Research Paper

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Effect of off-Ramp on A Single Lane Road Using Modified CA

Engineering

KEYWORDS : Cellular Automata, braking probability, off-ramp, deceleration lane

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ABSTRACT

Traffic flow is a realization of an open one-dimensional many body system with strong correlation among vehicles. To overcome the limitations associated with the conventional simulation techniques a new paradigm is required. The study of cellular automata (CA) is done for that purpose.
Cellular automata are mathematical idealizations of physical systems in which space and time are discrete, and physical quantities take on a finite set of discrete values. A cellular automaton consists of a regular uniform lattice, usually finite in extent, with discrete variables occupying various sites. The state of a cellular automaton is completely specified by values of variables at each site. Based on Nasch model of single lane traffic flow with off-ramp, a modified Cellular Automaton traffic flow model is proposed. The model is developed with reduced cell size, incorporating different acceleration characteristics depending upon the speed of each individual vehicle. Influence of the off-ramp probability over traffic flow is discussed. Phase transition on a highway for homogeneous traffic in velocity-dependent acceleration rate TCA model with an off-ramp is studied. Numerical simulations with open boundary conditions are carried out. Influence of off-ramp and injection probabilities over capacity flow of traffic system with off-ramp is discussed. Comparisons are made between Nasch model and modified model. It is observed that transition from free flow to congested flow and free flow to saturated flow is affected because of dissimilar acceleration capabilities. Effect of length of deceleration lane over flow rate of modified model is similar to Nasch model.

1. Introduction

In recent years Cellular Automaton (CA) traffic flow models have become quite popular for the simulation of traffic flow. Despite their ability to be modeled as simple model in statistical sense, CA have numerous applications to real problems. The first traffic flow model using Cellular Automaton was proposed by Nagel and Schrekenberg that was able to reproduce several characteristics of real-life traffic flows, e.g., the spontaneous emergence of traffic jams, stop and go traffic etc. This model is popularly known as Nasch CA model (Nagel & Schrekenberg, 1992).). In Nasch model start-stop waves appear in the congested traffic region as observed in real traffic. Recently there has been much interest in the study of traffic flow near off-ramps of a highway system, which attracted research interest from physicist (Chen, Liu, Lu & Behzadi ,2009). These models have practical implications for optimizing freeway traffic because of various non-linear dynamical phenomena like traffic jams (Kerner & Konhauser, 1993), stop and go traffic (Kerner & Konhauser, 1994), synchronized traffic (Kerner & Rehborn, 1997). Cassid, Anai, and Haigwood, (2002) show freeway bottleneck by visually extracting traffic data from video tape on a freeway segment whenever queues from the segment's off-ramp spilled over and occupied its mandatory exit lane. It was also shown that the length of these exit queues were negatively correlated with the discharge flows in freeway segment's adjacent lanes. Daganzo, Cassidi, and Berfini (1999) presented evidences of real world FIFO (first in first out). They show that an off-ramp queue propagated upstream moved in the transverse direction to flow and reduced the speed and flow on all lanes until the speed of all lanes was roughly equal. Munoz, and Daganzo (2002) analyzed the behavior of upstream of an oversaturated off-ramp on multi-lane free-way traffic based on empirical evidence from free-way I-880 (North bound) near Oakland CA. It was concluded that in a FIFO system, free-way discharge flow can change significantly without a change in off-ramp flow when percentage of exiting vehicle changes. Off-ramp system of the highway using Cellular Automata traffic flow model with out an exit lane and with an exit lane near off-ramp was investigated by Jia, Jiang, and Wu (2004). At smaller values of off-ramp probability p_{off} , capacity of the system is enhanced by presence of exit lane. However with respect to length of exit lane L_D , they found that it is not the longer the better, a proper value should be designed to get an optimal capacity. Zahraouy, Benrihane, and Benyoussef (2004) discussed the location of off-ramp on a highway using one-dimensional Cellular Automata traffic flow model with open boundaries using parallel dynamics to have a better fluidity. They concluded that when the off-ramp is located between two critical positions i_{c1} and i_{c2} the current increases with extracting rate β_0, for $\beta_0 < \beta_{0c1}$ and exhibits a plateau (constant current) for $\beta_{0c1} < \beta_0 < \beta_{o2}$ and decreases with β for $\beta_0 > \beta_{o2}$.

We present a modified Nasch model for traffic behavior near an off-ramp on a single lane traffic flow. Drivers of the exit vehicles usually decelerate near off-ramp on safety point of view. Effect of length of deceleration lane on throughput of the system is discussed. All the earlier CA traffic flow models were developed for homogeneous conditions with same cell size of 7.5 meters (average length of a car) and constant acceleration rate. These models lack the capability of reproducing realistic conditions of traffic flow on the road as a vehicle can not accelerate or decelerate in the multiple of 7.5 meters/s only. In the recent years some attempts were made to implement CA models for heterogeneous traffic by modifying cell size and updating CA rules for traffic flow (Lan & Chang, 2003). Mallikarjuna and Rao (2007), studied the suitability of different available CA based models for mixed traffic. Cell size is reduced to 1.5 meters for asymmetric two-lane model (Knospe, Santen, Schadschneider, & Schrekenberg, 2002).

Since traffic flow conditions in developing countries differ from other part of the world, therefore a modified cell size is needed to represent realistic traffic conditions in these countries. The cell size is actual vehicle dimension plus the safe distance with the leading vehicle in jam condition.

Table 1 gives the physical length of these vehicles.
Table 1: Physical length of vehicles

Actual length in meters	Design length in meters	Cell size in cells
3.72	6	10

2. Traffic Cellular Automata Model

Nasch model explicitly includes a stochastic noise terms to it's rules. The road is subdivided into cells of same size (δx =7.5 meters). Each cell is either empty or occupied by one vehicle with a discrete speed v varying from 0 to V_{max} , with V_{max} the maximum speed of vehicle. Vehicles are assumed as anisotropic particles, i.e. they only respond to frontal stimuli. The motion of the vehicle is described by the following rules:

Rule1 : Acceleration :

$$v_i^{(1)} = \min\{v_i^{(0)} + 1, V_{max}\}$$

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Rule2 : Deceleration :

$$v_i^{(2)} = \min\{v_i^{(1)}, x_{i+1}^t - x_i^t - 1\}$$

Rule3 : Randomization :

$$v_i^{(3)} = \max\{v_i^{(2)} - 1, 0)$$

with braking probability p ;

Rule4 : Movement :

$$x_i^{t+1} = x_i^t + v_i^{(3)}$$

Where $x_{i+1}^t - x_i^t - 1$, the number of empty cells in front of i[th] vehicle at time t and is called distance headway. x_i^t is the position of the i[th] vehicle at time t. A time step of $\delta t = 1$sec, the typical reaction time of driver with a maximum speed V_{max} = 5 cells/time step i.e.135 Km./Hour is taken in this model. Nasch model contains the rule of randomization that introduces stochasticity in the system. At each time step a random number between 0 and 1 is drawn from a uniform distribution. This number is then compared with a stochastic noise parameter p between 0 and 1; as a result there is a probability p, that a vehicle will slow-down it's velocity by 1.

3. Modified cell size and variable acceleration rate

Most of the CA traffic flow model consider a definite cell size of 7.5 meter for all type of vehicles and acceleration rate is assumed to be constant i.e. 1 cell/sec^2 for all type of vehicles. This means that all the vehicles on the road have the same acceleration rate, which is not realistic. When modeling realistic traffic stream that consists of different type of vehicles, having variable speed and acceleration rate, finer discretization is useful. Therefore we reduce the cell size and acceleration rate is chosen such that it depends upon the speed of each individual vehicle. Under this fine discretisation we can describe the vehicle moving process more realistically. Cell size is reduced to 0.5 meters and a vehicle occupies 10 cells with V_{max} = 60 cells which correspond to 108 km/h. With these characteristics, distance headway for i[th] vehicle becomes $x_{i+1}^t - x_i^t - 10$. Rule 1 i.e. acceleration rule of Nasch model is modified as:

Rule1 : Acceleration :

$$v_i^{(t+\delta t/3)} = \min\{v_i^{(t)} + a, V_{max}\}$$

Where acceleration a is determined as follows:

$$a = \begin{cases} \frac{V_{max}}{15}, & \text{if } v_n <= \frac{V_{max}}{4} \\ \frac{V_{max}}{20}, & \text{if } \frac{V_{max}}{4} < v_n <= \frac{V_{max}}{2} \\ \frac{V_{max}}{30}, & \text{if } v_n > \frac{V_{max}}{2} \end{cases}$$

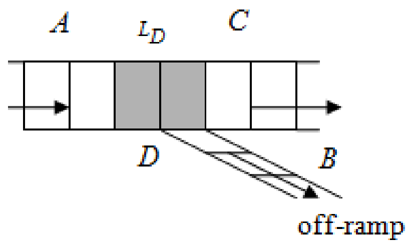

Figure 1: The schematic illustration of the system

4. Off-ramp model with deceleration lane

To make the problem simple, we assume that main road is a single lane road.

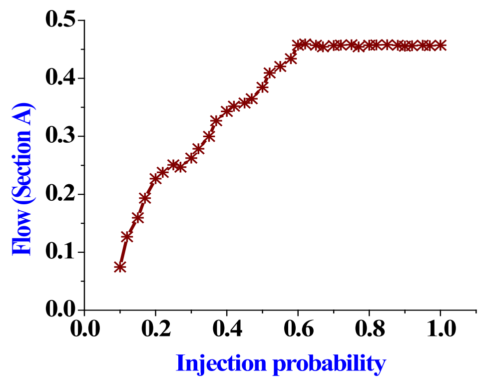

Figure 2: Relationship between flow on section A and α keeping off-ramp $p_{off} = 0.0$ for modified model.

Figure 1 shows the freeway system with off-ramp is divided into four sections: section A is freeway mainline upstream of ramp, section C is freeway downstream of off-ramp,

section B is off-ramp and section D is deceleration lane. The drivers of exit vehicles usually decelerate because of presence of off-ramp. A maximum velocity v_{max} is set for exit vehicles as they reach on the section D .Therefore Section D is deceleration lane, whereas sections A, B C are single lanes. The boundary conditions are adopted as follows: Position of the last vehicle on section A is denoted by x_{Alast} and position of leading vehicles on section C and off-ramp B are denoted by x_{Cfirst} and x_{Bfirst} respectively. After one time step, when update of all the vehicles on the road is completed, if $x_{Alast} > V_{max}$,

a vehicle with velocity V_{max} is injected with injection probability α at the cell min

$[x_{Alast} - V_{max}, V_{max}]$. p_{off} is the probability with which vehicles leave the main road and enter the off-ramp. Leading vehicles on section C and off-ramp B leave the sections if $x_{Cfirst} > L_C$ and $x_{Bfirst} > L_B$ respectively where L_C and L_B denote the position of rightmost cell on section C and off-ramp B respectively.

5. Numerical Simulation

The basic feature of this model is the relation between density (ρ) and flow (q) i.e. $q = \rho v$, where v is the average velocity. We perform numerical simulation on a long highway of length L with an off-ramp. The time interval δt is taken 1 sec., the driver's typical

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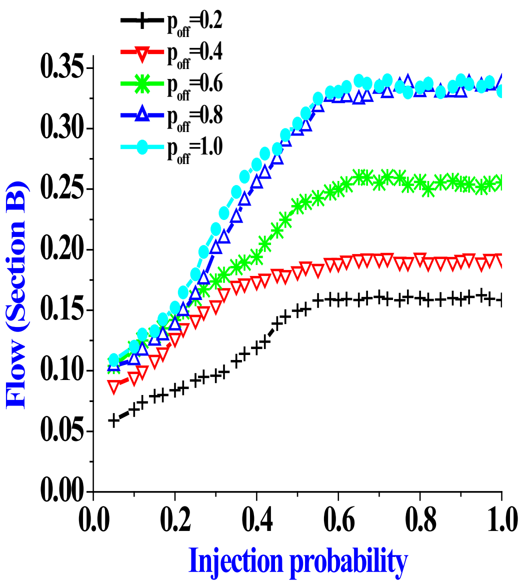

Figure 3: Relationship between flow on section B and α for different p_{off} for modified model.

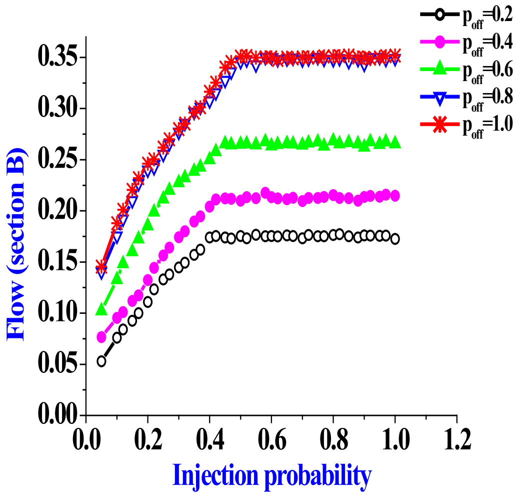

Figure 4: Relationship between flow on section B and α for different p_{off} for Nasch model of single lane with off-ramp.

reaction time. In our simulation process, sections A, C and B each are divided into 2500 cells i.e. equivalent to 2.5 km road section. Maximum velocity $V^{e}_{\max}$ for deceleration lane is set to be 40 cells. After a transient period of 10,000 time steps, we recorded value of traffic flow q (No. of vehicles moving ahead per unit time step) keeping braking probability $p = 0.1$.

The computational formulas used in numerical simulation are given as follows:

$$\bar{q}_i = \frac{1}{T}\sum_{t=1}^{t=T} m_i(t) \qquad (1)$$

Where equation (1) represents the flow of vehicles on site S_i; $m_i(t) = 1$, if at time $t-1$ there was a vehicle behind or at site S_i and at time t it is found after S_i (i.e. a vehicle is detected passing by site S_i) and 0 otherwise.

6. Results and Discussions

In order to show the effect of injection probability α on throughput, first we keep off-ramp probability $p_{off} = 0.0$. The problem reduces to stochastic Nasch model with variable acceleration rate in open boundary condition.

Figure 2 depicts that initially flow on section A increases with α, and becomes constant at $Q_{c1} =$ .45 after α surpasses a

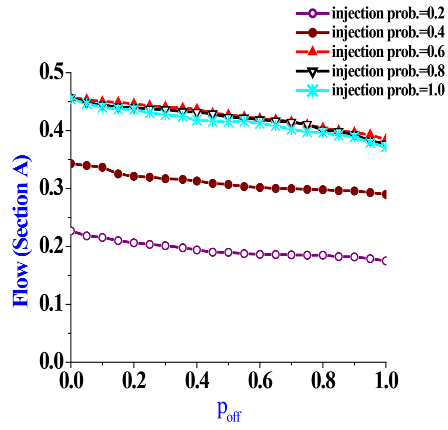

Figure 5: Relationship between flow on section A and p_{off} for different α for modified model.

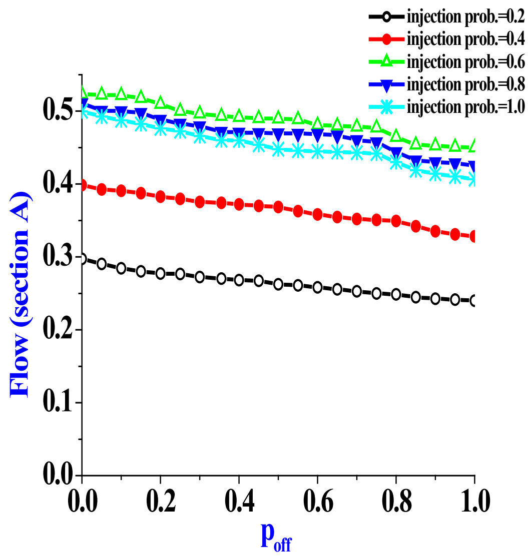

Figure 6: Relationship between flow on section A and p_{off} for different α for Nasch model.

critical value $\alpha_{c1} = 0.6$. This is due to that after $\alpha \geq \alpha_{c1}$, traffic jams begin to emerge and well-formed clusters moving with constant velocities are observed. So α plays an important role in finding out the transition between the homogeneous flow and traffic congestion.

Figure 3 represents the relationship between injection probability α and off-ramp flow for non-zero values of p_{off}. One can see that when α is small ($\alpha < \alpha_{c2}$), flow on section A and off-ramp remain in free flow state and the flow increases linearly with α. This is because initially off-ramp flow increases with α and when α surpasses a critical value α_{c2}, the number of exit vehicles entering the system also increases, which leads to a saturation in flow on section B. Therefore it does not increase further with increase in α. Value of α_{c2} increases with increase of percentage of exit vehicles (p_{off}), and becomes constant after $p_{off} > p_{offc0}$.

Figure 4 depicts the only difference between Nasch model of single lane with off-ramp and present model. For Nasch model these transition curves from free flow to saturated flow are steeper than that of present model. This is because once $\alpha \geq \alpha_{c2}$, jams begin to appear and vehicles that are coming out of jam have dissimilar accelerating values at different speed. Therefore velocity dependent acceleration rate affects transition from free flow to saturated one. However initially the flow on section B increases for off-ramp probability $p_{off} < p_{offc1}$ .Further increase in p_{off} does not lead to an increase in flow on section B . Therefore for higher values of α and p_{off} , the flow on off-ramp gets saturated.

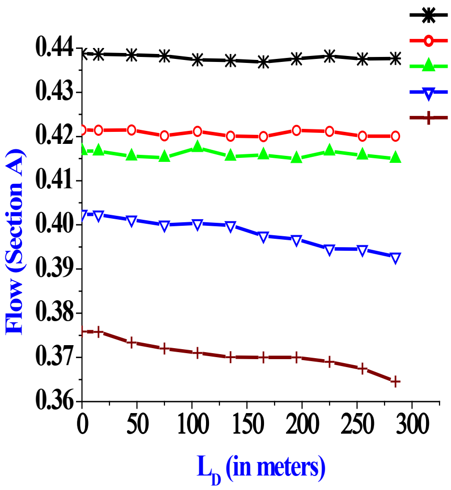

Figure 7: Relationship between flow on section A and length L_D for different p_{off} for modified model.

We show that flow decreases slightly with p_{off} . This is due to that as the number of exit vehicle increases the number of decelerated vehicles (v^e_{max} =40 Cells) also increases, that leads to reduction in flow. However as described earlier, flow becomes congested as α surpasses a critical value α_{c1} .As $\alpha \geq \alpha_{c1}$ traffic jams begin to emerge and well-formed clusters moving with constant velocities are seen. In case of Nasch model similar effect of p_{off} over flow on section A is observed except that slope of congested branch is steeper than modified model.

Figure 6 shows that for Nasch model free flow on section A is slightly higher than that of present modified model.

Now we investigate dependence of capacity of system on length of deceleration lane L_D .

Figure 7 shows that for smaller values of p_{off} , L_D almost has no effect on capacity of section A and flow remains constant. Flow is almost independent of length L_D . When p_{off} is small i.e. number of decelerated vehicles is small, the length of the decelerated lane does not matter. When $p_{off} > p_{offc1}$, L_D has negative effect on capacity. In this situation, the number of exit vehicles is large and they can not easily enter the off-ramp .Some of them stop on main road which results in a drop in capacity. Strong jams appear as L_D increases for higher value of p_{off} . However this does not happen in case of two-lane road [10], because the special lane changing rule in section D leads a positive effect of L_D over capacity of section A .

6. Conclusions

We investigate a velocity dependent acceleration rate CA traffic flow model with off-ramp. The dynamical behavior of traffic flow describing the phase transition is carried out through simulation with open boundaries. The transition from free flow to congested flow for main road and transition from free flow to saturated one for off-ramp flow are obtained. Comparisons have been made between modified model and the Nasch model. It is observed that there exists a critical value of injection probability α_c , above which transition from free flow to saturated flow takes place for off-ramp section. However the saturated branch is curved at transition point for modified model because vehicles that are coming out from jam have different acceleration rates depending upon the speed of each individual vehicle. Furthermore dependence of capacity of off-ramp system on length of deceleration lane L_D is also investigated and it is found that for smaller values of p_{off} , it does not matter how long the deceleration lane is. But it affects for higher values of p_{off} . The present model is quite powerful in dealing with realistic traffic flow phenomena for its variable acceleration capabilities. Simulating traffic flow by small cell size CA model captures minute variability in real traffic flow.

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