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Impacts of traffic congestion on fuel rate, dissipation and particle emission in a single lane based on Nasch Model

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HIGHLIGHTS

- NaSch model was applied to study impacts of congestion on the fuel and emission.
- Three different aspects of traffic conditions were considered separately.
- The impacts have been study both globally (whole lane) and locally (road sections).

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ABSTRACT

This paper presents simulation results of Traffic emitted particle modeling based on NaSch Model of a single lane. Three parts are constituted to the proposed model: traffic component (NaSch Model), fuel rate and dissipation component, and particle emission component. Impacts of speed limit, injection rate and extinction rate of the lane on the fuel cost and PM emission are disused in the periodic boundary condition and open boundary condition, respectively. Results from model simulation show that the critical transition point of the traffic system could also be used as a cut-off point for the change of the fuel and emission indexes. The high-speed limit was energy conservative and environmentally friendly until congestion occurred, while the low speed limit was better for smooth flowing traffic. The overall impact from the extension rate was more significant than the injection rate on all indexes, and the closer the road section was to the exit, the more fuel was consumed and the more particles were produced. The situation got better in descending order of the distance of the section to the exit.

1. Introduction

Particulate matter (PM) has become a vexing question and one of the most challenging global problems for air quality mitigation and for climate change policies [1]. Dealing with PM which originates from road transport constitutes an urgent task for megacities due to thousands of vehicles shuttling back and forth along every street. High frequency outbreaks of haze weather, PM related diseases and traffic congestion have once again appeared in the forefront as an inescapable obligation to safeguard the air quality of the general public. In addition, the variables that determine vehicular exhaust emissions are mainly fleet composition, speed, speed limits, acceleration and deceleration rates, queuing time in idle mode during the red phase, queue length, traffic flow rate and ambient wind conditions [2].

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However, the estimation of PM emissions from road traffic requires an in-depth understanding of traffic characteristics, which cannot be told by using traditional statistical methods that lack the capability to capture the dynamic process of traffic flow [3]. It is difficult to depict the relationship between traffic congestion and PM emissions by carrying out mobile measurements in a solo car. Consequently, the effects of congestion were only partially incorporated in the predictions and measurements. The effects of congestion on emitted PM are seldom incorporated in predictions and measurements.

To depict the traffic system and illustrate the mechanism physically, many traffic flow model have been proposed and developed [4–8], and formed an interdisciplinary that includes by introducing the idea of social dilemma to investigate its role on the evolution of traffic flow and formation congestion [9,10]; and incorporated with environmental consideration to evaluate the cost of energy and emission under different driving modes [11] and behavior [12,13], etc.

Yang et al. [14] studies the fuel consumption and gas emissions make by traffic by compared the results among three different traffic models in cellular automata, i.e., Nagel–Schreckenberg (NaSch), finite deceleration, and adaptive cruise control. Simulations suggested that keep driving smooth was the best way to reduce the expenditure of fuel and emission pollution. Madani and Moussa [15] investigated the fuel consumption and gas emissions caused by traffic in the NaSch model with closed boundary conditions, and found that the presence of a traffic light has a big effect on fuel consumption. In light of this, this paper combines the classical NaSch model and emission function based on empirical measurement, with objective is to investigate the effects of traffic congestion on the atmosphere due the emitted PMs from on-the-road vehicles, and also the impact on the fuel rate and dissipation.

2. Methodology

Three components were integrated in the model of this study: (1) traffic, (2) fuel rate and dissipation consumption, and (3) particle emission.

2.1. Traffic component

The aim of introducing the traffic component was to gain a speed–time profile to provide the necessary information that would enable the model with the ability to depict the macroscopic flux, fuel consumption, and particle emission of the traffic flow by simulating every individual vehicle movement microscopically. Among multiple traffic models [16], cellular automaton (CA) ones, microscopically, were most popular for their simple algorithm, high generalization and rich phenomena. The adopted CA model in this study was the NaSch model [17], which was able to reproduce the spontaneous emergence of traffic jams and was known as the first stochastic traffic cellular automaton model.

Generally, the NaSch model was defined on a one-dimensional array L in a dimensionless manner, in which each site may either be empty or occupied by one vehicle that has an integer speed in the range between zero and a maximum speed (s_{max}). For an arbitrary configuration, the NaSch model followed four consecutive steps, which were performed in parallel for all vehicles [18]:

***Step* 1**. Acceleration:

$$s\left(i, t+1/3\right) \rightarrow min\left(s\left(i, t\right)+1, s_{max}\right) \tag{1}$$

***Step* 2.** Deceleration:

$$s\left(i, t+2/3\right) \rightarrow min\left(s\left(i, t+1/3\right), gap_n\right) \tag{2}$$

***Step* 3.** Randomization with probability p:

$$s\left(i, t+1\right) \rightarrow max\left(s\left(i, t+2/3\right)-1, 0\right) \tag{3}$$

***Step* 4.** Car motion:

$$x\left(i, t+1\right) \rightarrow x\left(i, t\right)+s\left(i, t+1\right) \tag{4}$$

where $s\left(i, t\right)$ and $x\left(i, t\right)$ 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). These steps represent three common situations during the driving process. The randomization probability p is a stochastic braking noise that makes the vehicles decelerate without backing.

In general, there were two boundary conditions for CA simulation, i.e., periodic boundary condition and open boundary condition. The periodic boundary condition indicated that the number of vehicles in the system was conserved (conservation), determined by the occupation rate ρ; the lane was similar to a closed loop. While the open boundary condition meant that vehicles could move into or get out of the lane with certain probability, determined by two adjustable parameters (i.e., injection rate α and extinction rate β), and the number of vehicles was not conserved (non-conservation) in the simulation system. Compared to realistic traffic, it was easy to rescale the model and make comparisons with a realistic scenario by converting the length of one site and a simulation time step into 5 m of place and one second of time in a real road scenario, respectively. For example, the $s_{max}=5$ in the simulation system and was equivalent to the speed of 90 km/h. This conversion laid the foundation for the subsequent fuel and emission estimation.