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On- and Off-ramps Generating 1/f Noise in Traffic Flow

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A simple model of a motorway junction consisting of two connected periodic roads is presented; each of them is connected to the other by on- and off-ramps. This constitutes a detailed structure for the region of on- and off-ramps, which is a new aspect of this paper and a useful step towards a more realistic modelling of the vehicular dynamics near the ramps. The traffic flow through the ramps has an effect on the capacity of the main roads. This effect is identified by the formation of the so-called "plateau" in the fundamental diagram. The value increase of one of the probabilities *pin* and *pout* decreases the value of the indicated plateau.
Here *pin* is the probability to enter the main road through the on-ramp and *pout* denotes the probability to exit the main road through the off-ramp. The first important feature in the simulated system is the symmetry between the connected main roads. This symmetry does not depend on the variation of the difference between the probabilities *pin* and *pout*. The other most outstanding feature is the existence of correlations between the connected main roads, which can be traced back to the lane change of vehicles in the ramp regions. These correlations are characterized by the occurrence of $1/f^{\alpha}$ fluctuations in the global traffic flow of a chosen main road of the simulated system.

I. INTRODUCTION

Traffic flow has been viewed either as a stochastic process of individual vehicles, or as a continuum fluid, where in general the vehicle density and average velocity are considered. The first microscopic models of road traffic indicate the existence of a phase transition separating two distinguishable regimes: (i) the free flow (low density), and (ii) the congested flow (high density). The reported observations were interpreted [1] as a local first order phase transition.

In the case of the free-jam transition, all known models reach the maximal free flow at the density where the critical amplitude for the free to jam transition is zero [2, 3, 4]. The investigation of the empirical data has shown very complex behaviours of the traffic and has lead to the identification of three traffic phases (free, synchronized, and wide moving jams) [5, 6, 7, 8, 9, 10].

In general, synchronized flow can be observed near bottlenecks and wide moving jams can be formed if the inflow rate exceeds the outflow rate of an emerging jam. It is to stress here, that the well-known slow-to-start rule [11, 12] can lead to the occurrence of wide moving jams.

Several authors [2, 8, 13, 14, 15, 16, 17, 18] have also reported that the flow of a road network is mainly attributed to its capacity of supporting unexpected arising congestions (which occur if this capacity is locally reduced). In the case of highway networks, these congestions are often due to the existence of connecting on- and off-ramps [7, 18, 19, 20, 21, 22]. The dynamical behaviour near the onramp differs significantly in the fundamental diagram approach [5, 23, 24, 25]. It depends on both the flow rate to the on-ramp *qin* and the flow rate on the off-ramp *qout*. Often the congested traffic flow is characterized by stop-and go waves, near the bottlenecks, propagating in the upstream direction with a velocity of about 15 km/h [26]. Finally, it has been also shown that different types of congested patterns characterize the traffic flow near the bottlenecks [10, 27, 28, 29].

Traffic flow presents also many interesting phenomena from the viewpoint of physics: one such phenomenon is the $1/f^{\alpha}$ fluctuations in the traffic current [30,31] which Musha and Higuchi reported for the first time in 1976. They recorded the transit time of cars on a highway and calculated its power spectral density (PSD). As a result, they found a power-law behaviour in which the PSD is proportional to $1/f^{\alpha}$ in the low-frequency region and white noise behaviour in the high-frequency region. They obtained the power $\alpha = 1$ by fitting the data to the form $1/f^{\alpha}$ [30] and obtained $\alpha = 1.4$ by an analysis based on the Burgers equation [31]. Note, the value of the exponent α has not been fixed [14, 15, 30, 31, 32, 33, 34].

In this Paper, we discuss results of CA model simulations of traffic flow in a system of two coupled roads. The model is based on the Nagel-Schreckenberg model (NaSch model) [19]. We focus on the so-called $1/f^{\alpha}$ flow fluctuations, which are related to the road changes of individual vehicles in the indicated system by computing the power spectrum of the traffic flow (PSF). Especially we shed the light on the useful double feature of the coefficient α. This coefficient can in the same time

help to identify different traffic flow phases (which are clearly recognizable on the fundamental diagram) and to determine the correlations in the simulated system.

II THE MODEL

In this section the implementation of on- and off-ramps will be discussed. A system of two roads connected by on- and off-ramps is used (see Fig. 1). Each road has periodic boundary conditions and is of length $L = 3000$. The activity of the ramps is characterized by the probabilities of entering (leaving) vehicles *pin*(*pout*), respectively. The dimensions found on German highways motivate the chosen length of the on- and off-ramps and the distances between them. Here we have chosen *Lramp* = 25 sites as length of the ramps (usually the length of each site is identified with 7.5 meters). Starting from the reference point *xref* = L/2 on each road, The first site of the on-ramps is located at *xon*

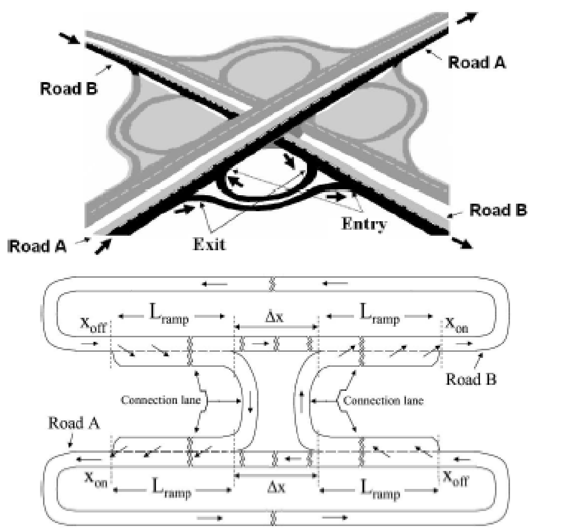

Figure 1: Schematic representation of the simulated system. Top: A junction between two main roads within the region of a real highway intersection is represented. Bottom: Two main roads are connected between them by on- and off-ramps. Each connection lane is limited by the positions *xoff* (at the leaved main road) and *xon* (at the target main road).

= *xref* + 60 and that of the off-ramps is located at *xoff* = *xref* - 60. Then the spacing between the on- and off-ramps is given by ¢*x* = *xon* - *xoff* - 2×*Lramp* = 70 sites. Considering the connection between both roads, the length of the lane between the off-ramp of the leaved road and the on-ramp of the target road is chosen to 25 sites. The connection lane is the lane, which connects the coupled main roads. It and begins from the position *xoff* of the leaved main road, finishes at the position *xon* of the target main road, and is of length *Lconnection* = 25 + 2 × *Lramp* (= *Lofframp* + 25 + *Lonramp*) (see. Fig. 1).

Before we describe the strategies entering and removing vehicles between both main roads (roads A and B), and for the sake of completeness, we recall briefly the definition of the NaSch model [19]. The NaSch model is a discrete model for traffic flow. In this model, the road is divided into sites, which can be
either empty or occupied by a vehicle with a velocity $v = 0, 1, ..., vmax$. The system update is performed in parallel for all vehicles according to the following rules:

1. Acceleration: $v \rightarrow \min(v + 1, vmax)$,
2. Deceleration: $v \rightarrow \min(v, gap)$,

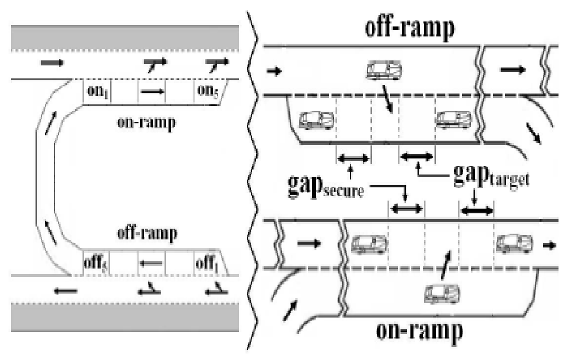

Figure 2: Detailed representation of the ramp regions. Left: Schematic representation of the subdivision of ramp regions. Right: Schematic representation of lane change procedure on the on- and off-ramps between the main roads of the simulated system.

3. Noise: $v \rightarrow \max(v - 1, 0)$ with probability p,
4. Motion: $x \rightarrow x + v$,

Here v denotes the velocity, *vmax* the maximal speed and x the position of a vehicle, *gap* specifies the number of empty sites in front of the vehicle. In order to extend the model to the connected roads one has to introduce the rules of the vehicle movement between both main roads within the ramp regions. Dividing the update into two sub-steps does this; (i) in the first sub-step, vehicles enter and leave a connection lane through the ramps, and (ii) in the second sub step, vehicles move on both main roads and on both connection lanes according to the NaSch model rules. The maximal speed will be given by $vmax = 5$.

The strategies entering and removing vehicles between both main roads will be now described.

2.1 Lane changing from the main road towards the off-ramp

For the simulation of the off-ramp region where vehicles can leave a main road towards the connection lane, a vehicle can be placed between two

consecutive vehicles on the connection lane if there is enough space between these three vehicles. In other words, if the following conditions are fulfilled:

1. *gaptarget* > *vmax*.
2. *gapsecure* > *vmax*.

Here *gaptarget* (*gapsecure*) denotes the number of free sites between the vehicle coming from the main road and the next vehicle ahead (back) on the desired lane, respectively (see Fig. 2). The desired lane is the connection lane.

Usually the vehicles leave more frequently (rarely) a main road towards a connection lane at the first (last) sites of an off-ramp. This means that it

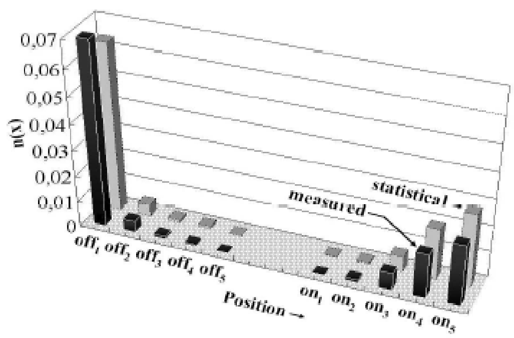

Figure 3: Comparison of the number $n(x)$ of vehicles changing on the ramp regions.

These rates $n(x)$ are measured experimentally on the motorway B9 in Germany (black), and calculated statistically (grey). The high rates of the lane change can be observed at the entry (exit) of the off-ramp (on-ramp) region, respectively.

is necessary to take into account of a distribution of the probability *pout* on the off-ramp sites. This probability distribution will be discussed in the next subsection.

2.2 Lane changing from the on-ramp towards the main road.

In the on-ramp region, each vehicle coming with the velocity v through the connection lane can enter the main road and can be inserted between two consecutive vehicles if it founds enough space on the main road. More precisely, if the following two conditions are fulfilled:

1. *gaptarget* ¸ min(v + 1, *vmax*).
2. *gapsecure* ¸ min(¸ × d, *vmax*).

The parameters *gaptarget* and *gapsecure* are defined in the same way as before, but here the desired lane is a main road (see Fig. 2). The parameter d is the site length, and ¸ is a parameter, which can take an integer value between 2 and *vmax* to control that of *gapsecure*.

Conversely to the case of an off-ramp, it is usually preferred that each vehicle moves until the first sites of an on-ramp to enter the desired main road. This procedure leads to a high (low) rate of lane change at the exit (entry) of the on-ramp region, respectively. For this reason the usage of a distribution of the probability *pin* on the on-ramp sites becomes necessary. This distribution will be discussed in the next subsection.

2.3 Distributions of the probabilities *pin* and *pout* As mentioned in both previous subsections; the choice of the distributions of the probabilities *pin* and *pout* will be now discussed. These distributions are

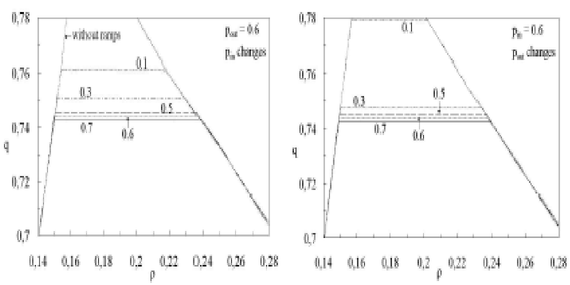

Figure 4: Comparison between the fundamental diagrams obtained by varying the difference between the values of the probabilities *pin* and *pout*. Generally, the capacity of the simulated system decreases if one of both indicated probabilities increases. Left: *pin* changes and *pout* remains equal to 0.6. Right: *pout* changes and *pin* = 0.6 remains constant.

Obtained experimentally by dividing each ramp into 5 equal sections and by measuring the rate of the lane change on each one of these sections. Fig. 3 shows that vehicles enter (leave) frequently a motorway main road at the last (first) sites of the on-ramp (off-ramp) region, respectively. The distributions of the lane-change rates obtained experimentally are similar to those of the lane change rates obtained by using the statistical distributions (0.9, 0.1, 0.08, 0.005,0.005) for the probability *pout* and (0.2, 0.2, 0.2, 0.2, 0.2) for the probability *pin*.

Note, these distributions do not lead to the bad impact of waiting vehicles on the connection lanes and allow a high traffic flow between the connected main roads. In the case of high density regime, adding the so-called «process of zipper circulation», which is well advised to the vehicle drivers in the vicinity of a partial lane reduction, can perform these distributions. This process helps to reduce the waiting time of vehicles on a connection lane and also to improve the traffic flow from the on-ramp to the motorway main road.

III. SIMULATION RESULTS

In this section, the effect of the variation of the difference between the values of the probabilities *pin*

and *pout* on the traffic flow in the described system (see fig. 1) will be discussed, and also the fluctuations of the traffic flow will be analysed by focusing particularly on its power spectrum which will be characterized by the occurrence of $1/f$ α fluctuations. In addition, simulation results will show the more interesting features of the coefficient α. Note, the plateau value formed in the fundamental diagram in the case of p = 0.01 and *pin* = *pout* = 0.5 is higher than that of the plateau obtained in [20] where the model of a one-lane road with additional on- and off-ramps were used by considering *pin* = *pout* = 0.5 and p = 0. In addition, no special distributions for the probabilities *pin* and *pout* were considered in [20].

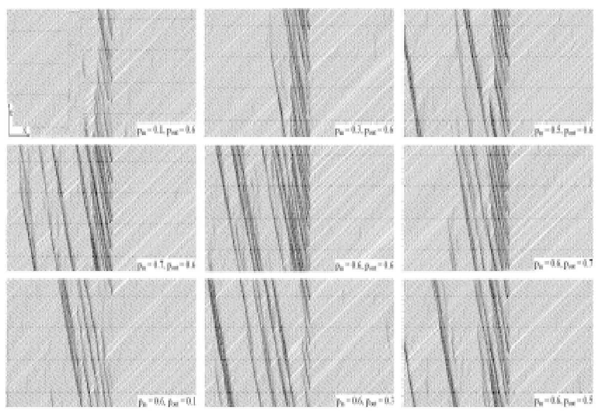

Figure 5: Space-time plots obtained by varying the difference between the values of the probability *pin* and *pout*.

III.1 Fundamental diagram and jam patterns near the ramps

The fundamental diagram will be compared with respect to the variation of the difference between the probabilities *pin* and *pout*. In order to emphasize only the effect of the ramps to the traffic flow, only a low value of p (p = 0.01) will be taken into account. Fig. 4 shows that generally the capacity of the simulated system is reduced in comparison to that of the system without ramps. It is clearly seen in Fig. 4 that in all cases of the difference between *pin* and *pout* a plateau regime can be identified in the fundamental diagram. In this plateau regime, which corresponds to the densities between ρ *low* and ρ *high*, an increase of the value of *pin* or *pout* leads to a decrease of the plateau value, and consequently to an increase of the plateau interval. Thus, The ramps act as a stationary local defect [35, 36], which reduces the road capacity. In the simulated system, one can distinguish three phases; the high and low density phases where the average flow takes the same values as in the case of the system without ramps, and the intermediate density phase where the average flow is constant and limited by the ramp capacity.

The new aspect of this paper is the system symmetry, which does not depend on the variation of the difference between the values of *pin* and *ppout*. This result can be explained by the fact that the on- and off-ramps constitute the boundaries of the connection lanes similarly to an open boundary road (this similarity will be explained in the subsection 3.2). In a connection lane, the inflow at its left (entry) boundary influences the outflow at its right (exit) boundary, and conversely.

The plateau formation in the fundamental diagram at intermediate densities can be explained by the emergence of a congested region (caused by the ramps), which grows in size by keeping its density constant. The jam patterns formed in this congested region depend on the difference between the values of the probabilities *pin* and *pout* (see Fig. 5). In the case of *pout* > *pin*, only less dense jams emerge between the on- and off-ramp regions and vanish quickly if *pin*

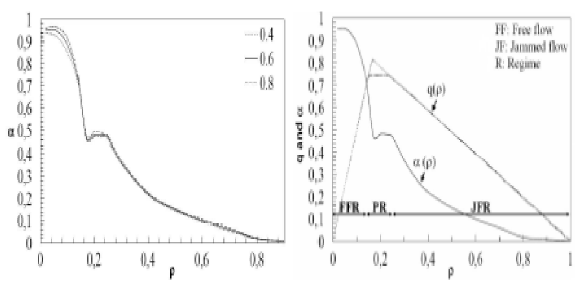

Figure 6: Dependence of the coefficient α on the density and on the probability *pin* = *pout*. Left: α reaches its maximal (minimal) value in the low (high) density

is regime, respectively. At intermediate densities, α fluctuates very slightly near 0.5. The increase of the value of *pin* = *pout* decreases slightly the value of α in the intermediate density regime. Right: The figure shows that α(ρ) can identifies the three traffic flow regimes, which are clearly recognizable on the fundamental diagram q(ρ). This result is obtained in the case where *pin* = *pout* = 0.6.

very low (*pin* = 0.1). If *pin* increases, the mentioned jams become denser and can also exceed the off-ramp region to propagate itself backwards. But in the case of *pout* < *pin*, the number of emerging jams is reduced although the value of *pin* is high (i.e. *pin* = 0.6). The emerging jams can also often propagate itself backwards if the value of *pout* is lower than that of *pin* (i.e. *pout* = 0.1 and 0.3). The space-time plots of Fig. 5 confirm the dependence between the in- and outflows of vehicles through the connection lane boundaries.

III.2 Power spectrum fluctuations (PSF)

As mentioned in the introduction, the power-law behaviour corresponding to the fluctuations of the traffic flow will be discussed in the following. This will be done by computing the time series of the values of the average and global traffic flow in a chosen main road of the simulated system (due to the symmetry which does not depend on the difference between *pin* and *pout*). In addition, simulations will be carried out in the case of *pin* = *pout* = 0.6, where a great number of vehicles can pass through the connection lane boundaries (see Fig. 5, middle-middle). The other model parameters will be not modified. The Fourier transformation will be used to obtain the PSF from the time series of the computed traffic flow. Fig. 6 (left) shows the dependence of the exponent α on the density and on the values of *pin* = *pout* in the low frequency region of the PSF. The $1/f^{\alpha}$ fluctuations are proportional to the PSF fluctuations and are obtained for the frequency interval between 103 and 105. Fig. 6 (right) shows that the three traffic flow phases, which depend on the density, can be also identified by α(ρ) in agreement with the results of the fundamental diagram *q*(ρ). In the low-density regime, the power-law exponent fluctuates near α ≈ 1 (Fig. 7 (top-left)), and it decreases later to reach the value corresponding to ρ *low*. Above the density ½*high*, α continues to decrease towards zero (Fig. 7 (bottom)). This means that the high long-time correlations in the

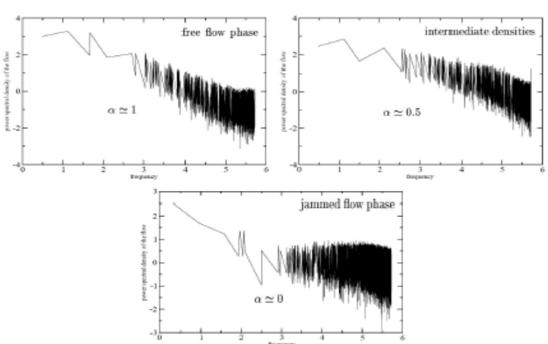

Figure 7: The log-log plots of the power spectrum of the traffic current fluctuations obtained for *pout* = *pin* = 0.6. Top-left: In the free flow phase (ρ = 0.02), the high correlations in the low frequency regime (α ≈ 1) can be seen. Bottom: The correlations in the simulated system are destroyed in the jammed flow regime (ρ = 0.9) and a white noise can be observed. Top-right: At intermediate densities (ρ = 0.23), the power spectrum of the traffic current is proportional to 1/*f* α (with α ≈ 0.5).

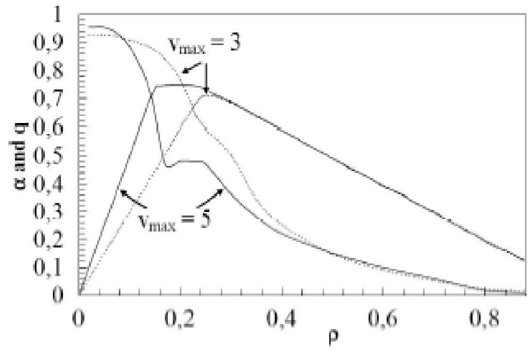

Figure 8: Comparison between the curves of α(ρ) obtained for two values of the maximal speed and for *pout* = *pin* = 0.6. Qualitatively, The same behaviour of α (ρ) can be observed for both values of *vmax* (*vmax* = 3 and 5), i.e. α is high in the free flow regime and low in the jammed flow regime. The width of the plateau regime decreases if *vmax* = 3.

simulated system persists only in the free flow phase and is destroyed by the occurrence of the transitions to the jammed states. However, the most interesting regime lies between the two densities ρ *low* and ρ *high*, where the maximal traffic current is constant and where the coefficient α fluctuating very slightly near 0.5 seems to be also constant. This result can be also shown for the fluctuations of the PSF in Fig. 7 (top-right). It is to note here that α tends to zero if *pin* =*pout* = 0 at high and low densities.

The occurrence of a power-law behaviour in the free flow regime is: (i) on the one hand, in accordance with the result obtained by Yukawa and Kikuchi [37]; their simulations are based on the deterministic coupled map lattice model on a closed single-lane circuit, and (ii) on the other hand, in contrast to the results obtained by Takayasu and Takayasu [14] because the power-law was observed only in the congested phase.

Up to now, the effects of the density ρ and of the probabilities *pin* and *pou t* on the 1/*f* α fluctuations has been discussed only for the case of *vmax* = 5. In the following, the case of *vmax* = 3 will be taken into account. Fig. 8 shows the variations of α (½) with respect to the maximal speed (*vmax* = 3 and 5). In both cases of *vmax*, the coefficient α is minimal in the jammed flow regime and is maximal in the free flow regime. The width of the density interval corresponding to the plateau regime decreases if *vmax* = 3.

The behaviour of α(ρ) observed for both cases of *vmax* are qualitatively the same and can be understood by looking at the density profiles on the connection lanes between the main roads of the simulated system. Fig. 9 shows that towards the left

(right) end of the connection lane an exponential increase (decrease) of the average density can be observed, respectively. This result is similar to the case of the open-boundary system studied in [38]. This analogy implies that a connection lane acts like a road with open boundaries and that the rates of injected and removed vehicles at these boundaries are controlled by the global density of the simulated system and by the lane change rates of the vehicles between the ramps and the coupled main roads. Fig. 9 shows also that for very low densities (½ = 0.06), a high density region can be found only near the exit of the connection lane (more precisely, near the exit of the on-ramp). The existence of enough spacing on the target main road (i.e. enough *gaptarget* and *gapsecure*) allows to the vehicles to leave rapidly or after a short waiting time the connection lane. For this reason only a small jam can be formed at the exit of the connection lane, and consequently high correlations between the coupled roads (α ≈ 1) can be reached.

In the plateau regime, the congested region of the connection lane increases in size during its density remains constant (see Fig. 9). More interactions between the vehicles occur near and in the ramp regions und lead to the very slight fluctuations of α near 0.5. In the high density regime, the jam formed in the connection lane widens and becomes very large (see Fig. 9). This leads to a very slow movement of the vehicles between the connected main roads, and consequently the coefficient α decreases towards zero. If *vmax* = 3 is taken into account, the length of the jams occurring near the ramps decreases and the value of α in the low density regime becomes slightly reduced.

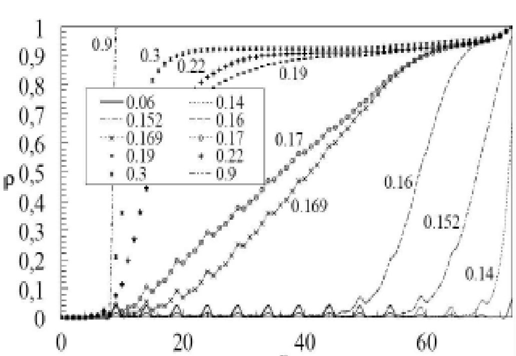

Figure 9: Density profiles on the connection lanes obtained for different values of the density and for *vmax* = 5. The probabilities *pin* and *pout* are equal to 0.6. A jam can occur at the exit of the connection lane, and its size and also its density depend on the increase of the vehicle density in the simulated system. The results shown in this figure confirm the behaviour of α in the three mentioned regimes of the density, i.e. the low, intermediate, and high density regimes.

IV. CONCLUSIONS

To summarize, we found 1/*f*α fluctuations in the power spectra of the traffic current fluctuations computed by considering a simple scenario that quantifies the effects of the ramps on the traffic flow dynamics. The simulations are investigated for a system composed of two periodic single lanes; each one is connected to another by on- and off-ramps. This system can be considered as a simplified construction of a motorway junction and as a useful step towards a more realistic modelling of the vehicular dynamics near the ramps. The model used here is based on that of Nagel-Schreckenberg with additional rules of the lane change in the ramp regions. We have introduced an in- and output strategy for the vehicles changing from a main road to another main road. A plateau formation in the fundamental diagram as well as a phase transition in the system is observed. The system symmetry does not depend on the difference between the probabilities *pin* and *pout* of the lane change in the ramp regions, and the system capacity decreases if one of both mentioned probabilities increases. The power-law behaviour occurring in low frequency region of the PSF depends on the density, on the probabilities *pin* and *pout*, and also on the maximal speed *vmax*. The correlations between the connected main roads are maximal (α ≈ 1) in the free flow regime and are destroyed (α ≈ 0) in the congested flow regime.

At intermediate densities, we found α ≈ 0.5. These results can be explained by the state of the traffic in the connection lanes between the simulated main roads.

The connection lanes act as an open-lane system where the rates of injected and removed vehicles depend on the global density and on the probabilities *pin* and *pout*. It is to stress here that the jam patterns formed near the ramp regions change with respect to the difference between *pin* and *pout*.

The results of this work have shed the light on more interesting features which are related to the effect of the ramp activity (*pin* and *pout*) and to the exponent α. This last coefficient can in the same time identify the traffic flow states with respect to the density and determine the correlations in the simulated system. The results of this paper can be important for a more detailed understanding of the real traffic flow behaviour, which is often influenced by the ramps.

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