Microscopic Analysis of Highway Congestion by DTCA Model

Ahmed S. AlGhamdi, Halit Eren, and Hariani Pakka

***Abstract*—Highway congestions can cause considerable impact on loss of time and delays displacement. This article introduces a new method of explanation of the congestion in contrast to conventional method of vehicles capacity on the highways. This method is primarily based on the Cellular Automata (CA) concept introduced by Nagel and Schreckenberg in 1992 [1]. Dynamic Traffic Cellular Automata (DTCA) is also explained with emphasis on the acceleration, the deceleration, and the reaction factors. Different in speeds changing and delays in start-up are discussed for being important reasons of the highway congestions. Recognizing the impacts of slandered deviation on congestion shapes is overviewed in this paper.**

***Index Terms*—Acceleration factor (α), cellular automata (CA), congestion, deceleration factor (β), dynamic traffic cellular automata (DTCA), reaction factor (p_d).**

I. Introduction

Most transport analysts subscribe to the application of economic theory to travel. It is generally held that travel is a derived from the demand of both national governments to increase gross domestic product (GDP) and of people increase their income and improve quality of their lives [2]. Consequence of the importance of transportation systems is that it affects the national economics hence the governments create the highways, which form the backbone of transportation networks. The metropolitan networks constitute more than a third of all vehicular travel [3].

Vehicle offers flexibility in time and moving from place to place that travellers find it attractive. The problem arises, of course, when too many cars are heading in the same direction at the same time [3]. Accumulation of many cars the same direction at the same time can result in congestions, which is defined as “so crowded with traffic or people as to hinder or prevent the freedom to move”[4]. Traffic engineers define congestion as the phenomenon that arises when the input volume exceeds the output capacity of a facility. Irrespective of different views, one implication of congestion is that it represents maximum or excessive use of a facility. Also, as the input volume increases, so the density of traffic increases (density being defined as the number of vehicles per lane per kilometre). As the density increases, the speed decreases, because of the close proximity of vehicles to each other [2]. Generally, the traffic congestion decreases the attractiveness of the automobile travel [3].

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Congestions have many other effects. For example, the drivers in high congestion conditions have been found to exhibit elevated levels of stress, frustration, irritation, and turn into negative mood [5]. Psychological and physiological health can badly be impacted by congested traffic conditions as well as increased heart rate and blood pressure[5]. Frequent stressful driving encounters may ultimately lead to a dispositional tendency to experience all driving encounters in a more negative manner[5]. Other potentially dangerous effects of driver stress that have been identified are increased aggressive driving , poor concentration levels, and increased accident occurrences[5].

Generally, recurrent congestion arises for two reasons; firstly, due to peaking in demand, and secondly, recurrent and non-recurrent congestion arise because of the bottlenecks. The bottlenecks may be defined as a location where the capacity of a facility is suddenly reduced [2]. Many bottlenecks perform a metering function, by reducing the flow at one point to a level that can be sustained in downstream sections of roadway. Removal of the bottleneck in one location may simply result in transferring the bottleneck to another point further downstream. In many cases, the newly formed downstream bottleneck may result in worse traffic conditions than maintaining the original bottleneck. Thus, bottlenecks may often play a useful and important function in regulating flows and controlling the level of congestion that occurs on a facility[2]. Therefore, Permanent bottlenecks require very careful study to determine whether or not they should be eliminated [2]. Moreover, there is a limit to how much the density can increase. Once vehicles are literally bumper-to-bumper, speed drops to zero, thereby defining jam density and maximum congestion [2].

For several years, we have been developing a general purpose road-traffic simulation system to analyze road traffic jam. This paper describes the concept of the system using the running line model, and a case study for general purpose simulation with Dynamic Traffic Cellular Automation model, which is modify from Cellular automata model[1]. In order to simulate congestion of road traffic system, it is essential to describe vehicles having their own decision-making capabilities, and to have detailed and exact road condition data on the road system [6].

Several studies have been done to realize road traffic simulation by a microscopic model. For example, there is a flattery model of a vehicle by a fuzzy theory and various theories such as a neural network work and cellular automata [6].

The Cellular Automata model had been suggested by Nagel and Schreckenberg in 1992. It was first used to study the congestion on the one lane highways [1]. Since then the model has been modified to study two and three lane highways [7]-[10]. Original CA model contains of one-dimensional array of L number of cells. Each cell is 7.5m and may be occupied or not. The velocity of the $_i$th vehicle, v_i, is an integer between "0" to maximum speed, "V_{max}" updating is carried out if the system consists of the following steps:

1) **Acceleration:** if the velocity v_i of a vehicle is lower than V_{max} and if the distance to the next car a head is larger than v_i+1, the speed is advanced by one [$v_i \rightarrow v_i+1$].
2) **Slowing down (due to other cars):** if a vehicle *i* sees the next vehicle at site *i*+*j*, where *j* is the gab a head, (with $j \leq v_i$), it reduces its speed to be [$v_i \rightarrow j-1$].
3) **Randomization:** with probability *p*, the velocity of each **vehicle** (if greater than zero) is decreased by one [$v_i \rightarrow v_i - 1$].
4) **Car motion:** each vehicle is advanced *v* cells.

This paper investigates congestions on the one lane highway traffic system by using Dynamic Traffic Cellular Automata (DTCA) model. [1],[7],[10],[11] .

In this article a brief explanation about Cellular Automata (CA) has been given in the introduction. The follow part provides the details about A Dynamic Traffic Cellular Automata (DTCA), and final part clarifies the new concept on congestion. In this article there are two reasons that create the congestion.

II. DYNAMIC TRAFFIC CELLULAR AUTOMATA (DTCA)

A Dynamic Traffic Cellular Automata (DTCA) that has been suggested in this paper can be compared with the original CA model. Basically it offers three main differences:

1) In the CA the road is divided into equal length cells, each cell being 7.5 m. A cell may or may not be occupied. The CA model assumes that a vehicle is restricted by fixed position, while the position of the vehicle in the DTCA is not limited with fixed cells on the highway. However, the vehicle in the MCA is viewed as a cell 7.5 m moving through the highway.

2) Nagel and Schreckenberg [1] used fix amount of acceleration and declaration, equal to 1 cell (±7.5 m/s^2). According to Bansal and Brar maximum deceleration is explained in Equation 1.

$$dec_{\max} = G\left(r\cos\theta_v + \sin\theta_v\right) \tag{1}$$

where G is the gravity (9.81m/s$^{2)}$, *r* is friction coefficient for dry seal roads (0.6) and θ_v is vehicle angle of inclination of the plane of the horizontal. It is assumed that ε equal to "0". This equation indicates that declaration cannot be greater than 5.886 m/s^2 while in Nagel and Schreckenberg model assumes 7.5 m/s^2, cell length, at all times [12]. different decelerations are achieved by different driver habits, road and traffic condtiones. These diffrences are stated by deceleration factor (β). β gives the proportionof the dec_{max}, and it will be $0 \leq \beta \leq 1$.

Similarly, the maximum acceleration (acc_{max}) is 4.905 m/s^2, which is equal to 17.658 km/hr^2. Maximum acceleration leads moving the vehicle from zero to 17.658 km/hr speed in first second. In six second with maximum acceleration the vehicle can approach 106 km/hr, which is reasonable for most vehicles. However, different accelerations are achieved by different driver habits, road and traffic condtiones. These diffrences are stated by acceleration factor (α). α gives the proportionof the acc_{max}. for example α is equal 1then *acc* will

$$dec = dec_{\max} \times \beta \tag{2}$$

equal to acc_{max}, and it will be $0 \leq \alpha \leq 1$.

$$acc = acc_{\max} \times \alpha \tag{3}$$

3) The original CA uses one randomazation factor (*p*) while DTCA uses three independent randomazation factors (α, β and p_d). α is acceleration facor, β is decleration factor and p_d is driver reaction factor, which mainly focus on the time delay of taking decision. Those factore describe the driving satuation on highways. *A*, β and p_d are very obviouse during vehicle moving up from zero or no movment, such as moving up from traffic light or normal congestion on the highway.

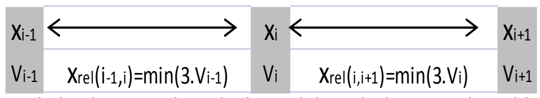


Fig. 1. Relation between the velocity and the gabs between the vehicles on the highway.

A. Changes in Speed Due to Acceleration

$$\begin{aligned} &if\ v_{i,n} < V_{\max}\ \&\ \varphi \cdot x_{\mathrm{rel}}(i,i+1) > v_{i,n} \\ &\text{then}\ \ v_{i,n+1} = v_{i,n} + T \cdot acc \end{aligned} \tag{4}$$

where *i* is a cell number

n the sequence number

T is the fixed time and we assume it equal to "1" second

φ is safety factor

B. Deceleration

$$\begin{aligned} &if\ v_{i,n} \leq \varphi \cdot x_{\mathrm{rel}}(i,i+1) \\ &\text{then}\ \ v_{i,n+1} = \max\begin{pmatrix} v_{i,n} - T \cdot dec_{\max} \\ \text{or} \\ \varphi \cdot x_{\mathrm{rel}}(i,i+1)/T \end{pmatrix} \end{aligned} \tag{5}$$

C. Randomization

$$\begin{aligned} &if\ v_{i,n} > 0\ \text{with probability}\ \beta \\ &\text{then}\ \ v_{i,n+1} = v_{i,n} - T \cdot dec \end{aligned} \tag{6}$$

D. Car Motion

$$x_{i,n+1} = x_{i,n} + T \cdot v_{i,n} \quad (7)$$

III. Acceleration Factor and Deceleration Factor in Real Life

TABLE I: Acceleration and Deceleration Factors Examples

factor		Acceleration factor (α)	Deceleration factor (β)
Driver	Skill	Good	Bad
	Age	Young	Old
	Experience	More experience	No experience
	Health	Healthy	Unhealthy
	Activity	Hurry and busy	Empty
	⋮	⋮	⋮
vehicle	Model	New	Old
	Performance	Strong	Weak
	Problems	Does not have	Have
	⋮	⋮	⋮
Weather	Fug	Clear	Unclear
	⋮	⋮	⋮
Road	Straight	Yes	No
	Crowd	No	Yes
	Asphalt	Good condition	Bad condition
	⋮	⋮	⋮

Before going forward in this article understand Acceleration and deceleration factors is very essential. Acceleration and deceleration factors or α and β is combination of driver, vehicle, whether, road activities [13], [14]. In Table I some examples of acceleration (α) and deceleration (β) factors such as Driver skill or vehicle model. The combination of α is contains of all factors are assisting of increasing the speed or accelerate of the vehicle. On the other hand, the combination of β is contains of all factors are restricting or decelerate of the vehicle movement. Both factors α and β are linked together as one combination but in this article we preferred to understand the relation between them and to find prober combined between them.

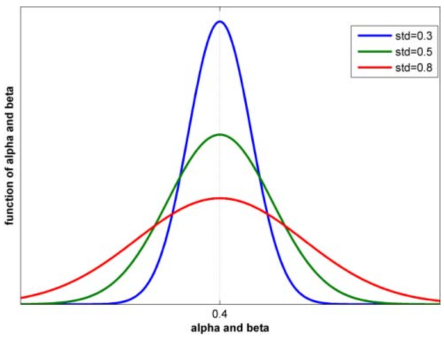


Fig. 4. Gaussian model

IV. Simulation

We consider k cars moving on a strait road, with no inclination, perfect weather and road conditions. The boundary condition adopted in this work is periodic. Since real traffic data can be well described by the parameters V_{max} = 110 km/h or 30.6 m/s, $p = 0.5$ and α and β =N(0.4, 0.2). We assume these parameters in our implementation. The length of the evolution time is 2000s.

V. Congestion

Best way to observe the congestion is looking at the

$$decs(t) = \left| acc_d(t) - acc(t) \right| \quad (8)$$

where $decs$ is deceleration strength, acc_d is acceleration to desired velocity

$$decs(t) = \left| \frac{dv_d(t)}{dt} - \frac{dv(t)}{dt} \right| \quad (9)$$

where $V_d(t) \approx V_{\max}$

$$decs(t) = \left| 0 - \frac{dv(t)}{dt} \right| \quad (10)$$

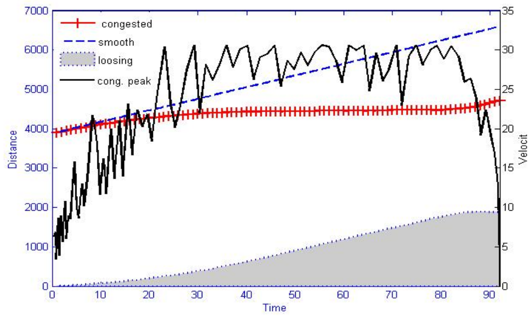


Fig. 5. Congestion loos

From the Figure (5) the black curve shows $decs(t)$. There are two things could get it from $decs(t)$ curve: 1) the limits of congestion (where the congestion starts and where it finishes). 2) Observing who the strength of congestion is and when that happened.

Another factor needs to notice is losing (LOSS)

$$LOSS = \int_{t_0}^{t_e} V_d - v(t)\,dt \quad (11)$$

where t_0 is the time starting congestion and we will assume it as 0, and t_e is the time of finishing of congestion. While $V_d \approx V_{\max}$

$$LOSS = \int_{0}^{t_e} V_{\max} - v(t)\,dt \quad (12)$$

$$LOSS = V_{\max} - (x(t_e) - x(t_0)) \quad (13)$$

$$LOSS = v_{\max} - x(t_e) \quad (14)$$

Fig. 6 illustrates the overview of traffic system in the simulation. It shows the shape and behavior of congestion in time on the highway. The global observation of the congestion lets us to investigate the reasons why congestions take place and how they are dispersed.

In this figure the movement of vehicle on the highway can be recognized by time and the position at the road. From Fig (6A), it can be observed that the vehicle (1), (**Bolded**), movement during the experiment and it can be recognized the movement through the congestion. Focusing on just small part of Figure (6A) to be appear in Figure (6B), which helps to understand the cluster of vehicles and how each of them can impacts on the next one, also by spotlight on one vehicle and how is it moving with the cluster to understand the reasons of creating of congestions, as well as peaking in demand and a bottleneck regarding to peter [2]. Figures (6 A&B) expressing the essential reasons of congestion, which are speed conflict and delay of start-up movement.

Referring to Fig. 4 shows the vehicle (1), in the Figure (6A), movement in two scenarios: 1) during the congestion and 2) during freeway. From the Figure (4), it can be seen the position difference. Congestion in this figure can be explained as time and position delay comparison to desired position at the same time. The gap between the curves of congested and desired vehicles is expanding from starting the congestion to be end. It is also can be observed the strength of congestion for individual vehicle and it is losing.

Fig. (6A&B) illustrates a vehicle individual is impacted by congestion and how it could affects on the congestion. It can observe the way of creating of congestion such as speed conflict between the trace drivers and delay start up movement. Those reasons of creating congestion mainly caused by acceleration factor (α), deceleration factor (β) and reaction factor (p). In figure (6), the model is designed as mention in section (5) p = 0.5 and α and β =N(0.4, 0.2).

VI. Congestion Shapes

In the Fig. 4, it reveals that how standard deviation impacts on the distribution data of acceleration and deceleration factors. When the standard deviation is low like (0.2), will find most of data around the mean value. However, when the slandered deviation is high such as 0.8 makes the data with high variety from 0 to 1. The effects of the probability used overview of system (vehicle on the highway).

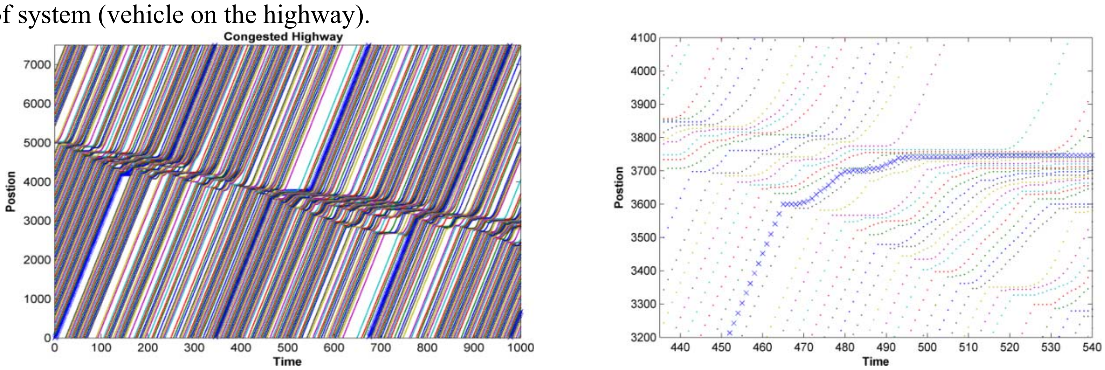
In this section we will discuss the impacts of α and β on the congestion's shape, size and angle. The relation between the factors (α, β and p) can influence each vehicle individually.

$$x_i = f(\alpha_i, \beta_i, p_i) \tag{15}$$

The individual reaction could transfer to the other vehicles as consequence of the safety concern, which is explained by Fig (1) and from equations (4 and 5) it can be revealed how the DTCA processing the reaction between the vehicles. Transferring individual reaction from vehicle to other makes the individual behavior accumulated to create the congestion.

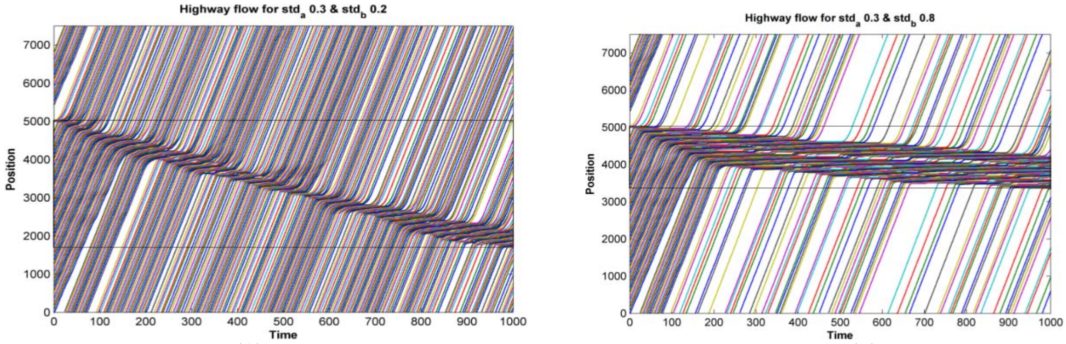
$$x_{rel} = x_{i,i+1} \geq 3 \times v_i \tag{16}$$

In Fig. 7, it can be detected that the difference of congestion shape depend on the different standard deviation for α and β to be in figure (7A) α=N (0.4, 0.3) and β=N (0.4, 0.2). it can be seen that the congestion is varying between high depth and low depth and between 100 to 400 meters , the congestion flux moves fast during the experiment and moved more three thousand meters in 1000 seconds, which approximately three meters per second. While in figure (6B) α=N (0.4, 0.3) and β=N (0.4, 0.8) the congestion is very high depth and most of the time more than 1000 meter. In figure (7B), the congestion is sucking in place and not moves more than 1800 meter during the experiment, which around less than one meter per second. In figure (7B) α=N (0.4, 0.8) and β=N (0.4, 0.2) the congestion is very thin depth and in med of simulation is disappear. The most indications give us a felling of that congestion flux will disappear after while such as the depth and flux movement. Finally figure (7B) α=N (0.4, 0.8) and β=N (0.4, 0.8) it can be seen that the congestion is varying between high depth and low depth and between 100 to 400 meters , the congestion flux moves more than two thousand meters in 1000 seconds, which approximately two meters per second.

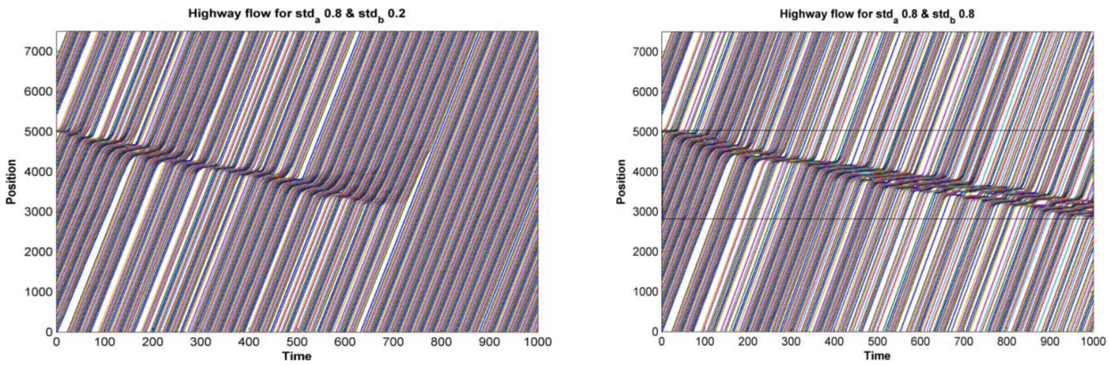


(A) (B)

Fig. 6. A. Congested highway, B. Congested high way foucusing on the congestion



(A) (B)



(C) (D)

Fig. 7. A. Congested highway, B. Congested high way foucusing on the congestion

CONCLUSION

In this article, Dynamic Traffic Cellular Automata has been discussed cooperation with Nagel and Schreckenberg CA model. Finding the time and distance loss equation as result of compression between congested and free highways. Acceleration and deceleration factors respectively with affect of standard deviation impacts on the congestion are defined.

REFERENCES

[1] K. Nagel and M. Schreckenberg, "A cellular automaton model for freeway traffic," *Journal de Physique I,* vol. 2, pp. 2221-2229, 1992.

[2] S. Peter R, "Reducing road congestion: a reality check," *Transport Policy,* vol. 11, pp. 117-131, 2004.

[3] B. D. Taylor, "Rethinking Traffic Congestion," in *ACCESS.* vol. 21 California: UCTC, pp. 8-16. 2002.

[4] "Oxford Dictionaries, Oxford: Oxford University Press, 2011.

[5] D. A. Hennessy and D. L. Wiesenthal, "Traffic congestion, driver stress, and driver aggression," *Aggressive Behavior,* vol. 25, pp. 409-423, 1999.

[6] M. Namekawa, F. Ueda, Y. Hioki, Y. Ueda, and A. Satoh, "General purpose road traffic simulation system with a cell automaton model," Melbourne, VIC, Australia, 2005, pp. 3002-3008.

[7] K. Rickert, K. Nagel, M. Schreckenberg, and A. Latour, "Two lane traffic simulation using cellular automata," *Physica A,* vol. 231, pp. 534-550, 1996.

[8] A. Awazu, "Dynamics of two equivalent lanes traffic flow model: self orgnization of the slow lane and fast lane," *Journal of Physical Society of Japn* vol. 64, pp. 1071-1074, 1998.

[9] K. Rawat, V. Katiyar, and P. Gupta, "Two-lane traffic flow simulation model via cellular automaton," *International Journal of vehicular technology,* vol. 2012, 2012.

[10] A. Daoudia and N. Moussa, "Numerical simulations of three-lane traffic model using celluler automata," *Chinese journal of physics,* vol. 41, pp. 671-681, 2003.

[11] L. Ke-Ping, "Car deceleration considering its own velocity in cellular automata model," *Commun. Theor. Phys.,* vol. 45, pp. 113-116, 2006.

[12] R. K. Bansal and J. S. Brar, *A text book of theory of machines (in S.I. units)*: Laxmi Publications, 2004.

[13] A. Zander and U. Wiesner, "Method and arrangement for avoiding and/or minimizing vehicle collisions in road traffic," Google Patents, 2000.

[14] M. Hatakka, E. Keskinen, N. P. Gregersen, A. Glad, and K. Hernetkoski, "From control of the vehicle to personal self-control; broadening the perspectives to driver education," *Transportation Research Part F: Traffic Psychology and Behaviour,* vol. 5, pp. 201-215, 2002.

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