I. INTRODUCTION

Undoubtedly, traffic management is nowadays considered as one of the basic ingredients of modern societies and large sums are invested by governments in order to increase its efficiency. The rapidly growing volume of vehicular traffic flow, limitations on expanding the construction of new infrastructure, hazardous environmental impact due to the emission of pollutants, together with unfavourable delays suffered in congested traffic jams, are among the basic features which necessitate the search for new control, as well as optimization schemes, for vehicular traffic flow. Inevitably, this task would not be significantly fulfilled unless a comprehensive survey of vehicular dynamics, within a mathematical framework, is developed. This has motivated physicists to carry out extensive numerical, as well as analytical research, in the discipline of traffic flow theory.

The statistical physicist’s contribution to the field has accelerated since 1990’s when computers provided the possibility of simulating traffic flow through the discretization of space and time. Ever since a vast number of results, both analytically and empirically, has emerged in traffic discipline [1-6]. In principle, the flow of vehicles can be regarded as an interacting system of particles. The techniques developed in statistical physics, which to a very great extent, can be applied to investigate the basic properties associated with the underlying dynamics of vehicular flow. Broadly speaking, the traffic flow theory can be categorized into two parts: high way traffic and city traffic, and now there is vast literature in both domains. In this paper we focus out attention on a particular aspect of city traffic, the so-called roundabout. We try to present a numerical investigation on controlling urban traffic via roundabouts. Traditionally, the conflicting flows in urban areas were controlled by signalised intersections. The basic question which
arises is under what circumstances should one control an intersection by signalised traffic lights? To address this fundamental question, we try to explore and analyze some basic characteristics of a typical roundabout, such as flow and delay, in order to find a quantitative understanding. In what follows we try to illustrate these fascinating aspects through computer simulations.

II. DESCRIPTION OF THE PROBLEM

We now turn to discussing the simulation of traffic at a roundabout. A roundabout is a form of intersection design and control which accommodates traffic flow in one direction around a central island and gives priority to vehicles within the roundabout (circulation flow). Let us first discuss the basic driving principles applied to roundabouts. In its most general form, a roundabout connects four incoming, as well as four outgoing flow directions. In principle, each incoming vehicle approaching the roundabout can exit from each of four out-going directions via making appropriate turning maneuvers around the central island of the roundabout. The following figure illustrates the situation.

The rules of the road give the movement priority to those vehicles which are circulating around the central island. The approaching vehicles should yield to the circulating traffic flow in the roundabout, and are allowed to enter the roundabout, provided some cautionary criteria are satisfied. In this paper we only investigate a simplified version in which all the streets, including the circulating lane around the central island, are assumed to be single-lane. Let us explain the entrance regulations in some details. Each approaching vehicle to the entry points of the roundabout should decelerate and simultaneously look at the left-ward quadrant of the roundabout. If there is any vehicle in this quadrant, then the approaching vehicle should come to a complete stop until the inside vehicle(s) leave(s) this quadrant. The stopped car is only allowed to enter the roundabout provided that no vehicle appears in its left side quadrant; otherwise, it has to slow down and stop. The stopped direction can flow as soon as the front car finds no car in the left-side quadrant of the circulating lane.

This is possible due to stochastic fluctuation in the space gap of the flowing direction. Once such an appropriate space gap has been found, the stopped car is allowed to enter the roundabout. This procedure is continuously applied to all approaching vehicles. Now we return to those vehicles which are moving around the interior island of the roundabout. Once a vehicle is permitted to enter the roundabout, it continues moving until it reaches to its aimed exit direction. Depending on the selected out-going direction, each interior vehicle moves a portion of the way around the central island. These turning movements are classified as: right-turn, straight ahead, left-turn and U-turn. For those who tend to make a U-turn, the whole circumference should be travelled. The interior vehicle can freely move around the roundabout until it reaches the desired exit. The above-mentioned driving rules establish a mechanism responsible for controlling the traffic in conflicting points. This mechanism blocks any direction which is conflicting with a flowing one, thereby producing waiting queues in blocked directions. In contrast to signalised intersections, intersecting streets through roundabouts are controlled via a self-organized mechanism of blocking.

It is evident that in congested traffic situations, where the in-flow rates are high, the probability of finding a large space gap is low. This leads to global blocking of other directions, which in turn gives rise to the formation of pronounced queues. In this situation, the roundabout performance is inefficient, and apparently signalised control strategy shows a better performance. Conversely, in relatively low traffic volume it is likely to find a large space gap (by fluctuation) in the circulating direction and hence, the possibility of entrance for the block direction increases. This increases the efficiency of the roundabout. The roundabout efficiency significantly depends on the incoming fluxes of cars and statistics of space gaps. The basic question raised is under what circumstance the self-organized control scheme becomes inefficient? In order to find a better insight to the problem, we have simulated the traffic flow and have investigated the roundabout performance for various traffic situations and geometrical sizes of roundabout. In the subsequent sections we present our simulation results.

III. FORMULATION OF THE MODEL

In this section we begin with the simplest flow structure of the roundabout. In this case, the roundabout connects two single-lane one-way to one-way streets. With no loss of generality, we take the direction of flows to be northward on street A and eastward on street B.
we take the number of cells to be \( L \) by a one-dimensional chain divided into cells which are discretized in such a way that each street is modelled \( L \). Delay at time step \( t + 1 \) is obtained by adding the queue length \( Q \) to the delay at time step \( t \). 

\[
delay(t + 1) = delay(t) + Q(t)
\]

(1)

This ensures that during the next time-step, all of the stopped cars contribute one step of time to the delay.

In order to capture the basic features of the problem, we have simulated the traffic movement in the framework of cellular automata. For this purpose, space and time are discretized in such a way that each street is modelled by a one-dimensional chain divided into cells which are the same size as a typical car length. The circulating lane of the roundabout is also considered as a discretized closed chain. Time is assumed to elapse in discrete steps. We take the number of cells to be \( L \) for both streets and \( L_c \) for the interior lane. Each cell can be either occupied by a car or be empty. Moreover, each car can take discrete-valued velocities \( 1, 2, \cdots, v_{max} \). To be more specific, at each step of time, the system is characterized by the position and velocity configurations of the cars on each road. We note that due to the turning maneuvers, the maximum velocity of circulating cars should be reduced. Here we assume that the maximum velocity for interior cars takes the value of 40 km/h.

The system evolves under a generalized discrete-time Nagel-Schreckenberg (NS) dynamics. The generalized model incorporates the anticipation effects of driving habits. It modifies the standard NS model at its second step i.e., adjusting the velocities according to the space gap. Let us briefly explain the updating rules which are synchronously applied to all the vehicles. We denote the position, velocity and space gap (distance to its leading car) of a typical car at discrete time \( t \) by \( x^{(t)}, v^{(t)} \) and \( g^{(t)} \). The same quantities for its leading car are denoted by \( x^{(t)}_l, v^{(t)}_l \) and \( g^{(t)}_l \). Assuming that the expected velocity of the leading car, anticipated by the one following, in the next time step \( t + 1 \) takes the form \( v^{(t)}_{l,anti} = min(g^{(t)}_l, v^{(t)}_l) \), we define the effective gap as \( g^{(t)}_{eff} = g^{(t)} + \max(v^{(t)}_{l,anti} - gap_{secure}, 0) \) in which \( gap_{secure} \) is the minimal security gap. Concerning the above-mentioned considerations, the following updating steps evolve the position and the velocity of each car.

1) Acceleration:

\[
v^{(t+1)} = \min(v^{(t)} + 1, v_{max})
\]

2) Velocity adjustment:

\[
v^{(t+2/3)} = \min(g^{(t+1/3)}_{eff}, v^{(t+1/3)})
\]

3) Random breaking with probability \( p \):

if random \(< p \) then \( v^{(t+1)} = \max(v^{(t+2/3)} - 1, 0) \)

4) Movement:

\[
x^{(t+1)} = x^{(t)} + v^{(t+1)}
\]
A. entrance of cars to the intersection

So far, we have dealt with those cars within the horizon of the roundabout which goes up to the boundary points located at site L up-stream from each incoming flow. It would be illustrative to discuss the entrance of cars into the roundabout. We take the distance of the boundary position to be 70-cells, equivalent to 400 metres to the central island. The time head-ways between entering cars at this entry location vary in a random manner which consequently implies a random distance headway between successive entering cars. As a candidate for describing the statistical behaviour of the random space gap of entering cars, we have chosen the Poisson distribution. The Poisson distribution function has been used in a variety of phenomena incorporating the modelling of "queue theories" and has proven to be a good estimation of reality [13]. In addition, it has the merit of taking only discrete values which is desirable to us in the view of the fact that in our model the gap is a discrete variable. According to this distribution function the probability that the space gap between the car entering the intersection horizon and its predecessor be $n$ is:

$$p(n) = \frac{\lambda^n e^{-\lambda}}{n!}$$

where the parameter $\lambda$ specifies the average as well as the variance of distribution function. The parameter $\lambda$ is a direct measurement of traffic volume. A large value of $\lambda$ describes light traffic, while on the other hand, a small-valued $\lambda$ corresponds to a heavy traffic state.

B. Simulation Results

We let the roundabout evolve for 1800 time steps which is equal to a real time period of one hour. We have averaged the results of 50 independent runs. Let us first consider the symmetric traffic states in which the traffic conditions are equal for both roads. In this case, we load the streets equally with approaching cars, spatially separated by a random space gap (Poisson statistics) from each other. Figure (3) depicts the total delay curves as a function of average space gap of entering cars $\lambda_A = \lambda_B = \lambda$ for various roundabout sizes. All vehicles leave the roundabout along the incoming direction viz. they are not permitted turn right, left or U-turn upon circulating the roundabout. According to the graph, the delay shows a rapid decline for light traffic states. This marks the high efficiency of roundabout in low-volume traffic situations. Roundabouts are designed in different sizes to serve various objectives and conditions. Even mini-roundabouts are effective at reducing speed and improving safety. Our simulation results confirm that roundabout size plays a dominant role in its performance. Figure three suggests the short-sized roundabouts operate more optimally. We next examine the impact of asymmetry in the traffic volumes of the streets. For this purpose, we fix the in-flow rate in street B at $\lambda_B = 13$ cells and vary the in-flow rate of street

IV. RIGHT-TURN PERMISSION

At this stage, we remove parts of the restriction on the exit direction and enable each car to leave the roundabout at its first exit i.e., a right-turn. This implies that the south-north direction (street A) is equipped with an extra south-bound lane along which the incoming B-vehicle can leave the roundabout through a right-turn. The following figure illustrates the situation. Analogously, the approaching A-vehicles can leave the roundabout through the exit leg of street B via a right-turn maneuver. Therefore, for each incoming vehicle we assign a parameter which determines the vehicle decision to exit along the incoming direction or leave the roundabout at its first exit by making a right-turn maneuver.
We denote this right-turn probability by $\sigma_A$ and $\sigma_B$ for incoming A- and B-vehicles respectively.

Before proceeding further, it would be illustrative to discuss the effect of displaying indicators. By the usage of indicators, each approaching vehicle can inform the others of his exit direction. Displaying the right-indicator corresponds to the case in which the driver intends to make a right-turn and leave the roundabout at the first exit. Those drivers who intend to exit straight ahead should not display their indicators. Indicator usage gives rise to an easier entrance to the roundabout. More specifically, consider a waiting A-vehicle which is yielding to the B-flow. If this stopped vehicle observes the displaying indicator of the approaching B-vehicle, then it, on a deterministic level, knows that the B-vehicle would not conflict with him (it exits from the roundabout by the south-bound of street A). Consequently, the waiting A-vehicle can enter the roundabout simultaneously with the B-vehicle without any conflict; whereas, without the use of an indicator, the A-vehicle should wait until the B-vehicle exits the roundabout. This would unfavourably increase the waiting times. The above argument predicts that the usage of an indicator leads to an easier entrance to the roundabout. Although this effect locally decreases the waiting times, our simulation results, nevertheless, prove the contrary. The following graph shows the waiting time for the symmetric situation in which the turning probability is equal to 0.5 for approaching cars of both streets. The inset sketches the delay in terms of $\lambda_A$ for various sizes of the roundabout. Indicators are off, right-turn probabilities are 0.5 and $\lambda_B = 13$ cells.

In the inset indicators are displayed. Make cars enter the central island more conveniently, but this leads to increase of car density in the central island which correspondingly increases the probability of blocking the in-flow direction due to yielding effect. Blocking effect is the dominant factor and leads to an overall increase of delay. We have also investigated the dependence of delay on the probability of right-turns for A-vehicles. The following graph shows the result.
According to the results, the delay in minimal size-dependent $\sigma$. It would be useful to discuss the results of varying the speed limit on the performance of the roundabout. Evidently, imposing restrictions on speed limit of vehicles leads to considerable effects on waiting time. The lower speed limit of incoming cars decreases the growth rate of queues which in turn decreases the waiting times. The following figure illustrates the situation for various amounts of $v_{max}$. Lower speed limits lead to less delay.

We have also examined the dependence of delay on maximum velocity for different roundabout sizes. According to the results, one reaches an asymptotic value independent of the maximum velocity. The following graph depicts the situation.

V. LEFT AND U-TURN AROUND THE ISLAND

Let us now consider a more realistic situation. In most general form, vehicles can enter from four directions i.e., north, south, east and west, to a roundabout. We denote these entries by $S_{in}, N_{in}, W_{in}$ and $E_{in}$ respectively. Moreover, there are four exit directions denoted by $S_{out}, N_{out}, W_{out}$ and $E_{out}$. Entering vehicles can exit from any of the outgoing directions by making an appropriate turning maneuver around the central island. Let us assume that vehicles enter only from $S_{in}$ and $W_{in}$ but can exit from every out-going directions upon their decision (see the following figure). In addition, to each incoming vehicle we assign a label which determines its exit direction. These labels are assigned in a random manner. To be more specific, for each incoming vehicle we let four numbers $P^{S}_\tau, P^{E}_\tau, P^{W}_\tau$ and $P^{N}_\tau$ denote the exit probabilities from south, east, west and north exits respectively. The index $\tau = A, B$ denotes the entrance direction. We note that for each value of $\tau$ we have $P^{S}_\tau + P^{E}_\tau + P^{W}_\tau + P^{N}_\tau = 1$.

In this case, B-vehicles should also yield to traffic in the roundabout since those vehicles intending to exit from $S_{out}$ have priority with respect to incoming cars from $W_{in}$ entry i.e., B-vehicles. Consequently, in this general case, both B and A-vehicles contribute to delay. Figure (11) exhibits the overall delay for a one-hour performance as a function of average space gap of entering vehicles (taken equal for both incoming flows) for some choices of
roundabout sizes. In the top graph, exit directions are chosen on an equal basis for incoming cars $P_S = P_E = P_W = P_N = 0.25$ and indicators are assumed to be off. Maximum velocities are 6 for the outer, and 4 for the inner vehicles. In the middle and bottom graphs the exit probabilities are chosen on a biased level. In the following graph (figure 12) We assume there is a preferential exit direction while the remaining exit probabilities are the same. Total delay is sketched for some choices of the preferred exit direction probabilities. The roundabout circumference is taken to be 24 cells and the in-flows are equal to each other.

In the following graph we draw the dependence of one-hour overall waiting time in terms of the probability of straight exit from the roundabout. For each approaching vehicle, the probability of right, left and U-turns are assumed to be equal and the in-flows are assumed to be symmetric. The top graph corresponds to $\lambda = 13$ cells, in the middle graph, $\lambda$ equals 20 cells and finally in the bottom graph $\lambda$ is chosen at 28 cells.

For the sake of comparison, we have simulated four cases corresponding to different exit situations. We describe the exit scenarios for A-vehicles. In case one, $P_S = P_W = P_E = 0$ and $P_N = 1$. In the second case we have $P_S = P_W = 0$ and $P_N = P_E = 0.5$. For the third case $P_S = 0$ and $P_E = P_W = P_N = 0.33$ and finally the fourth case considers $P_S = P_W = P_E = P_N = 0.25$. Similar arguments apply to B-vehicles. The following figure depicts the delay curve for these four exit cases as a function of the inverse traffic in-flow rate. The results show that right-turn exit is the main factor in reducing total delay which is justified by its least conflict.

VI. COMPARISON TO OTHER CONTROLLING SCHEMES

Let us now compare the roundabout performance with signalised control methods of an intersection. This comparison is our main motive for studying roundabout characteristics. Let us replace the roundabout with an intersection with traffic lights. For simplicity, we consider the intersection of two one-way to one-way streets which are assumed to direct single-lane traffic flow. Basically there are two types of signalisation: fixed-time and traffic adaptive. We first describe the fixed-time method. In this control scheme, the traffic flow is controlled by a set of traffic lights which are operated on a fixed-cycle. The lights periodically turn green with a fixed period (cycle length) $T$. This period is divided into two parts: in the first part, the traffic light is green for street $A$ (simultaneously red for street $B$). This part lasts for $T_9$ seconds ($T_9 < T$). In the second part, the lights change colour and movement is allowed for the cars of road $B$. The second part lasts from $T_c$ to $T$. This behaviour is repeated periodically. In [12] and [?] we have shown that
the optimal traffic flow is obtained at: $T_{g}^{opt} = \frac{\alpha_A}{\alpha_A + \alpha_B} T$

where $\alpha_A$ and $\alpha_B$ denote traffic volumes in street A and B respectively. This implies that the optimal green time given to street A should be proportional to its in-flow rate. In figure (16) we compare the performance of the corresponding roundabout with fixed-time signalisation strategy. Traffic volumes are assumed to be equal for both streets. Furthermore, we assume that incoming vehicles cannot turn and should move straight ahead.

According to the above graph, in relatively light traffic states, characterized by a large average space gap, a roundabout shows a better performance and gives rise to lower delays. Conversely, in more congested traffic situations, controlling the intersection by signalised traffic light leads to better results. Our simulation results give the critical in-flow rate below which the intersection should be controlled in a self-organized manner. This result can be explained by noting that in sufficiently light traffic states, the approaching cars can easily find the required space gap in the flow of conflicting direction hence they can enter the roundabout without spending much times whereas in a signalised scheme, they have to wait at the red parts of the signal even if the flow is negligible in the conflicting direction. This proves that below a certain congestion, the roundabout efficiency is higher than fixed-time signalised. We now discuss the traffic adaptive controlling scheme in which the light signalisation is adapted to the traffic at the
intersection. Nowadays, advanced traffic control systems anticipate the traffic approaching intersections. These adaptive systems have the capability to dynamically modify the signal timing in response to fluctuating traffic demand. Traffic-responsive methods have shown a very good performance in controlling city traffic, and now a variety of schemes exists in the literature \cite{8-10}. In these schemes, the data obtained via traffic detectors installed at the intersection is gathered for each movement direction, and it is possible to count the queue-lengths formed behind the red lights. One can also measure the time-headways between successive cars passing each lane; thus, it is possible to estimate the traffic volume existing at the intersection. There are various methods for the distribution of green times. In what follows we try to explain some standard ones. In each scheme, the green time of a typical direction is terminated if some conditions are fulfilled:

**Scheme (1):** The queue length in the conflicting direction exceeds a cut-off value $L_c$. This scheme only adapts to the traffic states on the red street.

**Scheme (2):** The global car density on the green street falls below the cut-off value $\rho_g$. Here the algorithm solely adapts to the traffic state in the green street.

**Scheme (3):** Each direction is endowed with two control parameters $L_c$ and $\rho_c$. The green phase is terminated if the conditions: $\rho^g \leq \rho_c$ and $L^r \geq L_c$ are both satisfied.

In scheme three the algorithm implements the traffic states in both streets. The superscripts "r" and "g" refer to words "red" and "green" respectively. We note that the first two schemes are special cases of the more general scheme (3). Schemes (1) and (2) are the limiting cases of schemes (3) by letting $\rho_c \to 1$ and $L_c \to 0$ respectively. In general, the numerical value of control parameters $L_c$ and $\rho_c$ could be taken different for each individual street. In what follows we present our simulation results for some types of adaptive signalisation schemes introduced above, and compare them to a self-organized scheme by roundabout.

Analogous to fixed-time method, here we see that below a certain traffic volume, roundabout is more efficient. We note that in the adaptive scheme, the numerical value of critical $\lambda$ is considerably reduced with respect to fixed-time method. This is due to the advantage of adaptive schemes over fixed-time ones. This comparison has thoroughly been discussed in \cite{12}. Fixed-time predicts $\lambda_c = 16$ cells while in adaptive method it goes to $\lambda_c = 22$.

**VII. SUMMARY AND CONCLUDING REMARKS**

Traffic signal control is a central issue in the design of advanced traffic management systems. Recent strides in the modelling and in the simulation of traffic flow have opened new possibilities for traffic control and optimization. In this regard, the micro-simulation of city traffic could be of practical relevance for various applications in urban traffic. Isolated intersections are fundamental operating units of the sophisticated and correlated urban
network, and their thorough analysis would be advantageous towards the ultimate task of the global optimization of the city network. While signalised intersections are traditional objects designed for controlling the traffic flow in conflicting directions, modern roundabouts, which have recently been designed and operated, account for an alternative strategy for traffic control. Enthusiasm for safety and for the high capacity of roundabouts has resulted in a huge increase in the number of roundabouts. In contrast, as growing traffic demand causes non-conforming traffic circles to fail, they are converted to other types of intersections. In addition to the features that characterize a modern roundabout, yield-at-entry, deflection and flare, roundabouts often have other important safety features. Although some people involved in vehicular traffic may be uncomfortable initially with the idea of a traffic roundabout, it is a solution that is environmentally friendly and requires less in annual maintenance costs since it replaces traffic signals. Nevertheless, the efficiency of roundabouts is still under debate, and many experts believe that signalised intersections show a better performance in most circumstances. To settle this debate, at least to a partial degree, we have tried to quantitatively explore the basic features of roundabout in order to have a better insight into the problem. In this paper we have investigated the characteristics of traffic at an isolated roundabout in the framework of cellular automata. For this purpose, we have developed and analyzed the performance of the various aspects of roundabouts, the most important of which is delay. Our simulation shows that overall delay is significantly affected by roundabout size. Our simulations gives the optimal size for various traffic volumes. Another relevant aspect is the indicator displaying, which noticeably affects the overall delay. The major conclusion made from our simulation results proves the existence of critical congestion, dominated by the statistics of arrival space gaps, over which the intersection is made more efficient by signalisation strategies. In a more realistic situation, the flow can circulate around the central island via an additional lane. The interior lane should be used by those vehicle intending to make left or U-turns while the exterior one should be taken by those drivers who tend to turn right or move straightforward. The second interior lane may drastically change the behaviour of indicator displaying thus leading to improvement of delay. In the present simple case of single-lane circulation, our simulations implies that injection of vehicles from more than two entries leads to global blocking of flows and growing delays. This effect is due to the saturation of circulating flow which hinders the incoming fluxes. Implementation of additional interior lane will certainly removes the blocking and gives rise to realistic results. In this general situation, roundabout performance undergoes fundamental changes, and many interesting phenomena arise which we are still currently exploring.

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