International Proceedings of Chemical, Biological and Environmental Engineering
Volume 94 of IPCBEE (2016)
DOI: 10.7763/IPCBEE. 2016. V94. 11

Traffic Emitted PM10 Modelling Based on NaSch Model with Periodic Boundary

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Abstract. Congestion has always been considered as a big trouble due to large amount of time wasting. Moreover, as high frequency outbreak of haze weather and particulate matter (PM) related diseases, traffic congestion has once again appear in the forefront for its inescapable obligation. However, the effects of congestion on emitted particulate matter are only seldom incorporated in the predictions and measurements, which also hard to accomplish. Hence, by using classical NaSch model and emission function based on empirical measurements, this study aims to investigate the effect of congestion on the emitted PM emission from vehicles on-road. The simulation results show that when vehicle emitted particulate matter levels start to increase as traffic system get into jamming states, and no matter congestion occurs or not, acceleration is the major pollutant maker for total PM emission load. Related analysis of PM emission, fuel consumption and energy dissipation are also conducted.

Keywords: Particulate Matter, Nasch Model, Traffic Congestion, Energy Dissipation, Energy Consuming

1. Introduction

Increasing health awareness and longstanding concerns to the environment have largely prompted the subject of particulate matter (PM) research in the past two decades with bunch of works regarding the mechanisms of production, transformation and removal of particulate matter [1-3]. Meanwhile, road traffic is the dominant anthropogenic source of air pollution in urban areas around the world [4-6] and its contribution to particulate matter concentration is multidimensional. Hence, many researches that aiming at providing sound understanding on physiochemical properties, temporal-spatial distribution, and dispersion characteristics, of traffic related particulate matter emission, either experimentally or numerically have been conducted world widely [7]. Among all traffic related emission processes, traffic congestion has repeatedly been indicated as a major factor in road traffic emissions and urban air quality degradation [8-10], which imply the need to explore the dynamic behavior between traffic emission and traffic-flow [11].

Congestion is the most important contributor and impact factor for total traffic emission. The variables that determine vehicular exhaust emissions are mainly fleet composition, speed, speed limit, acceleration and deceleration rates, queuing time in idle mode during the red phase, queue length, traffic flow rate and ambient wind conditions [10]. The estimation of PM emissions from road traffic requires in-depth understanding of traffic characteristics, which cannot be told by using traditional statistical method that lacking capability to capture the dynamic process of traffic flow [11]. And it is difficult to depict the relationship between traffic congestion and PM emissions by carrying out mobile measurements in a solo car. As a consequence, the effects of congestion are only partially incorporated in the predictions and measurements.

In this paper, we want to investigate how does traffic congestion have impact on PM emission by combining the NaSch model and speed-acceleration emission relation. Note that this study is only a preliminary results that aims at finding a general trend between congestion and emission. According to the

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results, it seems that the emission load of particulate matter and traffic flow cannot reach best situation at the same time. Hence, the preliminary result here may benefit the future research on optimal planning.

2. Methodology

The whole model consists of two parts: traffic modelling and emission component. The application of NaSch model can provide the speed and acceleration of every agent (vehicle car) in the system at every time step during the whole (traffic activity) simulation life span. Meanwhile, fuel consumption (fc), energy dissipation (ed) and PM10 emission at each current time will be calculated by using above instantaneous information. Finally, analysis about the collective behavior of every individual car and corresponding PM emission would be provided

3. Traffic flow Component Submitting

The aim of introducing traffic component is to gain the needed information that enable whole model with the ability to depict the macroscopic flux, consumption and emission of the traffic flow by simulating every individual vehicle movement microscopically. Among multiple traffic models [12], cellular automaton (CA) ones, microscopically, are most popular for their simple algorithm, high generalization and rich phenomena.

NaSch model[13], a CA model proposed by Nagel and Schreckenberg in 1992, was able to reproduce the spontaneous emergence of traffic jams. It explicitly includes a stochastic noise term in one of its rules, commonly knowns as the first stochastic traffic cellular automaton model, which makes it different from the many previously deterministic CA models.

Generally, NaSch model is defined on a one-dimensional array L in dimensionless manner with each site may either be empty, or be occupied by one vehicle. Because in every time step, the vehicle can only change its position from grid to grid, hence, the velocity is an integer number in the range between zero and maximum velocity ($v_{\max}$) that expressed as the number of cells per time step. For an arbitrary configuration, NaSch model following four consecutive step, which are performed in parallel for all vehicles [14]:

1) Acceleration

$$v(i,t+1/3) \to \min(v(i,t)+1, v_{\max}), \tag{1}$$

2) Deceleration

$$v(i,t+2/3) \to \min(v(i,t+1/3)+1, gap_n), \tag{2}$$

3) Randomization with probability p

$$v(i,t+1) \to \min(v(i,t+2/3)-1, 0), \tag{3}$$

4) Car motion:

$$x(i,t+1) \to x(i,t+1)+v(i,t+1). \tag{4}$$

where $v(i,t)$ and $x(i,t)$ are the speed and position of the vehicle i on the road at time step t. Before the determination of its motion for the next time step $t+1$, the vehicle i should go through three steps (i.e. acceleration, deceleration and randomization), which indicated three commonly situations during driving process. Comparing to realistic traffic, it is easy to scale the model to make comparison with realistic traffic by converting the length of one site and a simulation time step into 7.5 meters of place and one second of time in real road scenario when $v_{\max} = 5$, respectively, which is a velocity of about $135 km/h$ on a freeway.

4. Dimensionless Energy Consumption and Dissipation Component

According to the theorem of statistical mechanics, the kinetic energy of a moving car with mass m and velocity v is depicted in the formation as $mv^2(i,t)/2$, which could also be recognized as the fuel consumption of the moving car as the result of combustion, i.e., energy needed for acceleration, deceleration and following (cruising) the front car. Moreover, the reduced kinetic energy can be defined as dissipated energy [15]. Generally, energy dissipation was considered only in the scenario of deceleration occurred for kinetic energy decreasing. However, a board number of in-situ experiments indicate that, the biggest emission load emergence when vehicles accelerate [16], as energy dissipated due to road roughness affects rolling resistance and the resulting fuel consumption and pollutant emission [17]. Hence, energy dissipation would be considered in both acceleration and deceleration situation in our investigation.

For simplicity, it is supposed that the mass distribution of a car is uniform, which means if m_0 the mass of unit car length is, then the mass of the car with length l would be written as $m = m_0 \times l$. Hence, the dimensionless fuel consumption (fc) and energy dissipation (ed) for an arbitrary vehicle i at time step t are defined as:

$$fc(i,t) = \frac{l}{2} v^2(i,t) \tag{5}$$

$$ed(i,t) = \begin{cases} \frac{l}{2}[v^2(i,t-1) - v^2(i,t)], & for \quad v(i,t) < v(i,t-1) \\ 0 & for \quad v(i,t) = v(i,t-1) \\ \frac{l}{2}[v^2(i,t) - v^2(i,t-1)] & for \quad v(i,t) > v(i,t-1) \end{cases} \tag{6}$$

And the average fuel consumption of each car in every time step (F_C) is obtain as:

$$F_C = \frac{1}{T}\frac{1}{N}\sum_{t=1}^{T}\sum_{i=1}^{N} fc(i,t) \tag{7}$$

where N and T are the total number of vehicles in the system and corresponding total statistical time, respectively. Moreover, the fuel consumption fc can be catalogued into three types according to the speed of vehicles as acceleration (fc_a), deceleration (fc_d) and following (fc_f), which is shown as:

$$F_C = fc_a + fc_d + fc_f \tag{8}$$

Similarly, the energy dissipation ed is the sum of acceleration (ed_a) and deceleration (ed_d).

5. Dimensional Emission Component

The estimation modelling of pollutants cannot get rid of the help from emission factors which obtained from in-situ vehicle tracing measurements. Generally, the required 'factor' information can be categorized into two types: distance-based (g/km) and time-based (g/s). And in light of the NaSch model is distance-dimensionless with its simulation time step is equivalent to the real time, time-based (g/s) emission factor would be the priority choice. Hence, a general emission function proposed by using non-linear multiple regression techniques based on empirical measurements is given as [18]:

$$em(i,t) = \max[E_0, f_1 + f_2 v(i,t) + f_3 v^2(i,t) + f_4 a(i,t) + f_5 a^2(i,t) + f_6 v(i,t) a(i,t)] \tag{9}$$

where E_0 is a lower limit emission specified for both pollutant type and vehicle cetology, and f_1 to f_6 are emission constants determined by the regression analysis. As the study here concerns about only about the emitted particulate matter (PM_{10}) from petrol motor vehicles on the freeway which caused by acceleration (em_a), deceleration (em_d) and following (em_f), Table 1 only shows related values that would be used in after simulation.

Table 1: Parameters for Eq. (9)

E_0	f_1	f_2	f_3	f_4	f_5	f_6
0.0	0.0	1.57×10^{-5}	-9.21×10^{-7}	0.0	3.75×10^{-5}	1.89×10^{-5}

6. Results and Discussion

The simulation of the traffic behavior and related fuel consumption (fc), energy dissipation (ed) and PM_{10} emission is performed under periodic boundary condition, which means the number of vehicles in the system is conservation. In general, the averages are obtained by averaging over 30 independent initial realizations up to 3×10^5 iteration steps for each run and discarding the first 2×10^5 iteration steps as transient time. The length of the lane is set to be $L = 1\times10^5 \times l$ with related fixed parameters as $v_{\max} = 5, p = 0.2, l = 1$.

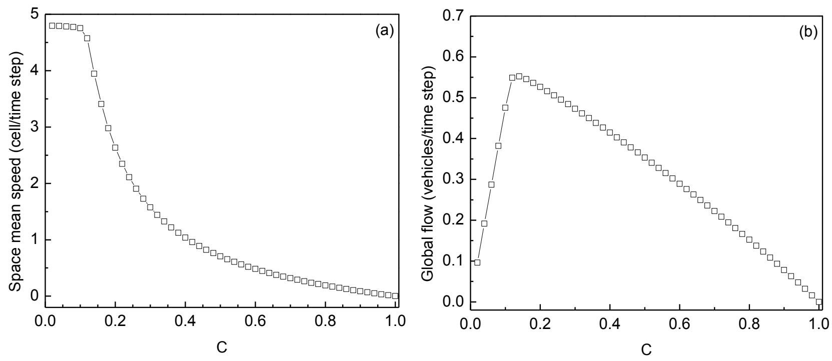

Fig. 1: Fundamental diagrams of the NaSch model (a) space mean speed; (b) global flow.

According to classical traffic theory, the estimation of vehicles moving capability on the road is based on the mean speed or flux, which we called fundamental diagrams as shown in Fig. 1. Here, the occupancy *c* indicates the proportion of lattices that have been occupied, which amount to the lane usage rate. As more and more cars occupy the road, space mean speed change (Fig. 1(a)) from a platform ($\bar{v} \approx 4.7$) into a slow crash at $c \approx 0.12$, which corresponding to a first phase transition process from free flow into jamming phase that increase first then collapse in global flow, and finally global congestion (Fig. 1(b)).

Fig. 2 presents the average of fuel consumption (fc) and energy dissipation (ed) of the NaSch model. It can be easily found the phase transition points (or critical point), both fc and ed, occur around the same occupancy rate shown in Fig. 1, which indicates that the trends of fc and ed are decided by the law of fundamental diagrams. Specifically, before the critical point, most of the fuel consumption was caused by the following behavior of the cars, then comes after acceleration and deceleration (Fig. 2(a)). After that the total of fuel consumption decrease for all three factors share goes down, which is the result of decreasing mean speed. Then, at some point (here about $c \approx 0.30$), acceleration took the place of following as the dominant contributor to the fuel consumption, which was caused by all vehicles in the system got stuck in the 'go and stop' mode. And the energy dissipation (Fig. 2(b)) told that the acceleration and deceleration had almost the same contribution to the total energy dissipation in the case study.

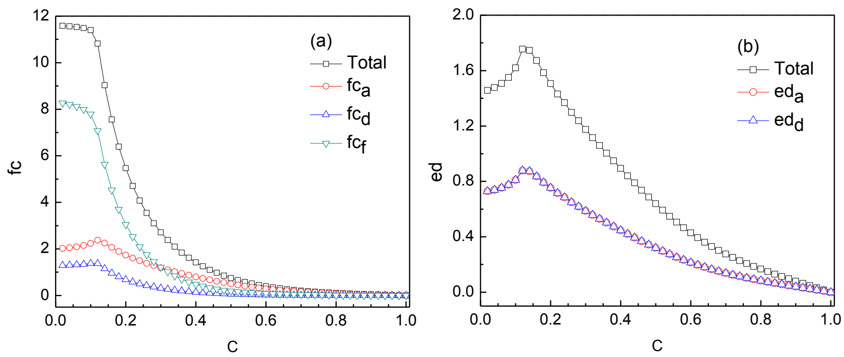

Fig. 2: Average of (a) fuel consumption and (b) energy dissipation of the NaSch model.

According to the emission function given by Eq.(9), we can calculate the average emission of PM_{10} per vehicle in every time step by using the instantaneous velocities and accelerations obtained from the NaSch model as provided in Fig. 3(a). Firstly, the acceleration vehicles had always lead the dominant role to the total PM_{10} emission in the whole span of the simulation, which agrees to most of the previous in-situ experiments. While car following behavior, vehicle speed at this moment was the same as last time step, produced least particulate matter. Another important point is that, before the critical value $c \approx 0.12$, almost all of the emission was caused by the behaviour of acceleration. And after that, where system goes into jamming phase, the emission suddenly climbed up, and the peaks of PM_{10} emission appeared at about $c \approx 0.30$, when acceleration began to act as the biggest fuel consumer as shown in Fig. 2(b).

In order to get better understanding of the emission activities, it is necessary to analyze the ratio of vehicles states. Fig. 3(b) presents the average ratio of vehicle states (acceleration, deceleration, following the frontal car, and jamming that speed equals zero) according to the increasing occupancy. In all situations of different vehicle lengths, before reaching the critical transition point, the majority of cars maintain in the following states within almost full speed (v_{max}), while can hardly spot the car in jamming states. Moreover, vehicles in the states of acceleration and deceleration receive the same share. When reaching the critical point, jamming cars begin slowly emerging and the proportion of cars in the states of following drops sharply. Meanwhile, the acceleration cars present a small growing peak and the deceleration cars slightly raise, where cross points are observed around $c \approx 0.30$ correspondingly among the ratio of deceleration, following and jamming with the emergence of the total PM emission peak values (Fig. 3(a)); while at the last stage, except the ratio of jamming states, all other three phases' proportions shrink to zero.

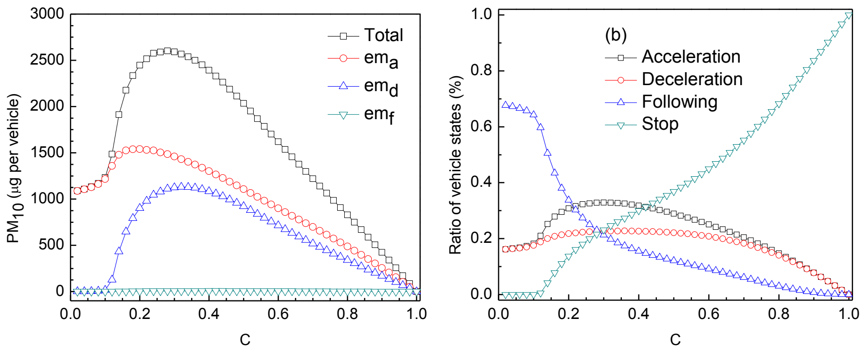

Fig. 3: (a) PM10 emission and (b) corresponding ratio of vehicle states of the NaSch model.

Lastly, rescaled parameters were used to quantify the trend of the PM emission per fuel consuming and dissipation as the traffic flow change from free flow to congestion with results shown in the Fig. 4. As a whole, the total PM_{10} per unit fuel consuming has little change until the system turn into the jamming phase that began to grow as the more cars appeared on the road. However, it is interesting to find that although acceleration produced most emission (Fig. 3(a)), it was the emission load for every unit fuel consuming for deceleration and following that grow exponentially after phase transition into traffic congestion, which means that the aggravating traffic jamming may have great influence on the emission load that made by energy combustion in unit for the broadening behavior of low speed following-deceleration-following. Although not in exponentially manner, the PM_{10} emission per unit energy dissipation reveals some similarities as PM_{10} emission per unit fuel consumption.

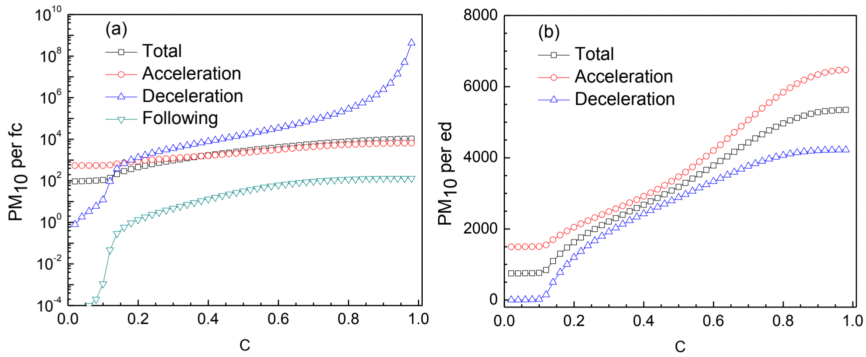

Fig. 4: PM10 emission per (a) fuel consumption and (b) emission dissipation of the NaSch model.

7. Conclusion

This study investigated the impact of congestion on traffic emitted PM_{10} based on NaSch model and empirical emission function. From the simulation results, the model here could well agree to daily measurement experience that vehicles produced more PM_{10} when congestion happened and acceleration was the major contributor to traffic emitted PM_{10}. Although results here were only obtained from a specific case study with limited traffic factors been considered, the model has shown its potential on studying the relation between congestion and emitted PM_{10} that called for further investigation and discussion.

8. Acknowledgements

The work was partially supported by Strategic Research Grant, City University of Hong Kong Grant (SRG-7004360), and National Natural Science Foundation of China (No. 11262003 & 11302125).

9. References

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