proposed model. It is defined on a one-dimensional lattice of length \( L \) cells with periodic boundary conditions, which corresponds to a ring topology with the number of vehicles preserved. Each cell is either empty, or it is occupied by just one vehicle traveling with a discrete velocity \( v \) at a given instant of time. All vehicles have a velocity that ranges from 0, \ldots , \( v_{max} \). In addition, and for simplicity, only one type of vehicles is considered. The time-step (\( \Delta t \)) is taken to be one second, therefore transitions are from \( t \rightarrow t + 1 \). It can also be easily modified.

Let \( v_i \) and \( x_i \) denote the current velocity and position, respectively, of the vehicle \( i \), and \( v_p \) and \( x_p \) be the velocity and position, respectively, of the vehicle ahead (preceding vehicle) at a fixed time; \( d_i := x_p - x_i - 1 \) denotes the distance (number of empty cells) in front of the vehicle in position \( x_i \) that sometimes is called headway.

The dynamics of the model are defined by the following set of rules, that are applied to all \( N \) vehicles on the lattice each time-step:

R1: Acceleration
If \( v_i < v_{max} \), the velocity of the car \( i \) is increased by one, i.e.,

\[
v_i \rightarrow \min(v_i + 1, v_{max}).
\]

R2: Randomization
If \( v_i > 0 \), the velocity of car \( i \) is decreased randomly by one unit with probability \( R \), i.e.,

\[
v_i \rightarrow \max(v_i - 1, 0) \quad \text{with probability } R.
\]

R3: Deceleration
If \( d_i^p < v_i \), where

\[
d_i^p = d_i + \left( 1 - \alpha \right) \cdot v_p + \frac{1}{2},
\]

with a parameter \( 0 \leq \alpha \leq 1 \), the velocity of car \( i \) is reduced to \( d_i^p \). \( \lfloor x \rfloor \) denotes the integer part of \( x \), i.e., \( \lfloor x + \frac{1}{2} \rfloor \) corresponds to rounding \( x \) to the next integer value.

The new velocity of the vehicle \( i \) is therefore

\[
v_i \rightarrow \min(v_i, d_i^p).
\]

R4: Vehicle movement
Each car is moving forward according to its new velocity determined in steps 1-3, i.e.,

\[
x_i \rightarrow x_i + v_i.
\]

Rules R1, R2 and R3 are designed to update velocity of vehicles; rule R4 updates position. According to this, state updating is divided into two stages, first velocity, second position. Note that this division follows the scheme in differential equation integration that first updates the time derivative and then the value of the state. It is important to mention that we are changing the order of the rules in comparison with NaSch model since R2 is applied before R3.

Rule R1 indicates that all the drivers would like to reach the maximum velocity when possible. Rule R2 takes into account the different behavioral patterns of the individual drivers in which with no apparent reason a driver decreases its speed. These situations include, for example, cases of overreaction in braking or incidents along the highway that distract drivers, and random fluctuations.
Rule $R3$ is the main modification to the original NaSch model [1]. In this rule the distances between the $i$th and $(i + 1)$th vehicles, and their corresponding velocities are considered. Knowledge of the preceding vehicle’s velocity is incorporated through the \textit{anticipatory driving parameter} $\alpha$ with range $0 \leq \alpha \leq 1$. Notice that, by only varying the parameter $\alpha$ in the term $d_i^a = d_i + [(1 - \alpha)v_p + 1/2]$, different anticipatory driving schemes that require different safe braking distance with respect to the preceding vehicle can be modelled. If $\alpha$ takes its maximum value ($\alpha = 1$) the speed of the vehicle ahead is not considered in the deceleration process, i.e. anticipation is not considered. On the contrary, when $\alpha = 0$ the speed of the vehicle ahead is considered without restrictions, i.e., without establishing a braking distance with respect to the precedent vehicle [20]. This last case occurs with either a very aggressive driver or when vehicles can obtain information about the velocity of vehicles ahead to allow small distances between vehicles (e.g. of the order 1 m). Intermediate values for $\alpha$ thus represent different braking spacing policies or degrees of automation in the vehicles or anticipatory driving schemes. Platooning schemes [21] imply values of $\alpha$ closer to zero and demand additional requirements to preserve safety, like coordinated braking [19]. Independent vehicle driving with low level of anticipation implies values of $\alpha$ closer to 1 in order to preserve safety levels: the larger $\alpha$ is the larger braking distance is. Note that in order to determine $v_n$ consistently for all vehicles in the case of periodic boundary conditions, rule $R3$ must be iterated at most $(v_{\text{max}} - 1)$ times. In real situations, the drivers always estimate the velocity of preceding vehicle and according to this and their way to drive (relaxed or aggressive behavior) they choose a safe headway distance to drive. Variation of $\alpha$ allows also to model these aspects.

Thus, the proposed model is able to represent different anticipatory driving schemes, and model the minimum braking distance required with only one parameter $\alpha$, here referred to as \textit{anticipatory driving parameter}.

We emphasize that the CA model as presented here is a minimal model in the sense that all four steps $R1$-$R4$ are necessary to reproduce the basic features of real traffic, however, additional rules may be needed to capture more complex situations [13].

### III. SIMULATION RESULTS

To simulate the CA model proposed in the previous section, the typical length of a cell is around 7.5 m. It is interpreted as the length of a vehicle plus the distance between cars in a dense jam, but it can be suitably adjusted according to the problem under consideration. With this value of the cell size and a time-step of 1 s, $v = 1$ corresponds to moving from one cell to the downstream neighbor cell in one time-step, and translates to 27 km/h in real units. The maximum velocity is set to $v_{\text{max}} = 5$, equivalent to 135 km/h. The total number of cells is assumed to be $L = 10^4$, and the density $\rho$ is defined as $\rho = N/L$, where $N$ is the number of cars on the highway. Initially, $N$ vehicles are distributed randomly on the lane around the loop with an initial speed taking a discrete random value between 0 and $v_{\text{max}}$. Since the system is closed, the density remains constant with time.

Velocities are updated according to the velocity updating rules $R1$-$R2$-$R3$ and then all of cars are moved forward in step $R4$. Each run is simulated for $T = 6L$ time-steps. In order to analyze results, the first half of the simulation is discarded to let transients die out and the system reach its steady state. For each simulation a value for parameter $\alpha$ is established by taking into account the desired anticipation degree and thus, controlling the safe braking distance among vehicles. In the following, the value of $\alpha$ is the same for all vehicles (homogeneous drivers).

#### A. Comparison with real non-automated traffic

The fundamental diagram is one of the most important criteria to show that the model reproduces traffic flow behavior. This diagram characterizes the dependence of the vehicles flow on density. We obtain a fundamental diagram for the proposed model with $R = 0.2$ and $\alpha = 0.75$, see Fig. [1]. This $\alpha$ value corresponds to cautious estimation of the preceding car’s velocity.

As we can see from Fig. [1] the curve of the proposed model (dashed line) is consistent with the characteristic curve of the measured fundamental diagram (solid line) taken from [23]. The critical density and the maximum flux of our model are $(\rho_c, q_{\text{max}}) = (16\%, 2417 \text{ cars/h})$, closer to the empirical curve values of $(\rho_c, q_{\text{max}}) = (17\%, 2340 \text{ cars/h})$, in comparison with other existing models, see [15]. Note the quantitative agreement between simulated and empirical curve of the fundamental diagram in its decreasing part.

Moreover, as we can see from Fig. [1] a decrease in the experimental curve slope is observed at (10%, 1692 cars/h), corresponding to a reduced mean velocity of vehicles near the critical density. Thus, we make a small modification to the proposed model based on an idea of [24]. We modified the deceleration rule such that a vehicle can only reach the maximum velocity if its braking distance to the precedent vehicle is greater than nine cells (67.5 m, i.e. the density is lower than 0.1). The modified rule $R3$ of the model is then as follows:

$R3^*$: If $v_i = 5$ (i.e. $v_i = v_{\text{max}}$) and $d_i^a \leq 9$ cells then

$$v_i \rightarrow \min(v_i - 1, d_i^a)$$

else (like rule $R3$ of our original model)

$$v_i \rightarrow \min(v_i, d_i^a).$$

In Fig. [2] the results obtained from our modified model are shown and compared with the experimental curve
from real traffic data. The curve resulting from the modified model fits the real curve in both its increasing part and its decreasing part quite well. Thus, the results from the modified model agree quantitatively with the experimental shape of the fundamental diagram. This is an indication that in real traffic the value of $\alpha$ may depend on velocity.

In this subsection, we have shown that the given model can reproduce some common characteristics of the real manual (non-automated) traffic flow. However, with the new parameter it is possible to consider several anticipation schemes for traffic flow: non-automated, mixed and automated traffic flow. This will be shown in the following for the original model ($R3$) defined in Sec. II.

### B. Modeling different anticipation schemes

Determination of the impact of different driving strategies is important in order to propose automated traffic alternatives. Following that proposal, we decided to investigate traffic flow behavior using our model. As mentioned above, the parameter $\alpha$ represents the way in which different driving strategies adopt a braking distance with respect to the preceding vehicles. Varying the parameter $\alpha$, these strategies can be tuned. In Fig. 3 we show the fundamental diagram of the proposed model with a fixed value of $R = 0.2$ and different values of $\alpha$. From this diagram, the impact of the driving strategies coded in $\alpha$ can be observed. Smaller values of $\alpha$ imply larger flows, that is, higher levels of anticipation. Here vehicles keep a less safe braking distance, leading to an increase in the vehicular capacity. This behavior is in agreement with, for example, platooning strategies that exploit the knowledge of the velocity of precedent vehicles and require a smaller distance among vehicles (near 1 m), so increasing the flow.

![Fig. 1: Typical form of an empirical fundamental diagram taken from (solid line) in comparison with simulations of the proposed model for $R = 0.2$ and $\alpha = 0.75$ (dashed line).](image1)

![Fig. 2: Fundamental diagram for the modified model ($R3'$). This diagram is in agreement with the experimental curve in a quantitative way ($R = 0.2$ and $\alpha = 0.75$).](image2)

![Fig. 3: Fundamental diagram for different values of the anticipation parameter $\alpha$ and $R = 0.2$.](image3)

It is important to notice that for values of $\alpha$ from 0.13 to 0.50 a second positive slope corresponding to a mixed branch is observed in the fundamental diagram. It is interesting that the initial positive slope, corresponding to a free-flow region where there are no slow vehicles, is similar for all values of $\alpha$. Here the vehicles travel at near maximum speed. For the second branch, on the other hand, the flow is increased with non-maximum velocity, indicating a mixed region due to anticipation effects (Fig. 3). In order to analyze the role of the anticipation, we show the average velocity as function of the density for the same parameter values as in Fig. 3.

As we can see from Fig. 3 higher levels of anticipation (smaller values of $\alpha$) imply a larger density interval for the free-flow region. For values $0.13 < \alpha < 0.50$, after
the free-flow region, traffic flow organizes in a so-called mixed region with a lower mean velocity. In this mixed region, in addition to free flowing vehicles, and vehicles moving in platoons where all cars have the same velocity and vanishing headway exist. The existence of this mixed region indicates that a suitable estimation of the velocity of precedent vehicle, coded in $\alpha$, allows that more cars to fit on the road and the flow increases ever for values of large-density.

FIG. 5: Space-time diagram showing the time evolution of a system simulated initially with $\alpha = 0.51$. After switching to $\alpha = 0.5$, the behavior changes dramatically.

On the other hand, it is also important to analyze the efficiency of traffic. In non-equilibrium situations, this is usually evaluated by analyzing the entropy of the system. However, for non-physical systems the analysis of the standard deviation of the main variable can give equivalent information [26]. In the context of traffic flow, high standard deviation of speed means that, on average, a vehicle would experience frequent speed changes per trip through the system. In turn, the high speed variance could also increase the probability of traffic accidents. Therefore, the standard deviation of speed can be seen as an indicator of the efficiency in traffic flow.

In order to analyze the efficiency of traffic with different automation levels, we calculate the standard deviation of speed (Fig. 6). For each value of $\alpha$ a maximum that occurs shortly after the free-flow region can be clearly seen. In the free-flow region, the speed variance is negligible since there are no slow vehicles and fluctuations are extremely rare. Since the free-flow region increases as $\alpha$ decreases, it is seems reasonable to attempt traffic with the higher level of anticipation in the range of density from 0 to 0.5. This selection not only produces a state with higher flow, but also the lowest standard deviation, so the efficiency is the highest. It can be clearly seen from Fig. 6 that beyond the efficient density range, the level of anticipation coded in $\alpha$ should be switched based on the density regime: for $\rho \in (0.5, 0.54)$, an effi-

 FIG. 4: Relationship between mean velocity and density for $R = 0.2$ and different values of $\alpha$.

 FIG. 5: Space-time diagram showing the time evolution of a system simulated initially with $\alpha = 0.51$. After switching to $\alpha = 0.5$, the behavior changes dramatically.

 FIG. 6: Standard deviation of the speed.
cient performance is found with $\alpha = 0.13$; however, for $\rho \in (0.54, 0.63]$ the highest efficiency is attained with $\alpha = 0.20$. Summarizing, the behavior observed in Fig. 6 indicates that the automation level should be determined depending on the density: higher densities require a lower automation level, that is, a safer braking distance.

Besides, we can also see from Figure 6, the standard deviation of speed resulting from assigning a random value of $\alpha$ between 0 and 1 to each vehicle. We stress that for each car, this value of $\alpha$ is not changed during the time evolution. Therefore, we simulate, by means of random values of $\alpha$, traffic with non-homogeneous drivers: aggressive, non-aggressive and relaxed drivers. We can see from Fig. 6 the region where the standard deviation is negligible is close to that resulting from homogeneous drivers with $\alpha = 0.2$ (high-level anticipation). However, the variance of vehicles speeds is 60% larger than that corresponding to homogeneous drivers.

In order to elucidate the effects of anticipation with non-homogeneous drivers, the fundamental diagram obtained for this random $\alpha$ case is compared with that for $\alpha = 0.2$ in a homogeneous system (Fig. 7). Note that the second slope corresponding to a mixed region is missing in the inhomogeneous system. In this case, the variance in the level of anticipation considered by the drivers produces higher fluctuations of speeds, and the flow decreases rapidly. Therefore some anticipation driving schemes have a strong impact on the efficiency of the system. All of these findings require physical explanations.

C. Structure of the mixed states

The behavior in the mixed states is determined by the existence of dense platoons in which vehicles move coherently with the same velocity $v$. In the following these will be denoted as $v$-platoons. The stationary state then shows phase separation into a free-flow region and a $v$-platoon. This is similar to the behavior observed in models with slow-to-start rules where the system separates into free flow and a dense jam, i.e. a 0-platoon.

Fig. 8 shows the velocity distributions of the different branches. It can be clearly seen that only cars with velocity $v$ and free flowing cars (with velocity $v_{\text{max}}$ or $v_{\text{max}} - 1$ due to the randomization) exist.

Since the headway $d_i$ of a car $i$ inside a $v$-platoon is $d_i = 0$, its new velocity is determined by $v'_i = \min(v_i, d_i^*)$ with $d_i^* = \left[\left(1 - \alpha\right)v_p + \frac{1}{2}\right]$. For a stable $v$-platoon, $v'_i$ must be equal to $v$. This gives the following stability condition:

$$v \leq (1 - \alpha) \cdot v + \frac{1}{2}. \quad (1)$$

Equation (1) can be regarded as a condition for the anticipation parameter $\alpha$. It implies that a $v$-platoon can only be stable for

$$\alpha_{v+1} < \alpha \leq \alpha_v \quad (2)$$

where $\alpha_v$ is defined by

$$\alpha_v := \frac{1}{2v}. \quad (3)$$

However, this condition is only necessary, not sufficient. The $v$-platoons that can be realized for a given $\alpha$ also depend on the randomization $R$. E.g. for $R = 0.2$, platoons with $v = 0, 1, 2, 3$ occur, whereas for $R = 0.4$ platoons with $v = 3$ can not be observed in the infinite system although they might exist in small systems. Simulations indicate that the slope of the mixed branch in the fundamental diagram has to be smaller than $(1 - R)\left(v_f - 1\right)$ where $v_f$ is the average velocity.
in free flow: \( v_f = v_{\text{max}} - R \). This will be discussed in Sec. IIIIE in more detail.

Another criterion for the stability of platoons can be derived from the condition that the inflow and outflow of the platoon have to be identical in the steady state. In the following we will derive estimates for these flows and in this way obtain the fundamental diagram in the mixed region.

The outflow from a \( v \)-platoon is determined by the average time \( T_w \) needed by the leading vehicle of the platoon to accelerate to velocity \( v + 1 \). Assuming that this car has a large headway, this time is determined by the randomization constant \( R \) through \( T_w = \frac{\Delta x_f}{(1 - R) v} \). Therefore, in the free-flow region of the system, the average headway \( \Delta x_f \) is given by \( \Delta x_f = T_w (v_f - v) + 1 \). This consideration is very similar to the reasoning used in [25].

Assuming that the platoon consists of \( N_v \) and the free-flow region of \( N_f \) vehicles, we have
\[
N = N_v + N_f, \quad \text{and} \quad L = N_v + N_f \Delta x_f. \tag{4}
\]

Here \( N \) is the total number of cars. Furthermore it has been assumed that the transition region between the platoon, where all cars have headway \( d_i = 0 \), and the free-flow region, where the average headway is given by \( \Delta x_f \), can be neglected. Eliminating \( N_f \) we find
\[
\frac{N_v}{L} = \frac{\rho \Delta x_f - 1}{\Delta x_f - 1}. \tag{5}
\]

We now can calculated the flow \( J = \rho \tilde{v} \) of the corresponding phase-separated state. The average velocity \( \tilde{v} \) in the presence of a \( v \)-platoon is given by
\[
\tilde{v} = \frac{N_v v + N_f v_f}{N}. \tag{6}
\]

A straightforward calculation using the results given above yields for the flow
\[
J_v = (1 - R) + (v - (1 - R)) \rho. \tag{7}
\]

These results are in excellent agreement with the results from computer simulations. Since \( 1 - R < 1 \) it implies that all slopes corresponding to mixed states in the fundamental diagram are positive, except those for 0-platoons \((\alpha > 0.5\) see Fig. 3) which are responsible for the jammed branch with low flow and negative slope.

D. Structure of the congested states

For large densities all anticipatory curves \((\alpha \leq 0.5)\) collapse on one congested branch where the flow decreases with increasing density. Simulations indicate that the structure of the corresponding states depends on the parameter regime. In the range [2], where a \( v \)-platoon can exist, the congested branch is characterized by the coexistence of a compact jam (0-platoon) and various \( v \)-platoons. The \( v \)-platoons are formed when a bunch of vehicles escapes from the jam. As argued in Sec. IIIIE the first car escapes after an average waiting time \( T_w = \frac{1}{R} \).

Due to anticipation, with probability \( 1 - R \) the second car can move in the same time-step, and so on. Therefore the average number of cars escaping in the same time-step is given by
\[
\tilde{I} = \frac{\sum_{i=1}^{\infty} i (1 - R)^i}{\sum_{i=1}^{\infty} (1 - R)^i} = \frac{1}{R}. \tag{8}
\]

These cars form a \( v \)-platoon of length \( \tilde{I} \) where the value of \( v \) depends on the parameter region as discussed above. Since the average waiting time for the escape of a car is \( T_w \), the average distance between two \( v \)-platoons is \( \Delta x_c = v T_w = \frac{L}{R} \).

To calculate the flow in the congested branch, we again neglect the transition regions and assume that only one jam with \( N_0 \) vehicles and \( n \) \( v \)-platoons with a total number of \( N_v \) cars are present. Then we have \( N_0 + N_v = N \) with \( N_v = n \tilde{I} \). Furthermore \( N_0 + N_v + n \Delta x_c = L \) where \( N_0 \) and \( N_v \) are the total lengths of the platoons and \( n \Delta x_c \) is the total space between the platoons. These relations yield
\[
1 = \frac{1}{L} (N + n \Delta x_c) = \rho + \frac{N_v}{L} \frac{\Delta x_c}{\tilde{I}}. \tag{9}
\]

The average velocity of the vehicles in the congested branch is \( \bar{v} = \frac{N_v x_c}{N} \). Using (9), this implies for the flow
\[
J_{\text{cong}} = \rho \bar{v} = \frac{N N_v}{L} v = (1 - \rho) \frac{\tilde{I}}{\Delta x_c} v = \frac{1 - R}{R} (1 - \rho). \tag{10}
\]

Note that this result is independent of the velocity \( v \) of the platoons! It is in excellent agreement with the simulation data, justifying e.g. the assumption made about the transition regions.

E. Stability regions

For fixed \( \alpha \) we now can estimate the stability region \( \rho_1 \leq \rho \leq \rho_2 \) for the mixed states. At the lower boundary density \( \rho_1 \) the number of cars \( N_v \) in the \( v \)-platoon vanishes. From [14] one has \( \rho_1 \Delta x_f - 1 = 0 \) which yields
\[
\rho_1 = \frac{1 - R}{v_f - v + (1 - R)}. \tag{11}
\]

The upper bound \( \rho_2 \) is not determined by the condition \( N_0 = N \) i.e. all cars belong to the \( v \)-platoon. This would correspond to the density \( \rho = 1 \). In fact, the instability of the mixed state occurs earlier. At the density
\[
\rho_2 = \frac{(1 - R)^2}{R (v + R - 2) + 1} \tag{12}
\]

the flow \( T \) of the mixed branch becomes larger than that of the congested branch, see [10] and therefore (at least
for random initial conditions) the flow of the congested branch is observed. However, our simulations have given indications for hysteresis effects and metastability in the large density regime. We will discuss these in more detail in a future publication [27]. For $v = 0$ the upper transition density becomes $\rho_2 = 1$, independent of $R$, consistent with the observation (Fig. 3) that the mixed region for $v = 0$ extends up to the maximal density.

Since $\rho_2$ has to be larger than $\rho_1$, this yields an additional condition for the stability of the branches. It is easy to check that $\rho_1 < \rho_2$ if

$$(1 - R)v_f > v.$$  \hspace{1cm} (13)$$

This is just the condition obtained in Sec. III C from computer simulations.

Summarizing, a mixed region with $v$-platoons can only exist for $1/(2(v + 1)) < \alpha < 1/(2v)$ and $R$ satisfying 13. If these conditions are fulfilled, $v$-platoons occur in the density interval $\rho_1 < \rho < \rho_2$ where $\rho_1$ and $\rho_2$ are given by 11 and 12, respectively.

IV. SUMMARY AND CONCLUSIONS

Forecasting the impact of different anticipation schemes plays a essential role in real traffic flow in order to propose automated traffic alternatives. In this paper we have introduced and investigated a modification of the NaSch model to better capture reactions of the drivers intended to keep safety on the highway. As a result, an anticipation parameter $\alpha \in [0, 1]$, that allows to determine a velocity-dependent safe braking distance of the precedent vehicle, is included. The addition of this parameter proves to be useful to describe different traffic situations of non-automated, automated, and mixed traffic.

Simulation results presented here for homogeneous drivers, corresponding to a cautious estimation of the preceding car velocity (large $\alpha$), are in excellent agreement with the shape of the empirical fundamental diagram.

On the other hand, simulation results for driving schemes associated to intermediate-levels of anticipation with $\alpha$ from 0.13 to 0.5 (homogeneous drivers), exhibit phase separation in a certain density regime into a free-flow region and so-called $v$-platoons. In these dense platoons vehicles move with the same velocity $v$ and have vanishing headway. The velocity $v$ of the platoon is determined by the level of automation.

This platoon formation observed in a mixed regime plays an important role in Automated Highway Systems (AHS) to increase the vehicular capacity. Therefore, results obtained help to elucidate the effects of anticipation coded in $\alpha$. The maximum flow and the density interval for free-flow regime go with the inverse of $\alpha$ smaller values of $\alpha$, (greater estimation of the precedent car velocity) imply larger flows and larger density interval for free-flow regime. This is also in accordance with, for example, the use of certain anticipation strategies to exploit the knowledge of the velocity of the precedent vehicle and so, reducing the distance among vehicles, increasing the capacity, and the density interval for free-flow regime.

Moreover, the analysis of the speed variance of individual vehicles also indicates the importance to anticipation effects. Results indicate that level of anticipation should be determined based on the density. The highest-level of anticipation should be considered before the corresponding maximum density for free-flow regime is reached. After that maximum density, larger density requires lower-level of anticipation. Therefore, this selection not only produces the highest flow, but also the lowest standard deviation, and so, efficiency is the highest.

The considerations in this paper show the flexibility of the CA approach to more complex traffic flow problems. A simple and natural modification of the rules of the NaSch model to consider different driving schemes allows us to describe the formation of coherently moving platoons observed in some anticipation schemes. We think that the results presented here are relevant to establish suitable levels of safety and automation not only for AHS, but also in real traffic. We stress that although in this paper the model is simulated in a single-lane on a ring, it is possible to apply it to complex highway topologies in a satisfactory way [27].

Apart from its practical relevance for traffic problems, our work also shows interesting physical aspects. The model suggested here exhibits various kinds of phase separation phenomena. At intermediate densities, phase separation into a condensed ($v$-platoon) and a non-condensed (free-flow) phase can be observed. In contrast to most other models of driven diffusion, the condensed phase is moving coherently for $v > 0$. At high densities an even more surprising state is found that exhibits phase separation between different condensates, a non-moving one ($v = 0$) and several coherently moving platoons ($v > 0$). To our knowledge such a behavior has not been observed before. It would be interesting to study these phases in more detail, especially since recently some progress in the understanding of phase separation in driven diffusive models has been made [28]. Work in this direction is currently in progress [27].

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[29] This will happen in Automated Highway Systems or in vehicles equipped with appropriate sensors [22].
[30] For a Java applet of the simulations, see http://www.cie.unam.mx/xml/tc/ft/arp/simulation.html.