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Analysis of Single-Lane and Two-Lane Traffic Models by using Cellular Automata

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Abstract – **The purpose of this paper is to extend the existing Cellular Automata (CA) models and to use the extended CA models to describe the influence of a car accident in single-lane and two-lane traffic flow. To evaluate dynamic traffic flow, we developed a traffic flow simulator that uses CA model. It is shown that the single-lane dynamics can be extended to the two-lane case without changing the basic properties of the model. The two-lane model considered here shows quantitative improvements over the single-lane model. We also add the lane changing rules to simulate the reality traffic condition. The space-time diagrams for single and two-lane models are considered to conclude that congestion appear to move faster through traffic as the maximum velocity increases and congestion formation in single-lane is much distinct than in two-lane. Using simulation results it has been shown that after the accident the speed of the downstream traffic tends to zero which results in serious congestion and once the accident ends the traffic flow begins to start again.**

Keywords – **Cellular Automata, Single-lane, Two-lane, Improved CA, Incident Rule, Simulation.**

I. INTRODUCTION

Modeling traffic transport problem is very interesting and important for its dynamics and serious dramatic consequences in real life. The main goal of traffic flow control is provide a qualitative description of traffic flow [1].

In real life situation car accidents are one of the root causes of traffic congestion. Hence there is a need to study the influence of car accidents in single and two-lane traffic flows.CA models can more adequately capture the complexity of real traffic. CA models, by being either deterministic or stochastic, can be more effective in accounting for the inherent variability in most real traffic. The objective of this paper is to explore a new modeling paradigm, (CA), which has emerged in the last few years as a very promising alternative to existing traffic flow models [2, 3 ,4 ,5]. CA models have the distinction of being able to capture micro-level dynamics and relate these to macro level traffic flow behavior.

II. TRAFFIC FLOW PARAMETERS

Traffic stream is defined as multi-dimensional traffic lanes with flow of vehicles over time. Generally, traffic stream is complex and non-linear. The main characteristics of a traffic stream are speed, density and flow which are called as traffic flow parameters.

Speed (v) is defined as distance traveled in unit time in a traffic flow. In practice, we calculate the average speed of the sample vehicles.

The mean speed v_m of a traffic stream is given by

$$v_m = \frac{1}{N}\sum_{i=1}^{N} v_i \ ,$$

where N denotes the number of vehicles passing the fixed point over a fixed period of time and v_i denotes the speed of the vehicle when it passes through the fixed point . Speed of a vehicle is the distance traveled by it in unit interval of time.

The density (ρ) of the traffic flow is defined as the numbers of vehicles per unit length of a road. Hence $\frac{1}{\rho}$ denotes the distance between two vehicles and this distance is known as the spacing. There are two types of densities, named as critical density and jam density. The former is the maximum density for an unlimited flow and the later is the density under congestion.

Flow (Q) of the traffic stream is defined as the number of vehicles that pass through a specified point in unit interval of time, (Usually, unit interval of time is one hour). As a consequence

$$Q = \frac{1}{h_{i+1} - h_i}$$

Where h_i denotes the time of the ith vehicle passes the specified point.

When the traffic has high density, the flow will be low. That is, there exists inverse relationship between them. The relationship among Q, V, ρ is given by

Q = V ρ .

The figure 1 shows the relationship between speed, density and flow.

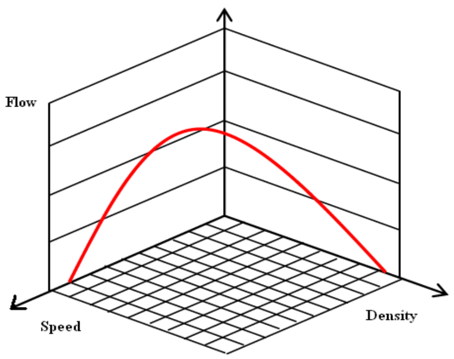

Fig.1. Flow, Density and Density relationship Chart

2.1 Traffic Congestion

Slower speeds, longer travel times and increased vehicular queuing are the indications of traffic congestion on the road. Traffic congestion causes lot of inconveniences to people. Due to great traffic demand, the interaction between vehicles shows the speed of the traffic stream. This results in traffic congestion, which will move up stream. Depending upon the up stream traffic flow and density, congestion varies in propagation length.

2.2 Classification of Traffic Flow Models

There are 3 types of traffic flow models, namely microscopic models, mesoscopic models and macroscopic models

Microscoping Models this model simulates single vehicle-driver units based on driver's behavior. In this model dynamic variables are represented by microscopic properties like the position and velocity of the vehicles. Car-following model due to Richards [6] and CA model are two modeling approach known to us. Car-following models are defined by ODE describing the position and velocity of vehicles. CA models describe the dynamical properties of the system in a discrete setting.

Macroscoping Models: In this model we study the characteristics, average velocity, density, flow and mean speed, of traffic flows. Using the comparability of traffic flow on long crowded roads with flood movements in long rivers, Lighthill and Whitham [7] established a model known as the L-W model .By introducing of 'shock - waves on the highway' into the L-W model, Richards [6] established LWR model. Helbing [8] proposed a third order macroscopic traffic model.

Mesoscopic Models: This model combines the properties of microscopic and macroscopic models; and simulates individual vehicles separately using the macroscopic view to express their activities and interactions. Gas-Kinetic based model is one such model.

III. CA Traffic Flow Models

This model is a microscopic traffic model. In this model time is made into discrete variable and the roadway is divided into cells so that vehicles move from one cell to another. Nagel and Scheckenberg [9] were the first to use CA models for traffic simulation. They have used a stochastic CA model to simulate a single-lane highway traffic flow. In the traffic flow, the basic rule is the movement of each vehicle to v sites at each time. There are some CA models that have been used as frequently as the models due to Nagel-Schreckenberg [9] and BJH model [10] . In the CA model, the street is divided into cells, each of length deplending on the length of the car and the distance to the preceding car. Each cell is occupied by at most one car and the velocity of each car is between 0 and v_{max}.

The simplest traffic CA model is one developed by Wolfram [11] and Biham et. al. [12].In this model the formula connecting the positions of the ith vehicle at time t and t+1 is given by

$$x_i\ (t+1) = x_i(t) + \min\ (1, d_i\ ) \qquad (1)$$

where $d_i = x_{i+1}(t) - x_i(t) - 1$

Fukui and Ishibashi [ ] extended this model by modifying the above relation as

$$x_i\ (t+1) = x_i(t) + \min\ (v_{max}, d_i\ ), \qquad (2)$$

by assuming the existence of the maximum speed v_{max}.

3.1 Simplest Rule Set of Nagel-Schreckenberg (Nasch) Model

The following is a set of rules introduced by Nagel and Schreckenberg .

Rule 1. All the vehicles whose velocity has not reached the maximum velocity v_{max} will accelerate by one unit.

(i.e) $v_i \to v_i' = v_i + 1,\ if\ v_i < v_{max}$

Rule 2. Let d_i be the distance along the road, separating car i and i+1. If the velocity of the car (v) is greater than d_i, then the velocity becomes d_i. If the velocity of the car (v) is smaller than d_i , then the velocity becomes v .

(i.e) $v_i' \to v_i'' = d_i - 1, if\ v_i' \geq d_i$

Rule 3. The velocity of the car may reduce by one unit with the probability p_i .

(i.e) $v_i'' \to v_i''' = v_i'' - 1$, with

Probability p_i $if\ v_i'' > 0$.

Rule 4. After 3 steps, the new position of the vehicle can be determined by the current velocity and current position.

(i.e) $x_i' \to x_i + v_i'''$

3.2. Traditional Single-Lane CA Model Simulation

In the traditional single-lane CA model the following 4 rules are formulated and followed: x_i is the position of the ith vehicle and v_i is the velocity of the ith vehicle. Before each movement, we first define the gap between successive vehicles. g_i is the gap between ith and (i-1)th vehicle. There are four rules in the model.

Rule 1. (Acceleration): If $v_i > v_{max}$, then the speed will increase by 'a'. Here 'a' is the acceleration rate.

(i.e.) $v_i \to \min\ (v_i + a, v_{max}\ )$

Rule 2. (Deceleration): The vehicles reduce its speed if the front gap is not enough for the current speed. The speed will reduce to g_i - 1.

(i.e.) $v_i \to \min\ (v_i, g_i - 1),$

where $g_i = x_i - x_{i-1}$

Rule 3. (Randomization): In the model, driver will decrease the speed randomized. If $v_i \geq 0$, then the speed of ith vehicle will reduce the speed one unit with probability p. According to.Chowdhury et.al [13] realistic data shows city traffic has a higher value of random

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probability than the number in highway traffic. For city traffic, we choose the probability of randomization p = 0.5. For highway traffic, we choose the probability of randomization p = 0.3.

(i.e.) $v_i \rightarrow \max(v_i - 1, 0)$ with probability p.

Rule 4 (Movement): After 3 steps, the new position of the vehicle can be determined by the current velocity and current position.

(i.e.) $x_i \rightarrow x_i + v_i$

where x_i = the position of the ith vehicle, v_i = the velocity of the ith vehicle, and g_i is the gap between ith and (i-1)th vehicle.

3.3 Algorithm for Single-Lane Traffic Model

The following is an algorithm for single-lane traffic to find the new position of the vehicle using the rules governing the acceleration, deceleration and randomization of the vehicle:

- **Input**
  The length of the highway, The length of the cell, Maximum velocity, Initial density, Incident details and Driver behavior probability p.
- **Initialization**
  Generate Initial vehicles.
- **Begin**
  Calculate gap
  $$g_i = x_i - x_{i-1}$$
  Acceleration
  $$v_i \rightarrow \min(v_i + 1, v_{\max})$$
  Deceleration
  $$v_i \rightarrow \min(v_i, g_i - 1)$$
  Randomization
  $$v_i \rightarrow \max(v_i - 1, 0) \text{ with Probability p}$$
  Vehicle position update
  $$x_i \rightarrow x_i + v_i$$
  Vehicle generation

Fig.2. Algorithm for single-lane traffic

3.4 Simulation of single-lane traffic flow

In order to simulation of single-lane traffic flow, first we define there are 500 cells in the roadway and then we randomly generate the position and speed for each car. Further, we assume that the probability of a car driver to slow down the speed is, given by p = 0. Time-space diagrams are used to show the movements of vehicles. We choose the last 100 movements of 500 steps movement. CA model can avoid the noise in the absence of slow down step.

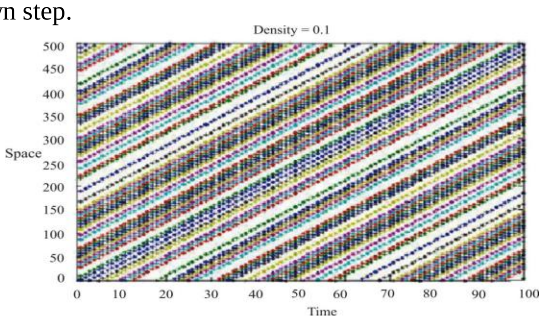

Fig.3. (a)

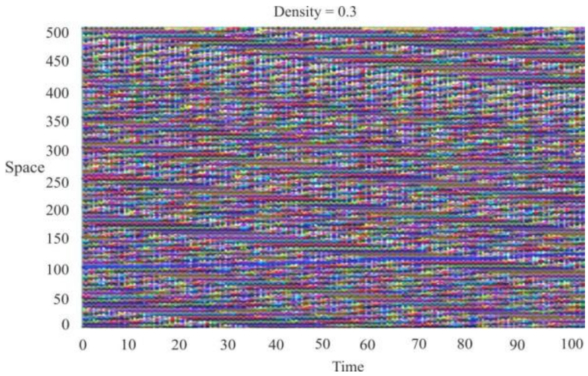

Fig.3. (b)

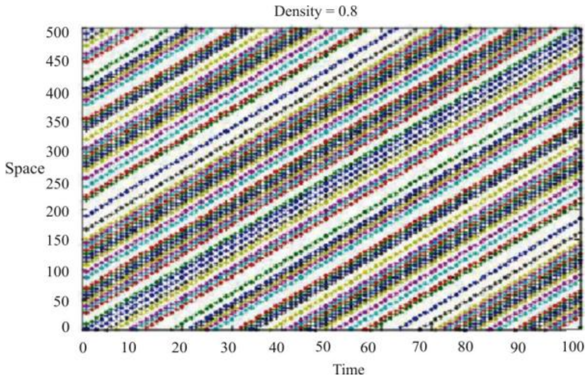

Fig.3. (c)

Fig. 3 (a), 3 (b), 3 (c) Time- Space Diagrams for one-lane with density = 0.1, 0.3, 0.8.

By varying the density the quantum of congestion is studied. In the time-space diagrams shown in figure 3(a), 3(b), 3(c) for a single-lane model, v_{max} = 5, total number of cells = 500, density = 0.1, 0.3, 0.8 and probability of slow down = 0.3. Only last 100 steps are considered out of 500 steps. Figures 3(a), 3(b), 3(c) show the traffic flow movements and congestion. Place where thick lines cluster congestion happened. Congestion tends to move up stream. In figure 3(a), thick lines cluster less, indicating the fact that when the density is low the congestion is little. As we increase the density from 0.1 to 0.3, figure 3(b) shows that thick lines cluster more and hence we conclude that the congestion is higher. From the figure 3(c) we see that when the density increases to 0.8, clustering of thick lines increases more than the previous cases which results in maximum congestion. At high level, congestion is more, but the speeds of the vehicles are lesser.

3.5 Calculation of Flow with Different Density and Maximum Speed

The Flow Q at a given time step is defined as $Q = \frac{\sum \rho_i v_i}{L}$, where L is the total number of cars, ρ_i is the density and v_i is the velocity of ith car. Figure 4 shows the relationship between flow and density with different maximum velocity. Points A, B, C, D, and E correspond to maximum flows when the maximum velocity are respectively 5, 4, 3, 2, 1. Hence when the maximum flow occurs the corresponding densities (critical

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density) are respectively .05, 0.33, 0.26 and 0.17. We also note that when the maximum speed is higher, the flow is more.

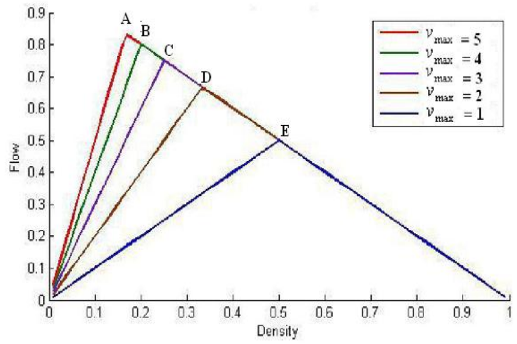


Fig.4. Density – Flow Diagram

IV. Traffic Flow Incident Simulation in Single-Lane

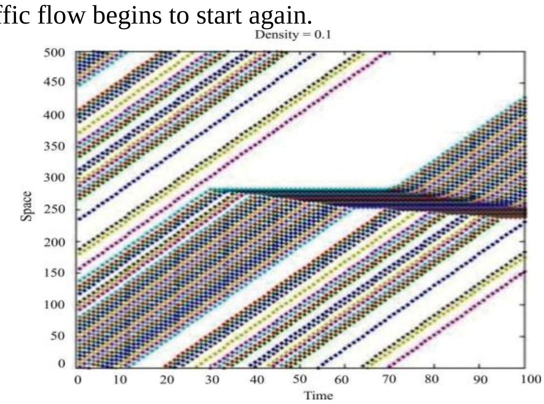
4.1 Rule of incident occurrence

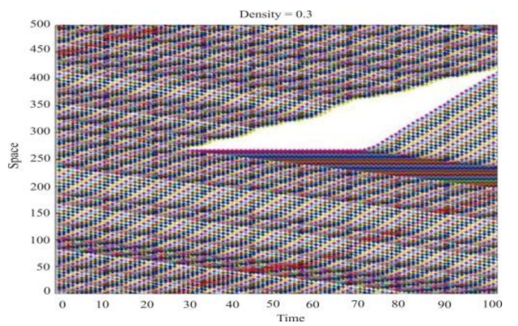
When an accident takes place in a road, the vehicles in the upstream are blocked at current time and the vehicles in the downstream are blocked at next time. Let x_{inc} , T1, and T2 respectively denote the incident place, time when the accident occurs and the time when the accident ends. Then the rule of incident occurrence in a single-lane is given by

$$v_{inc} = 0 \;\; for\; T1 \le t \le T2$$

4.2 Simulation of traffic flow when incident occurred

We assume that, in the last 100 steps, T1 = 30 and T2 = 70 and the incident place is in the middle of the roadway. Further, we assume at simulation that the accident occurred in the middle of the stream. After the accident, the speed of the downstream traffic reduces to zero which results in serious congestion. After the accident ends the traffic flow begins to start again.





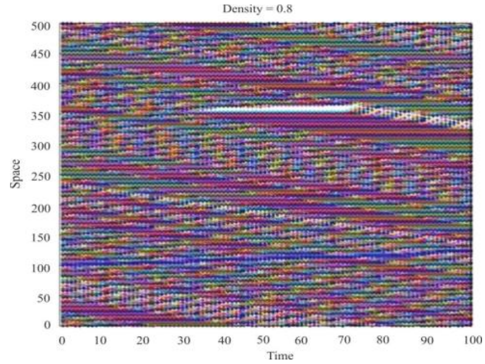


Fig.5. Time-Space Diagrams with accident in one-lane traffic

The time-space diagram, in figure 5, is constructed by taking the maximum velocity as 5 when the accident occurs, total cells number 500 and density = 0.1, 0.3 and 0.8. It is evident in the figure that during the time step 30-70 serious congestion exists. The time-space diagram, in figure5, is constructed by taking the maximum velocity as 5 when the accident occurs, total cells number 500 and density = 0.1, 0.3, 0.8. From the figure we see that the space reaches to a constant value during the time-step 30-70. As a consequence congestion exists during this time step. When the time reaches 70, one can see from the diagram that the space getting increased which suggests that the congestion is released.

Figure 6 shows the relationship with time and flow, when different density values are considered. We can see that the flow reduces when the accident occurs at time 30. Also, we see that the traffic flow tends to zero during the accident period 30-70. When the accident ends at time 70, we see that the curve increases indicating the fact that the flow begins to restore.

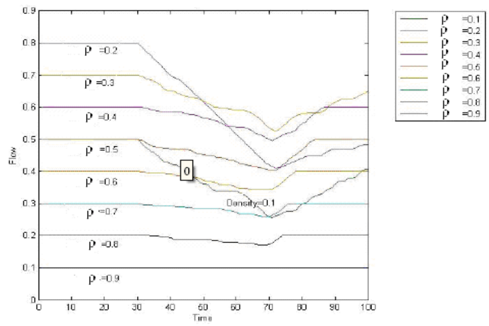


Fig.6. Time-Flow diagrams with accident for one-lane for various density.

4.3. Modeling of Single-Lane Traffic With Improved Ca Model

In traditional CA model the initial car will forever stay in the road, which does not meet the reality. In the new model, we set the following rules: For each time step, a car will come to the road with a probability λ.

- If the cars can not entry into the road, they will line up in the entrance.
- The length of queuing is I.
- The cars reach the end of the road will leave.

The rules for the movements of an improved single-lane traffic model are given as follows:

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Rule 1 : Acceleration $v_i \rightarrow \min(v_i + 1, v_{\max})$
Rule 2 : Deceleration $v_i \rightarrow \min(v_i, g_i - 1)$
Rule 3 : Randomization $v_i \rightarrow \max(v_i - 1, 0)$
with probability p
A new car come with probability λ, come into the queue.
Rule 4 : Vehicle position update $x_i \rightarrow x_i + v_i$

With a fixed density, we determine the initial number of cars in the roadway. Following the rules of each time step the cars are allowed to move. The gap, forward velocity and maximum velocity determine the new speed of each vehicle. The cars that reach the end of the road will not be considered further. For each time step, with probability λ, a new car will come. If the first grid of the road is not empty then the car will wait outside the road.

In the single-lane traffic model with open boundary and queuing system there exists a probability λ_c, known as critical entry velocity, satisfying:

(i) If $\lambda < \lambda_c$ then the length of queue I is around zero

(ii) If $\lambda > \lambda_c$ then the length of queue I will increase with time (i.e., the capacity of the roadway is beyond the limit), where λ is the entry probability, λ_c can be used to describe the capacity of the roadway.

V. Modeling of Two-Lane Traffic With Improved CA Model

To simulate two-lane traffic, we have started with NaSch model in which the traffic flow system is assumed as a closed boundary system where no incoming or outgoing car is permitted. Now we improve the model with open boundary and queuing system. We simplify the model as a two-lane highway. Here, $v^1_{\max}$ and $v^2_{\max}$ respectively denote the maximum velocity of lane 1 and lane 2. We introduce a parameter q denoting the probability that a car changes lane if that is allowed. For cars in one lane, there are 4 steps namely acceleration, keep safety distance, decrease velocity randomized and movement. The movements of vehicles in two-lane traffic model are subject to the following rules:

Rule 1. (Acceleration):

All the vehicles whose velocity has not reached the maximum $v^1_{\max}$ or $v^2_{\max}$ will accelerate by one unit.

(i.e.) $v_i \rightarrow \min(v_i + a, v_{\max})$

Rule 2. (Deceleration):

The vehicles reduce its speed if the front gap is not enough for current velocity. The speed will reduce to $gap_i - 1$.

(i.e.) $v_i \rightarrow \min(v_i, gap_i - 1)$,

where $gap_i = x_i - x_{i-1}$

Rule 3. (Randomization):

In the model, driver will decrease the speed randomized. If the $v_i \geq 0$, then the speed of i[th] vehicle will reduce the speed one unit with the probability p. According to D. Chowdhury et.al [13], realistic data shows city traffic has a higher value of random probability than the number in highway traffic. For city traffic,we choose the probability of randomization p = 0.5. For highway traffic, we choose the probability of randomization p = 0.3.

i.e., $v_i \rightarrow \max(v_i - 1, 0)$ with probability p.

Rule 4 (Lane Change):

A vehicle will change its lane for its own benefit. We list the following criteria for lane-changing.

1. The distance ahead in current lane is smaller than the car speed.
2. The distance ahead in another lane is larger than in the current lane.
3. There exists an empty cell right in another lane.
4. The distance ahead of the following vehicle in another lane is larger than the speed of the following vehicle.

Criteria 1 and 2 are known as the trigger criteria (incentive criteria). Incentive criteria describe motivation that drivers are likely to drive fast in the target lane. Criteria 3 and 4 are the safety rules which assure the lane changing will not cause the bump of following vehicle. The vehicle which are meet the criteria will allow to switch lane with the probability q. If the accident happened, the vehicle drivers attempt to switch lane more often for the purpose of changing behavior. Because of the fluctuations of the vehicle, the vehicles will not keep a constant speed in the roadway.

(i.e.) Incentive Criteria : $gap_i < v_i$

$gap_{pred} > gap_i$

Safety Criteria: $gap_{succ} > gap_{safe}$

Here gap_{safe} is the maximum possible speed of the succeeding vehicle in the target lane. For simplicity we choose the safety distance is the speed of the following vehicle.

Rule 5. (New Car Entry):

For each time step, a vehicle will come to the road with a probability λ. If the vehicle cannot entry into the road, they will line up in the entrance. The length of the queue is I.

Rule 6. (Movement):

After 5 steps, the new position of the vehicle can be determined by the current velocity, current position and the change of lanes.

(i.e.) $x_i \rightarrow x_i + v_i$

VI. Traffic Flow Incident in Two-Lane

6.1 Rule of Incident Occurrence

Let x_{ip}, x_i^{t-1}, x_i^{t} be respectively denote the incident place, position of the i[th] vehicle at time t-1 and at time t. As above T1 and T2 represent the time at which the accident occurred and the time at which it ends. The rule of incident occurrence is given by:

$$(x_i^{t-1} \leq x_{ip} \text{ and } x_i^{t} \geq x_{ip}) \Rightarrow x_i = 0$$

for T1 ≤ t ≤ T2

6.2 Simulation of traffic flow when incident occurred

Assume that the accident happens between T1 and T2 and it occurs in the first of 2 lanes. At current time the vehicles in the upstream and in the next time the vehicles in the downstream area blocked. Blocked vehicles have the option of switching the lane. We assume that, in the last 300 steps, the accident happens at time 100 and in the 1000^{th} cell which is in the middle of the roadway. After the accident the downstream traffic flow blocked and hence the speed of the downstream traffic reduces to zero. As a consequence congestion begins. At time 150, when the accident ends the traffic flow begins to start again.

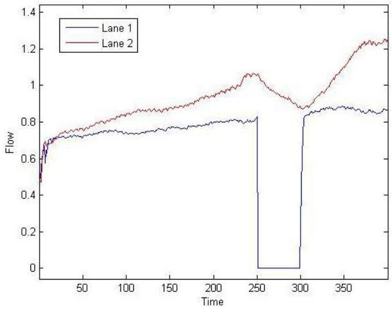

Fig.7. Time-Flow Diagram with accident in Two-lane.

Figure 7 is the Time-Flow diagram when an accident occurs. In this figure we see that the flow reduces to zero when the accident occurs in first lane at time 250. As most cars move to the second lane after the accident occurs in the first lane, the flow in the second lane decreases which is evident from the figure.Also we see from the diagrom that the traffic flow begins to restore when the accident ends at time 300.

VII. Conclusion

Traffic on streets and highways can be simulated efficiently by the improved microscopic CA model. When comparing the Space-Time diagrams for single and two-lane models, we would like to point out two facts: (1) congestion appear to move faster through traffic as the maximum velocity increases, (2) congestion formation in one lane is much distinct than in two-lanes. Congestion in single-lane takes much longer to dissolve and are composed of perceptibly more cars.

For p = 0 there is never congestion formation in steady state because there are no random "human" errors and the system follows a regular pattern. On Time-Space diagrams, traffic congestions are denoted by large sections of thick lines. By calculating the slope of these sections, the speed of the traffic congestion can be calculated. For both the single-lane and the two-lane models, it is apparent that as the maximum velocity increases, the flow is higher at low densities. At high densities, the maximum velocity is unimportant in calculating the flow of the road because high car densities limit the cars' velocities. Existing CA models have been extended to describe the influence of a car accident in the middle of a road in single and two-lane traffic flows. From the simulation it has been shown that after the accident the speed of the downstream traffic reduces to zero which results in serious congestion and once the accident ends the traffic flow begins to start again. Our two-lane model shows some quantitative improvements over the single-lane model, but qualitatively the behavior is not very different. The improvement under the two-lane system would be noticeable. As the model approaches reality, the advantages of the two-lane model might be more apparent.

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