Intelligent Controlling Simulation of Traffic Flow in a Small City Network

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We propose a two dimensional probabilistic cellular automata for the description of traffic flow in a small city network composed of two intersections. The traffic in the network is controlled by a set of traffic lights which can be operated both in fixed-time and a traffic responsive manner. Vehicular dynamics is simulated and the total delay experienced by the traffic is evaluated within specified time intervals. We investigate both decentralized and centralized traffic responsive schemes and in particular discuss the implementation of the green-wave strategy. Our investigations prove that the network delay strongly depends on the signalisation strategy. We show that in some traffic conditions, the application of the green-wave scheme may destructively lead to the increment of the global delay.

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I. INTRODUCTION

The ever-increasing volume of vehicular traffic flow together with the lack of money and space in developing further infrastructure of urban transportation systems are major reasons for seeking advanced traffic management methods. It has been more than fifty years since the scientists have intensively tried to understand the fundamental spatial-temporal aspects of vehicular phenomena to gain a better insight to the optimal control of vehicular flow. The phenomena related to the formation of traffic jams have been attractive to traffic engineers as well as statistical physicists for many years and now there exists a proliferation of results both empirically and theoretically in the literature [1–8]. The physics contribution to the subject has been rapidly growing since 90'th. Aside from efforts to understand the basic features of a typical traffic flow via empirical data, over the last decade physicists have seriously attempted to model the movement of vehicles to understand fundamental principles governing the vehicular flow. These investigations have mainly been concerned with highway traffic. Interested readers can refer to the elaborate reviews in the literature [3,4]. On the other hand, notable investigations have, in parallel, dealt with the challenging subject of city traffic. Physicists' contributions to city traffic started through the pioneering work of Biham, Middelton and Levine who developed a two dimensional Cellular Automaton (CA) model of city network [9]. The BML model was later generalized to take into account several realistic features such as faulty traffic lights, turning of vehicles and green-wave synchronization etc [10–24]. Quite recently, more serious network models, in the framework of Nagel-Schreckenberg CA model [25], have come into play which have significantly contributed to the city network simulation discipline and have opened promising strides in the city traffic controlling schemes [26,27]. Despite incorporating global signalisation schemes in these very recent investigations and similar ones proposed by traffic engineers, the problem of optimisation of traffic flow in a realistic city network has not yet thoroughly been solved. Diverse degrees of freedom makes the problem a formidable task. Basically there are two types of control for traffic lights at city intersections: fixed-cycle and traffic responsive. Fixed cycle intersections operate with a constant period of time $T$ which, for each driving direction, is divided into a green period, a yellow-red period and a red period. Fixed cycle intersections can be coordinated by offsetting the start of green period of consecutive intersections along a desired path in order to create the so-called green-wave of lights [28]. In the traffic responsive scheme, the period of traffic lights, and consequently its sub-phases, are simultaneously adapted to the traffic characteristics and are therefore not constant in the course of time. It is now an almost well-established fact that, in general, adaptive controlling of coordinated intersections should be the ultimate method towards the global signalisation of traffic lights. The complexity of the problem still remains regarding the fact that there are numerous schemes of adaptive controlling. Examining new control schemes on real traffic is not always possible and practical. Alternatively computer-based simulations offer a cheap and useful method for testing new strategies that can be of practical relevance for various applications in city traffic. It is our objective in this paper to simulate the flow of vehicles at a simplified set of intersections which operate under adaptive controlling schemes. Our investigations aim at seeking the optimal control strategy and to gain a deeper insight into the problem of city traffic control.

II. FORMULATION OF THE MODEL

We begin our investigations by considering the most simplified city network i.e., a cluster of two intersections. In our primitive network, two south-north streets A and B are intersected by a west-east street C. Figure one
illustrates the situation. For simplicity we assume the south-north streets allow single-lane traffic flows northward and that the west-east street conducts an eastward single-lane flow. A set of traffic lights controls the traffic at each intersection. Each street is modelled by a chain divided into cells which are as large as a typical car length. Each cell can be either occupied by a car or being empty. The car velocity 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 cars and the traffic light states at each road.

The movement dynamics is governed by a generalized version of the Nagel-Schreckenberg model which has recently been proposed by Knospe, Santen, Schadschneider and Schreckenberg [29]. The model basically differs from the NS model in the sense that it incorporates adaptation effects, absent in the minimal model of NS, in realistic traffic. The model successfully reproduces, on a microscopic level, the generic features of empirical data. The model incorporates additional parameters and concepts such as brake lights, safety distance, temporal interaction horizon, finer discretization of space etc which are the ingredients of an adaptive look-ahead driving strategy [30]. Let us briefly explain the movement rules. 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 $g(t)$ and the same quantities for its leading car by $x_{l}(t), v_{l}(t)$ and $g_{l}(t)$. Assuming that the expected velocity of the leading car, anticipated by the one following, in the next time step $t+1$ takes the form $v_{l, ant}(t) = \min(g_{l}(t), v_{l}(t))$, we define the effective gap as $g_{eff}(t) := g(t) + \max(v_{l, ant}(t) - gap_{secure}, 0)$ in which $gap_{secure}$ is the minimal security gap. Concerning the above considerations, the following updating steps evolves the position and the velocity of each car.

1) Acceleration:

$$v(t+1/3) := \min(v(t) + 1, v_{max})$$

2) Velocity adjustment:

$$v(t+2/3) := \min(g_{eff}(t+1/3), v_{l}(t+1/3))$$

3) Random breaking with probability $p$:

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

4) Movement : $x(t+1) := x(t) + v(t+1)$

We now return to our network. Let us now specify the physical values of our time and space units. Ignoring the possibility of existence of long vehicles such as buses, trucks etc, the length of each cell is taken to be 5.6 metres which is roughly the typical bumper-to-bumper distance of cars in a waiting queue. Concerning the fact that in most urban areas a speed-limit of 60 kilometre/hour should be kept by the drivers, we quantify the time steps in such a way that $v_{max} = 6$ corresponds to the speed-limit value (60 km/h). In this regard, each time step equals two seconds and correspondingly each discrete increment of velocity signifies a value of 10 km/h. We set the length of streets before the intersections (horizon length), denoted by $L_{A}, L_{B}$ and $L_{C}$ respectively, equal to 70 cells and the distance between intersection as 40 cells. The state of the system at time $t + 1$ is updated from that in time $t$ by the synchronous application of the anticipated NS dynamical rules to all the vehicles through the following steps:

**Step 1 : signal determination.**

We first specify the signal states for all of the driving directions. In subsequent sections we will, in detail, explain the scheme at which the traffic lights change their colour.

**Step 2 : movement at the green roads.**

At this stage, we update the position and velocities of cars on the green road according to the dynamical rules which are synchronously applied to each car.

**Step 3 : movement at the red roads, delay evaluation.**

Here the updating is divided into two parts. In the first part, we evaluate, for each street, the delay of cars waiting on the red period of the signalisation. In the second half, we update the position and velocities of the moving cars approaching the waiting queue(s). We recall
that once the light turns red, the moving cars continue
their movements until they come to a complete stop by
reaching to the end of the waiting queue. As soon as a
car comes to halt, it contributes to the total delay. In
order to evaluate the delay, we measure the queue length
(the number of stopped cars) at time step $t$ and denote it
by the variable $Q$. Denoting the configuration of site $i$ ($i$ increases in the opposite direction of traffic flow) at time $t$ by $pos^{ed}[i,t]$, we have $pos^{ed}[i,t] = 1$ for $i = 1 \cdots Q$
and zero at $i = Q + 1$. Delay at time step $t+1$ is obtained
by adding the queue length $Q$ to the delay at time step $t$.

$$delay(t+1) = delay(t) + Q(t)$$

This ensures that during the next time step, all the
stopped cars contribute one time step to the delay. The
next part of the update goes to the positions and velocities
of the moving cars. Moving cars can potentially be
found in the cells $Q + 2, Q + 3, \cdots, L$. We update their
positions and velocities in a similar manner described for
green streets.

**step 4 : entrance of cars to the intersection.**

So far, we have dealt with those cars within the hori-
zons of the intersections. Here we discuss the entrance of
cars into the network. Evidently from our everyday driv-
ing experience, we observe that the time head-ways be-
 tween entering cars vary in a random manner which con-
sequently implies a random distance headway between
successive entering cars. As a candidate for describing
the statistical behaviour of random space gap of entering
cars, we have chosen the Poisson distribution. Very re-
cent empirical studies on high way traffic confirms that in
some traffic phases, the distribution of the time headways
between successive cars agrees well the Poisson distribu-
tion function [31]. According to this distribution func-
tion, 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 the distribution func-
tion. The parameter $\lambda$ is of direct relevance to the traffic
volume. A large value of $\lambda$ describes light traffic while
on the other hand, a small-valued $\lambda$ corresponds to heavy
traffic. Car-injection to the streets has been thoroughly
discussed in [32].

The above *ad hoc* rules updates the configuration of
the intersections at time $t$. In the course of time the cars
enter the intersections and a fraction of them experience
the red lights and consequently have to wait until they
are allowed to go through intersections during the up-
coming green periods. For the sake of simplicity, we have
assumed that each street has a single lane. For streets
with more than one lane, one simply should multiply the
value of delay by the number of lanes. Moreover, we al-
low those fractions of northward (eastward) cars tending
to turn right (left) manage to turn via a by-pass road.

Therefore the cars in our simulation denote those which
wish to go through the intersection without turning. We
are now able to simulate the performance of this small
network and obtain the delay for each intersection.

**III. SIGNALISATION OF TRAFFIC LIGHTS: TRAFFIC RESPONSIVE**

We now discuss the main essence of the paper which is
the simulation of intelligent signalisation schemes. Nowa-
days advanced traffic control systems anticipate the traf-
fi c approaching intersections. Traffic-responsive methods
have shown a very good performance in controlling the
traffic in city network and now a variety of schemes ex-
ists in the literature [28,35–39]. In principle, there are
two major strategies for controlling an intersection in the
traffic-adaptive methods: centralized and decentralized.
In decentralized schemes, the traffic lights are adapted
to the local traffic at the intersection and are not in-
fluenced by the traffic volume approaching the intersec-
tion from adjacent intersections. On the other hand, in
a centralized scheme, the signalisation is performed in
a more intelligent manner and incorporates the traffic
states at the up stream intersections. Whether to con-
trol an intersection via centralized strategy is a subtle
question and often controversial. While empirical studies
confirm that in special circumstances, decentralized local
adaptive strategies operate more effectively than globally
adaptive ones [39], the general trend in controlling central
areas of cities is toward the adaptive coordination of in-
tersections. We first discuss the decentralized adaptive
controlling scheme.

**A. decentralised adaptive scheme**

In this scheme, each intersection adapts its signalisa-
tion to the local traffic in its vicinity and does not take
into account the up-stream traffic state in the neighbor-
ing intersections. The data obtain via traffic detectors
installed at the intersection is gathered for each move-
ment direction and it is possible to measure the queue
lengths. One can also measure the time-headways be-
 tween successive cars passing each lane detector. Thus it
is possible to estimate the traffic volume existing at the
intersection. There are various methods for distributing
green time to streets. Let us first introduce $T_{min}$ which
is the minimum green time devoted to a direction. If a
typical direction goes green it will definitely remain green
for $T_{min}$ seconds for practical purposes the main one of
which is the slow movement of standing vehicles. Now
we try to explain some standard termination algorithms.
In each scheme, the green time of a typical green street
is terminated if some conditions are fulfilled. By green
(red) street we mean the street for which the traffic light
is green (red). We now state the termination schemes.

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

**Scheme (2):** The time headway between successive cars, denoted by $T_h$, going through the green light exceeds the cut-off value $T_{h}^{c}$. Here the algorithm only concerns the traffic state in the green street.

**Scheme (3):** Each direction is endowed with two control parameters $L_c$ and $T_{h}^{c}$. The green phase is terminated if the conditions: $T_{h}^{g} \geq T_{h}^{c}$ and $L_{h}^{r} \geq L_{c}$ are both satisfied.

Here 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 behaviour of schemes (3) by letting $T_{h}^{c} \to 0$ and $L_{c} \to 0$ respectively. In general, the numerical value of control parameters $L_c$ and $T_{h}^{c}$ could be taken different for each individual street. In [32] we have shown that scheme (1) is the optimal algorithm for isolated intersections. In what follows we present our simulation results for the first signalisation scheme introduced above.

**B. Simulation Results**

We let the network evolve for 1800 time steps which is equal to a real time period of one hour. We evaluate the aggregate delay for both intersections. We first consider the symmetric traffic state in which the traffic conditions are equal for all streets. In this case, we equally load the intersections with entering cars spatially separated by random space gap, obeying the Poisson statistics, from each other. Fig. (2) depicts the total delay curves for some various cut-off lengths.

We note that by increasing $\lambda$ i.e. decreasing traffic volume, the delay decreases. For a fixed value of $\lambda$, the lower cut-off length leads to lower delay. This is expected since the lower $L_c$ terminates the queue sooner and hence less contribution is given to the delay. Furthermore, we have examined the behaviour of delay curves for a wide range of control parameters space ($L_{c}^{A}, L_{c}^{B}, L_{c}^{C}$). The following graphs (figure 5) exhibit this behaviour for fixed traffic volumes. We have taken $L_{c}^{A} = L_{c}^{B}$.

Fig. 2: Total delay of the network in terms of mean space gap of entering cars for various cut-off queue lengths (taken equal for all streets).
The above graphs confirms the conclusion that the optimal algorithm is the one in which all the cut-off lengths are equal and taken as short as possible. Let us now investigate the situation in which two of the streets are major while the third one is minor. Three cases are distinguished corresponding to minority of streets A, B and C respectively. Fig (4) exhibits the results for the case where street A is minor. The traffic volume at major streets are fixed at $\lambda = 14$ cells.

The result for the cases where the minor street is taken as B an C are similar to the above graph. It would be useful to analyze the delay in the individual intersection.

C. centralized adaptive scheme: green-wave method

We shall now turn to the main issue of the paper and present our simulation results of the centralized responsive method. Here the downstream intersection adapts its signalisation to the approaching traffic flow from the up-stream one. In this paper we restrict ourselves to the green-wave strategy in which the green time of the street C at intersection with street B is set in such a way that the platoon coming from the up-stream intersection can go through the intersection without being interrupted by the light changing to red. The up-stream intersection, the platoon source, acts as an independent intersection in a manner explained earlier. Its signalisation is performed by scheme (1). Note that the platoon length is determined by the $L_c$ in the up-stream intersection.
In the time interval between the passage of the platoon and arrival of the next platoon, the downstream intersection is controlled by adaptation to its local traffic. According to the figure, the optimal timing is obtained by taking the platoon green-time at $t = 6$ seconds. This corresponds to the time required for the entire passage of a platoon of the length 100 metre moving with the maximum velocity of 60 km/h. It would be plausible to assume that the vehicles inside the platoon are separated by an average headway of car length (4.5 metres). Therefore the average length of an $N$-platoon is $5.6N + 4.5(N - 1)$. In the above graph, $N$ equal to cut-off length at the up-stream intersection which is taken as $N = 5$ vehicles. Correspondingly our platoon length is 48 metres which gives the required time roughly 3 seconds. However, we should consider that for practical reasons, the lights in the downstream intersections should go green at least several seconds before the arrival of the incoming platoon to the border of the intersection. Otherwise the platoon slows down because of the red light and this contradict the philosophy of the green-wave method. In figure (7) we compare the predictions of the green wave method to that of decentralised scheme. It exhibits the overall delay in terms of traffic volume which is assumed to equal for all three streets.

According to the above result, the efficiency of the green-wave strategy is limited to a certain traffic volume. For more congested situations (corresponding to $\lambda = 16$ cells), the decentralised scheme acts more opti-

mally than the green-wave method. The implementation of the green-wave strategy has always been an argumentative subject. For obvious reasons, the utility of the green-wave is suppressed when the perpendicular street to the street in which the green-wave is produced carries a high traffic volume. This is due to delaying the vehicles of the perpendicular street so that the platoon of the green-wave street goes through the green light. Therefore one should be able to determine the efficiency of the green-wave with respect to the traffic volume in the perpendicular streets. Simulation reveals that the green-wave strategy fails to optimise the traffic flow even in our simple network in the whole range of the traffic volumes. Figure (8) depicts the overall delay in terms of traffic volumes of the perpendicular streets A and B (taken equal to each other). The green wave is produced in street C with constant traffic volume set to $\lambda_C = 14$ cells.

In the top graph of figure (8), green wave efficiency isenhanced with decreasing of traffic volume in the perpendicular streets. This is expected since for relatively light traffic volume in streets A an B, less vehicles are delayed in the red periods when the platoons are crossing street C. We next investigate the delays in another asymmetric traffic state in which the traffic volumes are equal in streets A and C but different to that of street B (middle graph). We compare the overall delay in green-wave with decentralised adaptive scheme by varying $\lambda_B$. One observes that there is crossover traffic volume for street B ($\lambda_B \sim 18$ cells) below which the optimised traffic flow through the network is obtained by implementation of decentralised scheme. For traffic congestion below this value, green wave strategy dominated over decentralised
scheme. In order to gain a better insight to the problem, in the following graphs we draw the overall delay in terms of two parameters which are the traffic volumes in the perpendicular streets and the green-time interval devoted to the platoon approaching to the down-stream intersection $T_{\text{platoon}}^{g}$.

![Graph 9](image9.png)

**Fig. 9:** Overall network delay in terms of traffic volume in the streets A and B. The green-wave is produced in street C. Cut-off lengths are equal to five in the up-stream intersection. Traffic volume is taken as $\lambda = 14$ cells street C.

The above graphs give us the optimal green-time $T_{\text{platoon}}^{g}$ devoted to the platoons in terms of the traffic volume on the perpendicular street. According to the simulation results, $T_{\text{platoon}}^{g}$ not only depends on the platoon length, but also depends on the traffic volume in the perpendicular streets. This result could be of practical relevance for real traffic situation. Our final result (fig. 10) concerns the general comparison of decentralized and the green-wave method for the whole traffic volume range of the perpendicular streets to the green-wave street. As can be seen, for a wide range of the traffic volume space, the green-wave method is less efficient with respect to the decentralized scheme.

![Graph 10](image10.png)

**Fig. 10:** Overall network delay in terms of traffic volume in the streets A and B. The green-wave is produced in street C. Cut-off lengths are equal to five in the up-stream intersection. Traffic volume is taken as $\lambda = 14$ cells street C. The surface with higher slope corresponds to the green-wave strategy.

### IV. SUMMARY AND CONCLUDING REMARKS

Recent strides forward, particularly influenced by the contributions from statistical physics to the subject, have opened new possibilities for traffic control. In this paper, we have developed and analysed a prescription for the traffic light signalisation at a small set of linked intersections. We have proposed an optimising adaptive decentralized scheme on the basis of minimised total delay concept. Borrowing from the traffic engineering literature, we adopt optimised traffic as a state in which the total delay of vehicles is minimum. We have simulated and analysed the green-wave method and shown that it is efficient only in a limited range of traffic volume. We believe that the optimisation of traffic flow at a small cluster of intersections is a substantial ingredient towards a global optimisation. Local clusters of intersections are fundamental operating units of the sophisticated and correlated urban network and thorough analysis of them would be advantageous toward the ultimate task of the global optimisation of the city network. Our simulation results admit that local adaptive intelligent strategies fail to improve the traffic state on a global scale. This effect justifies more explorations on the control of traffic via the coordination of intersections a subject which is under intensive investigation in the traffic engineering. We believe the methodologies developed in the framework of statistical physics to deal with the many body interactive systems could foster the investigations on city traffic. Our next objective is the challenge for finding alternative improved traffic responsive control methods in city network which are more advantageous over the primitive green-wave solution. This subject is under our current investigation.

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[1] Traffic Flow Fundamentals, Prentice Hall (1990) by A.D. May.
