Analysis of traffic flow with micro-cars with respect to safety and environmental impact

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Abstract

This study analyzes the characteristics of traffic flow in the presence of micro-cars in a vehicle mix. A two-lane multi-cell traffic cellular automaton (TCA) model is formulated to simulate mixed traffic flow comprising conventional passenger cars and micro-cars. The segments of an urban highway and arterial road, both with two lanes and measuring 700 m in length, are simulated; the latter includes an intersection delay with a signal cycle at the midpoint. Traffic flows with different proportions of micro-cars are investigated in the simulation. Four aspects of traffic conditions are calculated: the number of lane changes, the number of decelerations, the coefficient of speed variation (which may be indicative of safety performance), and the HC, CO, and NO_x emissions (as a measure of environmental impact). The simulation results suggest that mixed flow with micro-cars leads to higher frequencies of lane-changing on both highways and arterial roads, although the incremental change on the latter is smaller. With the introduction of micro-cars on the highway, the frequency of decelerations increases in free flow and decreases in congested flow; however, on the arterial road, it decreases the frequency of decelerations and has an insignificant impact on free flow. The introduction of micro-cars has a similar impact on the coefficient of speed variation. Under free flow conditions on highways, the introduction of micro-cars has a negative influence on the three aforementioned parameters related to safety. However, for free flow on arterial roads or congested flow on highways and arterial roads, the results are inconclusive because the effect of micro-cars is contradictory in terms of the three parameters. Vehicle emissions, such as HC, CO, and NO_x, increase during free flow on highways, but are always lower on arterial roads.

Key Words *Micro-car, Safety, Emissions, Simulation, Cellular automaton model*

1 Introduction

1.1 Background

The conventional automobile is undergoing a transformation (Mitchell et al., 2010). We are on the cusp of a future when the traditional automobile may not be able to fulfill its function sustainably as the primary provider of self-powered mobility. The survival of the conventional cars is currently threatened by several problems, such as oil availability and rising fuel prices, legislations to reduce carbon emissions, and other factors pertaining to climate change, congestion, and parking limitations. Alternative vehicles have been developed and produced by niche manufacturers for decades, and these will certainly enjoy mainstream popularity in years to come. Micro-cars are probably the type of alternative vehicles that car owners find most suitable and the type that major original equipment manufacturers (OEMs) might start producing on account of their similarity to traditional cars (Richardson and Rose, 2010). Global mainstream OEMs have already started building the initial market momentum—more than 30 micro-car models were introduced at the 2010 Paris Motor Show and 2011 Geneva

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Motor Show. Moreover, Global Industry Analyst Inc. has announced the release of a comprehensive global report on micro-cars; the sales of micro-cars in North America, Japan, and Europe are projected to exceed 1.9 million units by 2020.

The micro-car, usually a two-seater two-door lightweight vehicle and less than 3 m long, is the smallest in the standard category of small cars; it is smaller than the ubiquitous city car (a small automobile intended for use in urban areas). A city car offers greater speed and capacity than a micro-car. In Japan, city cars are called K cars. A K car's engine has a maximum displacement of 660 cc, and the car's length is less than 3400 mm. It evolved out of necessity in post-World War II Europe because of the short supply of raw materials and money; thereafter, it has seen a rebirth in the changing mobility landscape where it now performs an important function.

The problems faced by the traditional automobile, as mentioned above, are encountered most strongly in metropolitan areas. To resolve these problems, the future automobile world is poised to depend on electric engines and wireless communications; vehicles are becoming lighter and cleaner. Micro-cars are a perfect fit for this scenario because they are convenient for short and medium distance trips that are typically traversed in urban areas. They can provide convenient personal urban mobility at a cost lower than that of conventional cars, occupy less space for parking, and significantly improve the throughput of streets and roads.

The effects of introducing micro-cars into traffic flow from a congestion perspective have been studied in a previous research (Mu and Yamamoto, 2012); it proved that micro-cars will relieve traffic congestion to some extent, and the movement of high density traffic will become smoother and faster as the number of micro-cars on the roads increases. However, the effects of micro-cars on traffic safety and environment have never been analyzed. Because the characteristics of micro-cars considerably vary from those of traditional cars, traffic flows with and without micro-cars are also distinctly different. For example, the presence of micro-cars in traffic flow might be a safety hazard because of their inferior performance compared with conventional cars. To analyze the impact of micro-cars on traffic flow, we conducted a series of traffic simulations with and without micro-cars on an urban highway and arterial road.

There is a strong possibility that the presence of micro-cars might disrupt the existing balance of traffic flow that only involves conventional vehicles. The apprehensions regarding the impact of micro-cars on road safety are also valid and significant. Traffic safety has two aspects: one is to avoid the occurrence of accidents, and the other is to minimize injuries when accidents occur. Multiple studies have been conducted on the relationship between vehicle mass and size and the extent of injuries when the vehicle encounters an accident (Evans, 1984a, 1984b; Krishnan, 1985; Evans and Frick, 1993; Wood, 1997; Tolouei et al., 2013). With conventional vehicles, it is typically believed that because of their small size and mass, their occupants suffer more damage when accidents occur. However, Sparrow (1985) presented a different perspective on the safety of smaller cars, asserting that mechanical construction is merely one factor that influences the extent of injuries in accidents. There are several other aspects; among them, driving speed and driving behavior are major factors. The number of times that the driver changes lanes, the frequency of accelerations or decelerations, and the variation of traffic flow speed reflect driving behavior. It is evident from a number of studies that lane-changing is one of the main factors associated with traffic accidents. Pande and Abdel-Aty (2006) surmised that lane-changing behavior is a leading cause of vehicle collisions and requires further analysis and investigation. Earlier research (National Highway Traffic Safety Administration (NHTSA), 2005; Li and Milgram, 2008) states that inadequate or late detection of the leading vehicle's deceleration is the main cause of rear-end collisions. Hence, the frequency of decelerations is also an important indicator by which traffic safety can be assessed. Speed variation is another key factor that influences road safety (Taylor et al., 2000; Boonsiripant et al., 2007; Mattar-Habib et al., 2008). Thus, we focus on these three traffic flow parameters—frequency of lane-changing, frequency of decelerations, and speed variation; these do not directly measure safety (such as the number of accidents), but are surrogate safety measures. Nonetheless, based on literature, we believe that these measures are useful when direct measurements are not available.

In recent years, automobile-related air pollution has attracted considerable attention. The emission of CO from vehicles accounted for 60% of the total CO emissions in the United States in 2011, and NO_X emissions from vehicles exhibit similar proportions (National Emissions Inventory (NEI), 2012). Vehicle emissions contribute significantly to overall air pollution, and CO, HC, and NO_X emissions are considered as key indicators of the impact of vehicular pollution. Hence, in this research, we focused on estimating these three types of emissions.

Various studies have been conducted on mixed traffic flows: mixed traffic consisting of cars and trucks have been investigated, whereas others have examined the mix of motorized and non-motorized vehicles. However, mixed traffic flows that consist of conventional cars and micro-cars have not yet been scrutinized in detail, and thorough investigations are necessary in this area as micro-cars become more prevalent. Therefore, the purpose of this study is to explore certain fundamental characteristics of mixed traffic consisting of cars and micro-cars in terms of safety and environmental impact.

Among the approaches available for investigating traffic flows, the traffic cellular automaton (TCA) model has proven excellent for simulating real traffic because of its efficient and fast performance when used in computer simulations (Maerivoet and De Moor, 2005). Hence, we have chosen this model to implement the simulations described in this study.

1.2 Structure of the paper

The remainder of the paper is organized as follows: Previous studies are reviewed in Section 2. In Section 3, the TCA model and the actual model used in this research are explained. Section 4 presents the mixed traffic simulation results and discusses the accuracy of the TCA model used. The analysis with respect to safety based on the number of lane changes, the number of decelerations, and the coefficient of speed variation are discussed in Section 5. In Section 6, environmental analysis based on HC, CO, and NO_x emissions is elaborated. Conclusions and suggestions for future research are summarized in Section 7.

2 Literature Review

2.1 The prospect for micro-cars

Richardson and Rose (2010) gathered information concerning alternative means of personal mobility and concluded that an increasingly diverse range of alternatives are becoming available; alternatives that assure more transport options in the face of the climatic, social, and financial problems that confront society. Recent international motor shows have demonstrated a marginal increase in alternative vehicle concepts presented by OEMs, with two vehicle types dominating the spectrum: micro-cars and personal mobility devices (PMDs). Whereas PMDs have several limitations, micro-cars offer a small spatial footprint that eases congestion and parking problems; they afford greater fuel efficiency, weather protection, and some luggage capacity. Thus, micro-cars are the most probable alternative to conventional cars. Mitchell et al. (2010) indicated that conventional cars are appropriate for transporting multiple passengers over long distances at high speeds; however, they are inefficient for personal mobility within cities, where most of the world's people now live. They reconceptualized the automobile and envisioned vehicles of the near future that are green, smart, connected, and fun to drive.

2.2 Multi-class simulation

There has been no research focused on multi-class traffic that includes micro-cars. However, in several ways, the micro-car and conventional car pairing is parallel to the conventional car and truck pairing: both pairs involve two considerably different sizes of vehicles in traffic flow. Hence, studies of mixed traffic with conventional cars and trucks are reviewed here as reference for this study.

In the area of microscopic multi-class simulation, early studies simulated different types of vehicles; they are the origin of multi-class traffic simulations (Stock and May, 1977, St John, 1977, Rioux et al., 1977, Sibley, 1985). Mason and Woods (1997) proposed a multispecies car-following model for traffic flow analysis and provided an understanding of multispecies traffic in such a model. A subsequent study by Treiber et al. (2000) simulated congested truck-and-car traffic states on a continuous microscopic single-lane model using realistic data, and formulated a theoretical phase diagram for bottlenecks. Kesting et al. (2007) proposed a lane-changing model and applied it to traffic simulations of cars and trucks using the intelligent driver model as the underlying car-following model for verification.

Moussa and Daoudia (2003) presented computerized simulations of traffic flow utilizing the TCA model on a two-lane roadway with two different types of vehicles: cars and trucks. Moreover, the importance of the braking parameter and the proportion of trucks on a two-lane roadway were investigated. Chen et al. (2004) placed different types of vehicles (cars and trucks) with different driver behaviors on a three-lane highway to investigate traffic flow using the TCA method.

The multi-class concept has been rarely employed for macroscopic traffic flow modeling in the last century, but Hoogendoorn and Bovy (2000) derived the multiclass macroscopic flow model from the user-class specific phase–space density. Subsequently, a number of reformulations and extensions of the concept followed (Wong and Wong 2002; Zhang et al., 2006; Zhang et al., 2008). Wong and Wong (2002) developed a multi-class traffic flow model as an extension of the Lighthill–Whitham–Richards (LWR) model with heterogeneous drivers. Zhang et al. (2006), in an attempt to solve hyperbolic conservation laws with spatially varying fluxes, applied the weighted and essentially non-oscillatory method to develop a multi-class traffic flow model for a heterogeneous highway. Zhang et al. (2008) extended the d-mapping algorithm to develop a multi-class traffic flow model on a heterogeneous highway that is characterized by spatially varying fluxes and considerably complex waves.

There have also been certain other studies related to multi-class traffic that includes passenger cars and trucks. Ye and Zhang (2009) elucidated the existence of a qualitative difference in vehicle-type-specific headway and distribution in mixed truck-and-car traffic; such knowledge can be utilized to improve microscopic traffic simulation models. Abdelgawad et al. (2011) simulated a multi-class traffic with trucks in order to assess the impact of exclusive truck facilities, including truck-only highway and truck-lane conversion on a highway.

The multi-class studies mentioned above mainly considered an operational point-of-view to assess the traffic and its impact; the conduct of an impact study on the safety and environment resulting from the introduction of micro-cars is an exigent task.

2.3 Traffic flow characteristics influencing safety and effect of car size on safety in accidents

Crash risk assessment has always attracted interest. Based on data from the 1999 GES (General Estimates System) crash database of the US NHTSA, the universe of two-vehicle lane-change crashes in the US consists of 539 000 events involving 1 078 000 vehicles. This constitutes approximately 10% of the 12.1 million vehicles listed in the 1999 GES, and approximately 9% of the 6.3 million crashes recorded (Sen et al., 2003). Based on the study of Wang and Knipling (1994), it can be safely hypothesized that sideswipe crashes occur when a vehicle intentionally changes lanes; angle crashes, which occur on the inner through lanes of a freeway, are assumed to be related to lane changes.

Based on the statistics on rear-end collisions, the US NHTSA 2005 report states that rear-end collisions accounted for 29.6% of all crashes (1.9 million), 29.6% of all injury crashes (0.57 million), and 29.8% of all property-damage-only crashes (1.3 million) in 2003. The major cause of rear-end collisions is the incorrect driver reaction to the behavior of the vehicle in front because of the inappropriate or delayed detection of the forward vehicle’s deceleration (Li and Milgram, 2008). Taylor et al. (2000) analyzed the speed–accident relationship and found that accident frequency increases exponentially as the coefficient of speed variation. Numerous studies identify potential relationships between speed characteristics and roadway safety. More specifically, the crash risk may be positively correlated with speed variation, and higher vehicle speeds are generally correlated with increased crash severity (Boonsiripant et al., 2007). Speed inconsistency is a common contributing factor to crashes on two-lane rural highways (Mattar-Habib et al., 2008).

Vehicle mass and size are also significant aspects of traffic safety considerations. According to the crash data in the United States, Evans (1984a, 1984b) found that the probability of driver fatality in a vehicle with a 900-kg mass is 2.6 times that in a 1800-kg vehicle. However, the probability of a 900-kg vehicle to be involved in accidents is lower (i.e., 0.72 times) than that of a 1800-kg vehicle. Based on automobile insurance data in the United States, Krishnan (1985) concluded that small cars increased injury risk to their occupants. Evans and Frick (1993) assumed relative risk to be a function of the ratio of masses of vehicles in two-vehicle crashes; the function corresponds well with the fatal accident reporting system data. The driver fatality risk in lightweight cars increases exponentially than in heavier ones. Wood (1997) derived generalized equations using the fundamental relationships of Newtonian mechanics for frontal collisions and combined these with overall injury criteria to propose a series of predictive relative injury risk relationships. The theory has a high level of correlation with field evaluations of relative injury risk to car occupants that have been performed in the United States and Europe. In all cases of collisions, the relative injury risk is proportional to the mass ratio of partner car or case car to the power of some number. Vehicles with small sizes and masses are associated with higher relative injury risk than those that are larger. Tolouei et al. (2013) confirmed the notion that a higher vehicle mass reduces the driver injury risk, and a lower vehicle mass increases the driver injury risk in case of a two-vehicle collision. They further confirmed that beyond that of vehicle mass, a protective effect exists because of vehicle size in case of frontal and front to side collisions. The aforementioned studies demonstrate the negative impact of smaller cars on traffic safety in the United States and Europe. However, Sparrow (1985), using statistical data from 1981 and 1982, discovered that K cars in Japan were involved in fewer accidents than other larger vehicles and attributed this phenomenon to the K car speed limit imposed in this country (80 km/h for K cars, whereas 100 km/h for conventional cars). The situation remains the same in Japan (annual statistic data of traffic accident and annual statistic data of transportation volume). The impact of speed on traffic safety can be evaluated using relationships between two parameters: speed and accident risk or speed and crash severity. Recent studies and reviews find that vehicles that travel above the mean speed are involved in more crashes (Fildes and Lee, 1993; Vivienne M. et al., 1995; Aarts and Schagen, 2006). The probability of injury in a crash increases exponentially with the collision speed (Fildes and Lee, 1993; Transportation Research Board, 1998; Elvik et al., 2004; Elvik, 2009).

3 Model

3.1 Argument for utilizing TCA model

In several studies, when describing traffic, the focus is not on the movement of individual vehicles, but on the macroscopic properties of the entire system. The properties can be expressed as probability distributions or averages calculated by aggregating objective vehicles. Thus, for example, it is clearly inefficient to use precisely detailed models of individual driver behavior if only the flow-density relationship or lane-changing distribution has to be obtained.

This is the starting point of TCA modeling. A TCA model is able to simulate large traffic systems several times faster than practical situations that makes prediction feasible; this makes the model extremely efficient computationally. Although TCAs may be intuitively considered approximate, they are discrete in time and space, and the unit time and unit length of a cell can be defined depending on particular requirements. Hence, they can be as precise as can be conceived. Traffic phenomena, such as the transition from free to congested flow, lane inversion, platoon formation, meta-stable states, and hysteresis phenomena can be accurately reproduced using the TCA models. Similar to the velocity-dependent randomization (VDR) model (Barlovic et al, 1998), the TCA model can mimic meta-stable states and hysteresis phenomena apart from establishing the fundamental relationship among traffic characteristics.

3.2 Brief introduction to TCA

In 1992, Nagel and Schreckenberg proposed the well-known Nagel–Schreckenberg (NaSch) model (Nagel and Schreckenberg, 1992), commonly known as the stochastic traffic cellular automaton (STCA) model. Although it is considerably simple, the NaSch model can reproduce certain real-traffic phenomena, such as the occurrence of phantom traffic jams and realistic flow–density relationship. The NaSch model is a minimal model in the sense that any further simplification leads to unrealistic behaviors. Emulating the NaSch model, several extensions were proposed, such as the Fukui–Ishibashi (FI) model (Fukui and Ishibashi, 1996), TT model (Takayasu and Takayasu, 1993), VDR model (Barlovic et al, 1998), velocity effect model (Li et al, 2001), and Kerner–Klenov–Wolf model (Kerner et al., 2002).

Because most roads are multi-lane in real traffic, multi-lane models were proposed. Rickert et al. (1996) examined a simple two-lane model based on the single-lane cellular automaton model proposed by Nagel and Schreckenberg. Wagner et al. (1997) proposed a set of asymmetric lane-changing rules for the TCA to simulate a multi-lane traffic. Chowdhury et al. (1997) developed the particle-hopping of two-lane traffic models with two different types of vehicles characterized by two different values of the maximum allowable speed. Their study proposed two-lane models that are symmetric and asymmetric to investigate the effects of lane-changing. Nagel et al. (1998) summarized different approaches to lane-changing, including their results, and proposed a general scheme; thereafter, they compared the model results with real data. Knospe et al. (1999) discussed the effect of slow-moving cars in two-lane systems. It was shown that the anticipation of drivers drastically reduces the influence of slow-moving cars. Subsequently, Knospe et al. (2000) proposed an improved discrete model that incorporates anticipation effects, reduced acceleration capabilities, and enhanced interaction horizon for braking. Knospe et al. (2002) analyzed the reproduction of lane usage inversion and the density dependence of the number of lane changes. It was proved that single-lane dynamics can be extended to the two-lane case without changing the basic properties of the model. Jia et al. (2004) extended a single-lane model by taking into consideration the effect of the velocity of the preceding car as well as the “honk effect” on traffic behavior in a two-lane system. Li et al. (2006) proposed a realistic two-lane TCA model considering the aggressive lane-changing behavior of fast vehicles.

There are also other newly proposed models that are applicable to particular conditions (e.g., highway on-ramps or off-ramps) or those that focus on traffic flow characteristics. Recently, several studies have been using the mechanism of cellular automata to simulate bicycle and pedestrian behaviors.

3.3 Basic parameters

In the TCA models, space, time, and velocity are discrete. Roads are divided into unit cells fitted end-to-end in series, and each cell is either empty or occupied by a vehicle. A two-lane multi-cell TCA model is developed for the simulations in this investigation.

The length of one cell is 1 m. All parameters and variables must, as a result, be natural numbers as they must be divisible by unity as per the TCA definition. A highway and an arterial road, both with two parallel lanes, are modeled with a 700-m length comprising 700 end-to-end cells. Table 1 summarizes the actual vehicle lengths, maximum speeds, average accelerations, and average decelerations (micro-cars are assumed the same as conventional vehicles). Based on the listed vehicle lengths in Table 1 and the typical length of conventional vehicles (7.5 m, e.g., Nagel, 1996; Barlovic et. al, 1998), it is assumed in the simulation (as summarized in Table 2) that one conventional car occupies seven cells. On the other hand, one micro-car is assumed to occupy four cells, which is slightly half the length of a conventional car. The foregoing are not the physical lengths of vehicles, but are interpreted as the average headway in a jam; this interpretation is a common concept in TCAs.

A one-time step lasts 1 s, which is the reaction time of a human driver. In Japan, the speed limit is 100 km/h in highways and 60 km/h in arterial roads, which have isolation strips and more than two lanes for one direction within the town. The lower values are chosen as the maximum desired speeds for vehicles on the highway and arterial road (these speeds are distinct for each thoroughfare) after a comparison between the technical maximum speed and the speed limit. Accordingly, the velocity of conventional cars are natural numbers with a maximum value of 28 cells per update on the highway or 17 cells per update on the arterial road, whereas that of micro-cars are natural numbers up to 17 cells per update; these correspond to a maximum speed of 100.8 km/h for conventional cars and 61.2 km/h for micro-cars.

The maximum acceleration and deceleration units are set as 2 and −2 m/s^2, respectively; these values are used in order to best imitate reality after gathering related information, especially from the analysis of historical data pertaining to vehicle acceleration and deceleration behaviors. On the highway, vehicle acceleration values ranged from 0 to 3.7 m/s^2, and deceleration values ranged from −1.5 to 0 m/s^2 in a dataset applied by Ahn et al. (2002). The dataset was obtained from the Oak Ridge National Laboratory; this dataset was originally used to develop energy and emission models utilizing the instantaneous speed and acceleration or deceleration levels of vehicles as independent variables. Eight normal light-duty vehicles were selected, and vehicle fuel consumption, emission rate, instantaneous speed, and acceleration or deceleration were measured every second; from 1300 to 1600 individual measurements were conducted for each vehicle. For acceleration and deceleration at signalized intersections, Kamalanath Sharma (2010) presented results from a literature review. The reviewed deceleration ranges from −4.9 to −0.98 m/s^2, and the acceleration ranges from 0.86 to 1.74 m/s^2. Maurya and Bokare (2012) also reviewed the deceleration rates observed by various studies and found these to range from −4.9 to −0.4 m/s^2. Bogdanovic et al. (2013) measured the values of acceleration at signalized intersections in Novi Sad, Serbia, using the procedure based on video recording processing. The measured vehicle accelerations ranged from 0.79 to 4.86 m/s^2 at a close measuring point and from 0.7 to 3.51 m/s^2 at a far measuring point. By taking the average of the above values, the acceleration and deceleration values can be assumed to be approximately 2 and −2 m/s^2, respectively.

Table 1 Actual vehicle attributes

Attribute	Conventional car	Micro-car
Length (m)	4.0–5	2–3
Maximum speed (km/h)	More than 160	60
Average Acceleration (m/s^2)	2	2
Average Deceleration (m/s^2)	−2	−2

Table 2 Simulated vehicle attributes (unit length = 1 m)

Attribute	Conventional car	Micro-car
Minimum space headway (cell)	7	4
Maximum speed (cells per update) considering speed limit	28 on highway; 17 on arterial road	17
Maximum acceleration (cells per update)	2	2
Deceleration unit in stochastic deceleration step	−2	−2

Vehicles run within a periodic boundary (vehicles do not drive away from the road, but drive from end of the segment to the beginning of the segment, such as driving in a circle) on the road and initial vehicle positions are distributed probabilistically. A signal cycle that results in an intersection delay with a 60-s cycle and 30-s green time is arranged at the mid-point of the arterial road. The total number of time steps is 10 000, whereas the results calculated from the last 3600 s are used as output, as summarized in Table 3. Usually, in TCA models, several previous time steps are discarded to ensure that the results are obtained after the system reaches a stable status (e.g., Nagel and Paczuski, 1995; Rickert et al., 1996). Thus, the results from the previous 6400 s are discarded, although a steady state is achieved after considerably fewer time steps in this study.

Table 3 Simulation parameters

Variable	Situation
Boundary	Periodic
Unit time (s)	1

Time steps (s)	10 000
Time steps taken as output (s)	3600
Total length (cells)	700
Total length (m)	700

3.4 Rules for speed updating

In a multi-lane model, the update step is typically divided into two sub-steps. In the first step, vehicles may change lanes in parallel according to lane-changing rules. Thereafter, the system updates according to the independent single-lane model in the second sub-step.

The following speed updating rules proposed by Nagel and Schreckenberg (1992) are used. The situation is updated in parallel for all vehicles.

$$V'_{n,t+1} = \min(V_{n,t}+a, D_{n,t}, V_{max,n}) \quad (1)$$

$$V_{n,t+1} = \max(0, V'_{n,t+1}+d), \text{ with probability } P_{brake} \quad (2)$$

$$V_{n,t+1} = V'_{n,t+1}, \text{ with probability } 1–P_{brake} \quad (3)$$

$$X_{n,t+1} = X_{n,t}+V_{n,t+1} \quad (4)$$

where

t: current time step

$V'_{n,t+1}$: intermediate parameter for calculation

$V_{n,t}$, $V_{n,t+1}$: velocity of vehicle n at time *t or t+1*

a: maximum acceleration

$D_{n,t}$: gap between vehicle n and vehicle in front at time t

$V_{max,n}$: maximum speed of vehicle n

d: deceleration unit in stochastic deceleration step

P_{brake}: braking probability that models erratic driver behavior; typically set to 0.3 and 0 for vehicles at a distance of 30 m to or from the physical center of intersection on arterial road

$X_{n,t}$, $X_{n,t+1}$: position of vehicle n at time *t or t+1*

If the brake probability is always set to 0.3, even in the area near a traffic light, the maximum traffic flow on the arterial road is approximately 660 vehicles per hour per lane (veh/h/lane), which is considerably lower than the usual traffic capacity at the intersection. A long time is necessary to cluster the vehicles end-to-end and achieve a speed that is higher up to their desired speed after a red light. Two reasons for this are observed in the simulation: first, the acceleration is limited to 2 m/s^2 and second, the vehicles are set to decelerate with a certain probability (0.3) even in such special situations. Finally, the brake probability is assumed to be 0 near an intersection on the arterial road to correspond to the maximum traffic flow in real-life traffic.

3.5 Rules for lane-changing

Lane-changing rules can be symmetric or asymmetric with respect to lanes and vehicles; the symmetric form is used in this work. Rickert et al. (1996) assumed a set of symmetric rules where vehicles change lanes if the following criteria are fulfilled:

$$A.\ D_{n,t} < \min(V_{n,t}+1, V_{max,\,n}) \quad (5)$$

$$B.\ D_{n,t\ other} > \min(V_{n,t}+1, V_{max,\,n}) \quad (6)$$

$$C.\ D_{n,t\ back} > 5 \quad (7)$$

$$D.\ rand\,() < P_{n,\,change} \quad (8)$$

where

$D_{n,t,other}$: gap between vehicle n and that in front in other lane at time t

$D_{n,t,back}$: gap between vehicle n and that behind it in other lane at time t

rand (): random number between 0 and 1

$P_{n,change}$: lane-change probability of vehicle n; set to 0.8 for both lanes

In the comprehensive examination of realistic lane changes by Lee et al. (2004), it is observed that drivers of fast vehicles are willing to change lanes even when a vehicle is approaching from behind in the adjacent lane. Thus, in this study, the trigger criterion, which pertains to the space between vehicle *n* and the vehicle behind it in the other lane, is modified with the aim of emulating a real-life situation. Here, if vehicle *n* satisfies the four following conditions, it can change lanes:

$$A.\ D_{n,t} < \min(V_{n,t}+a,\ V_{max,\ n}) \tag{9}$$

$$B.\ D_{n,t\ other} > \min(V_{n,t}+a,\ V_{max,\ n}) \tag{10}$$

$$C.\ D_{n,t,\ back} > \min(V_{n,t,\ back}+\mathrm{a},\ V_{max,\ n,\ back}) \tag{11}$$

$$D.\ rand\ () < P_{n,\ change} \tag{12}$$

where

$V_{n,t,back}$: speed of vehicle behind vehicle *n* in other lane at time *t*

$V_{max,n,back}$: maximum possible speed of vehicle behind vehicle *n* in other lane at time *t*

Condition A is a motivation standard. If the headway between vehicle *n* and the vehicle in front is insufficient for vehicle *n* to accelerate or maintain its maximum speed, the driver of vehicle *n* is willing to change its lane. Condition B is used to check whether driving conditions in the other lane are better. Condition C is used to check if the condition of the other lane permits the driver of vehicle *n* to change lanes. Condition D sets the probability for lane-changing.

4 Simulation Results

4.1 Inputs and outputs

The input data for the simulation include the number of vehicles on the road (10–200 in steps of 10 for two lanes). The maximum vehicle number is 200 for conventional vehicle traffic because the road length is 700 m, as defined in Section 3.3 with different micro-car rates, *r* (ranging from 0% to 100% in steps of 20%), as summarized in Table 4. By multiplying the vehicle count by 1.43, it can be expressed as density; this is based on the calculation that one vehicle on a lane means a density of 1.43veh/km/lane. Simulations in which the braking probability, *p*, and the lane-changing probability are equals 0.3 and 0.8, respectively, are performed. Because the simulation includes stochastic elements, each simulation is executed 10 times to allow the averaging of results; accordingly, to some extent, randomness can be avoided.

Table 4 Simulation parameters

Attribute	Values	Step
Micro-car rates (*r*)	0%–100%	20%
Number of vehicles	10–200	10
Braking probability (*p*)	0.3	0
Lane-changing probability	0.8	0

The simulation outputs are as follows: number of lane changes in the ultimate 3600 time steps; number of decelerations in the ultimate 3600 time steps; speed variation in the ultimate 3600 time steps; vehicle-specific power (VSP) (Section 6) of every vehicle in the ultimate 3600 time updates.

4.2 Macroscopic results: Flow–Density relationship

In the results, the traffic flow increases more or less linearly for densities of up to 25 vehicles per kilometer per lane (veh/km/lane). This represents the free-flow branch of the fundamental diagram on the highway and arterial road (Fig. 1). At this critical density, the flow reaches a maximum value of approximately 2300 veh/h/lane on the highway. In a state of congestion (that is, at densities higher than the critical density), the flow decreases with increasing density until the jam density is reached, the traffic halts, and zero flow results. The fundamental diagram in Fig. 1 is a reasonable depiction of typical correlations among traffic flow characteristics. The density–flow correlations are similar to most of the TCA models investigated by Maerivoet and De Moor (2005). These include the following: the STCA with cruise control (Nagel and Paczuski, 1995), which sets no braking probability for vehicles driving at the maximum speed; the Takayasu–Takayasu TCA (Takayasu and Takayasu, 1993), which sets a slow-to-start rule for updating the speed of vehicles; the VDR–TCA, which sets a higher brake probability for stationary vehicles than for those that are non-stationary. At the critical density (25 veh/km/lane), the flow attains a maximum value of approximately 850 veh/h/lane on the arterial road. It is less than half of that on the highway, and evidently, the low value is because of the presence of the traffic signal. The time for which the green light is on is half of the entire signal cycle, and if the maximum value on the highway is divided by two, then the highest flow would be 1150 veh/h. However, vehicles become static when the red light is on, and they have to start from 0 km/h when the light turns green. Hence, flow considerably slows down until the vehicles reach their desired speed; this is the reason that the actual highest flow is lower than 1150 veh/h. The highest flow is maintained at approximately 850 veh/h for a broad density state ranging from 28 to 117 vehicles per kilometer (veh/km). This is also because of the traffic signal: there is a broad space for vehicles to rapidly increase their speed after a red light turns green. Thereafter, the flow of the entire segment can attain a certain value.

The one-hour-average results of vehicle flow on the highway (denoted by blue points linked with red lines in Fig. 1) show two stable branches: free-flow and congested. As traffic evolves from a free-flow to congested state, it creates a typical reversed λ shape, which indicates a capacity drop. This occurs because of a stabilization effect, defined as the combination of the finite size effect and the high-resolution effect. The finite size effect means that in a finite system, two traffic flow phases (free phase and jammed phase) do not coexist in a dynamic equilibrium when the overall density in the system is only slightly above the equilibrium density of the free phase. This is because any macroscopic traffic jam would absorb numerous cars such that the density in the free phase would drop below the equilibrium density (Krauss and Wagner, 1997). In our model, the segment's length is 700 m; it is a finite system because vehicles that exit at the downstream end of the segment thereafter re-enter at the upstream boundary.

The finite size effect is one of the reasons for the capacity drop; another reason is the high-resolution effect. Initially, the TCA model was developed as a single-cell model in which one vehicle occupies one cell. Several years later, the multi-cell CA model was conceived. A multi-cell model means that one vehicle may occupy a number of cells (i.e., one cell has a length shorter than that of the vehicle), and the road has a higher discrete level. The higher the discrete level, the more moving space choice the vehicles have. Therefore, vehicles can attain higher speeds when the system is in a medium phase—between the free phase and congested phase. For instance, in a system in which one cell equals 0.5 m, the vehicle speeds can be 27, 27.5, or 28 m/s (within a speed range 27–28 m/s). On the other hand, for a system in which one cell equals 1 m, the vehicles can only have a speed choice of 27 or 28 m/s. Because drivers prefer to increase vehicle speed, most would choose a speed of 27.5 m/s instead of 27 m/s if they can. The higher discrete level can result in a higher critical flow for the system. However, the system will undergo a reduction in capacity when the density reaches a limit based on the finite size effect. The capacity drop will become more distinct because a better resolution will cause higher critical flow, whereas the traffic dynamics in the congested state will remain the same. This is referred to as the high-resolution effect. There must be a capacity drop because of the finite-size effect, and the resolution or discretization level determines the outstanding extent of the capacity drop. Thus, a stabilization effect is defined as a combination of the finite-size effect and the high-resolution effect.

In Fig. 2, the upper branch denotes a 1-h average flow when it starts from a homogeneous initial condition (vehicles are uniformly located on the road with the same average gap, and all are travelling at maximum speed before the first time step). On the other hand, the lower branch denotes a compact super jam as the initial condition (vehicles on the road are closely packed without gaps, and all have zero speeds before the first time step) with the same global density as the upper branch. There are two methods to increase or reduce density. One is to add vehicles to the already homogeneous or jammed traffic, whereas the other is to reset the initial conditions and conduct a new simulation; the latter approach is used in this research. The curves are less stable in this case because vehicles are randomly allocated over the two lanes (with a 50% possibility for each lane) one after the other with a fixed interval for each density. The number of vehicles on each lane may differ at the beginning of the simulation. In this way, a hysteresis loop can be traced (indicated by arrows in Fig. 2), and a meta-stable state is reached.

The time–space plots shown in Figs. 3 and 4 indicate the positions of all vehicles on the roadway. The braking probability causes unstable phantom jams in traffic with no micro-cars and with a 50% micro-car rate at a density of approximately 36 veh/km/lane. The lifetime of these jams is irregular. For this traffic, with a density slightly higher than the critical density, the jams may dissipate within a short time, propagate upstream, or reappear downstream after a brief disappearance. The comparison shown in Fig. 3 between the 0% micro-car traffic and 50% micro-car traffic demonstrates that the 50% micro-car case results in several small short-lived fluctuations instead of the bigger and longer-lived jams that develop in the 0% micro-car case. This result demonstrates that the introduction of micro-cars can reduce congestion even if the maximum speed is only approximately 60 km/h. Because of the lane-changing behavior, the locations of jams in the two lanes are slightly staggered.

Figure 5 shows the relationship between average speed and density. In free flow, the average speed reduces significantly with the introduction of micro-cars in the system because of their lower speed. The average speed decreases sharply when the density increases from 21 to 28 veh/km/lane, which is also the density state at which the capacity drop occurs (discussed in the previous section). At densities higher than 28 veh/km/lane, the average traffic speed without micro-cars is lower than that of traffic with micro-cars. This means that for a given number of vehicles in the system (i.e., if the density is the same), traffic with micro-cars will be less congested than that without micro-cars. There are two possible explanations for the sharp decrease in the average speed without any micro-car traffic. One is the braking probability, which can cause jams at any density. These jams can dissipate quickly if the density is sufficiently low. However, jams will persist if the density is above critical. The other explanation is that if the density is higher than the critical density, then the vehicles do not have sufficient space to reach their desired speed. These observations establish that the critical influencing factor on average speed is space. The combination of these two effects causes a sharp reduction in the average speed; it also explains the capacity drop as described above.

In comparing Figs. 3c and 3d with Figs. 4a and 4b, it can be observed that with 100 vehicles on the highway, the jams are considerably bigger and longer than when there are only 50 vehicles. Small jams are also observed in Figs. 4a and 4b because of the braking probability, whereas big jams result from the combined effect of brake probability and high density. Cyclic jams can be traced in Figs. 4c and 4d; they are ascribed to the periodicity of traffic lights. In addition, it can also be observed that intersection delays exacerbate blockages on the arterial road. Figure 6 demonstrates that the average speed of traffic with micro-cars on the arterial road remains the same or becomes higher than that without micro-cars. The more the number of micro-cars introduced, the higher the average speed becomes. This is because micro-cars have the same speed limits as conventional vehicles. Moreover, micro-cars have smaller sizes, giving vehicles more space to drive.

5 Safety Analysis

5.1 Sensitivity analysis for brake probability and lane-changing probability

A causal relationship exists between the assumed braking probability, the lane-changing probability in the model and lane-changing frequency, the number of decelerations, and the coefficient of speed variation. Moreover, the sensitivity of simulation results to the two parameters affects the results of the study. Because the flow results of several combination settings of the two parameters are not representative of reality, the results of the combination of brake probability (0.2, 0.25, and 0.3) and lane-changing probability (05, 0.6, 0.7, 0.8, and 0.9) when the micro-car proportion equals 20% are shown. The lane-changing frequencies are shown in Figs. 7 and 8 for the highway and arterial road, respectively. The number of decelerations and coefficient of speed variation when the proportion of micro-cars is 20% are shown in Appendix A. The frequency of lane changes, number of decelerations, as well as the coefficient of speed variation demonstrate similar trends on the highway as well as on the arterial road (Figs. 9, 11, 12, 13, and 14); however, this trend differs from the frequency of lane changes for lower density traffic flow on the highway (Fig. 9).

In a state of congested traffic (with densities from approximately 35 to 120 veh/km/lane), higher probabilities of braking and lane-changing result in an increased frequency of lane-changing with some disturbances because of the stochastic system on both highway and arterial road. For a lower traffic density on a highway, it is difficult to establish a unique trend; this is also because of the stochastic system. The curves display more fluctuations when the brake probability is 0.3; again, this demonstrates the causal standpoint of the stochastic system. Another reason for the frequent lane changes in light traffic flow is that the road can offer more combinations of space for vehicles with high speeds to make their decisions pertaining to lane-changing on the highway. However, in the case of low traffic density, the number of lane changes on the arterial road is not significantly affected by the two parameters; instead, it is affected by the traffic signal. The traffic signal creates a distinct demarcation; it separates the flow in a stated time period, aggregates vehicles in one side, and leaves a broad space without any vehicle in another side. It makes lane-changing difficult with the limited availability of an appropriate space combination.

On the number of decelerations, the difference among the cases with various lane-changing probabilities is extremely small that the difference between the highway and arterial road figures is practically unrecognizable. It demonstrates that the lane-changing behavior would not result in a forced deceleration by the following vehicle on the target lane. If the lane-changing behavior would cause forced deceleration, the number of decelerations should increase following the increase in the lane-changing probability. On the contrary, the higher brake probability yields a reasonably small number of decelerations.

The lane-changing probability has an insignificant effect on the coefficient of speed variation on both highway and arterial road. The higher probability of braking results in a considerably higher coefficient of speed variation on the highway. The brake probability has a minimal effect on the arterial road when compared with the effect of traffic signal; the situation slightly changes in case of heavy traffic congestion on the arterial road. However, the coefficient of speed variation increases twofold following the increase in traffic density. The increase rate of the coefficient of speed variation following the increase in traffic density is lower for the 0.2 brake probability than for the other two higher brake probability values.

In conclusion, the lane-changing frequency is sensitive to both the brake probability and lane-changing probability on both the highway and arterial road in case of congested flow. It is somewhat sensitive to the brake probability on the highway in low-density flow; however, it is not affected by the two parameters on the arterial road in case of low-density traffic flow because of the presence of the traffic signal. The frequency of decelerations and the coefficient of speed variation are slightly sensitive to the brake probability, but not to the lane-changing probability on both the highway and arterial road.

The sensitivity to the frequency of lane-changing, number of decelerations, and coefficient of speed variation reacting to brake probability and lane-changing probability are mostly linear, and the trends exhibited by the curves demonstrate slight changes on account of the two tested parameters. Hence, it is acceptable to choose one combination of the two parameters among the tested combinations for the micro-car rate sensitivity analysis.

5.2 Frequency of lane changes

In Fig. 9, it can be observed that all curves that depict the frequency of lane changes against vehicle density for all proportions of micro-cars on the highway have an "S" shape. The frequency increases from 0 to a certain value with an increase in density of up to 7 veh/km/lane when the proportion of micro-cars is 40–80%, up to 14 veh/km/lane when the proportion is 0–20%, and up to 21 veh/km/lane when the proportion is 100%. Thereafter, the frequency decreases until a density of 28 veh/km/lane is reached (except for the case when there are no micro-cars, in which case this density is 21 veh/km/lane). Subsequently, the frequency values increase again until the density reaches 90 veh/km/lane, followed by a second fall when the maximum density is reached. These S-curves converge when the traffic density ranges from 60 to 90 veh/km/lane. As the maximum number of lane changes occurs in the state of congestion and traffic with more micro-cars results in higher values of lane-change frequency, at this point, especially, there must be a state of transition for cases with a higher proportion of micro-cars where the changeover from fewer to more lane changes occurs. This transition range is from 30 to 90 veh/km/lane.

If focus is set on the number of lane changes based on different proportions of micro-cars, it can be observed that the introduction of micro-cars into traffic flow results in instability as the density ranges between 0 and the maximum value. The free-flowing traffic with no micro-cars exhibits the lowest number of lane changes, whereas in traffic with micro-cars, greater proportions of micro-cars result in fewer lane changes. In the case of a traffic density of 7 veh/km/lane, the number of lane changes ranges from 0.04 to 0.56/veh/km. This is a wide range because vehicles have ample space to change lanes, and several conventional cars are inclined to change lanes to attain higher speeds because micro-cars may hinder speeding. Lane-changing at a high speed is a risky scenario. On the other hand, for micro-cars, it is not necessary to change lanes frequently because they can reach their desired speeds in a traffic of such density. The number of lane changes is particularly high when there are 20%–60% of micro-cars in the traffic. It can be observed that lane-changing is more common among conventional vehicles than among micro-cars in a free flow; it is a phenomenon that continues as density increases until it reaches 50 veh/km/lane.

On the contrary, a higher proportion of micro-cars results in more lane-changing when the traffic density is more than 90 veh/km/lane, and the 60%–100% micro-car curves have small fluctuations; meanwhile, the traffic without micro-cars again results in the fewest lane changes. This arises because greater proportions of micro-cars leave more space on the road and provide better opportunities for lane-changing than in traffic with fewer micro-cars; that is, traffic conditions are worse with fewer micro-cars than with more of these vehicles. If conventional vehicles were to be replaced by micro-cars, then the static state for the no-micro-car case would have an approximately half-empty lattice because the length of one conventional vehicle is approximately twice that of a micro-car. Thus, there are more lane changes when micro-cars are present, whereas there is no traffic flow (and no lane-changing) when there are no micro-cars at densities higher than 143 veh/km/lane. The maximum number of lane changes (approximately 1.02/veh/km) arises when there is an 80% micro-car proportion and 90 veh/km/lane.

Another phenomenon that has caught interest is that the number of lane changes of micro-cars is considerably higher than that of conventional vehicles when the density ranges from 80 to 143 veh/km/lane. This is because in congested traffic as a result of their shorter lengths, micro-cars are able to change lanes, whereas conventional vehicles, under certain conditions, cannot.

The decision on whether or not to change lanes is based on three vertical gaps defined among the vehicles in the model. Consider the example in Fig. 10. Assume that vehicle 1 is contemplating to change lanes. To reach a decision, gap 1 between it and the vehicle in front of it (vehicle 2), gap 2 between it and the vehicle in front on the other lane (vehicle 3), and gap 3 between it and the following vehicle in the other lane (vehicle 4) must all be determined. Gaps 1 and 2 are both independent of the type of vehicle 1, whereas gap 3 is dependent because it is between the front of vehicle 1 and the front of vehicle 4 minus the length of vehicle 1. Thus, if vehicle 1 is a micro-car, gap 3 would be longer than if it was a conventional vehicle; consequently, the chance of satisfying the third lane-changing condition in our model is greater. This explains why micro-cars change lanes more frequently than conventional vehicles do under the same conditions of congestion in this example. However, it might be a limitation of the model; accordingly, a similar gap 3 is necessary for both conventional cars and micro-cars in the event of a lane change.

To summarize the highway results, when traffic density ranges from 30 to 90 veh/km/lane, the introduction of micro-cars results in lesser lane change frequency compared with those in other ranges of vehicle density. In traffic without micro-cars, minimal lane-changing instances are exhibited practically throughout all density ranges of traffic. At lower densities (from 7 to 14 veh/km/lane), these lane changes represent an interaction among vehicles with potentially significant speed differences. These lane changes seem potentially extremely hazardous than those at higher densities because higher collision speeds result in considerably more serious injuries. (Fildes and Lee, 1993; Elvik, 2009) The introduction of micro-cars on highways results in more lane-changing; hence, it has a negative effect on safety.

Figure 11 shows a relationship similar to that in Fig. 9 between density and number of lane changes under different micro-car rates when the density is higher than 50 veh/km/lane, this time for an arterial road. In this case, there is no “S” trend. The number of lane changes rises from a low value in free flow, thereafter drops again as density increases. The mixed free flow traffic does not exhibit considerable lane-changing, possibly because of the presence of traffic signal. Traffic flows that consist only of micro-cars generally exhibit the lowest number of lane changes when traffic density ranges from 0 to 90 veh/km/lane, whereas other curves concentrate around the same values at each density in this range. When the traffic density exceeds 90 veh/km/lane, the number of lane changes is larger in mixed flow than in conventional vehicles only; when the proportion of micro-cars is high, the number of lane changes increases further because there is more space available for lane-changing (as discussed earlier). However, because of the low speed of micro-cars, this has a few safety implications.

In general, a higher micro-car proportion results in fewer lane changes, especially when the density is less than 90 veh/km/lane. It can be concluded that the introduction of micro-cars will not change the frequency of lane changes and may have no impact on the safety on urban roads from the perspective of lane-changing provided that the density is less than 90 veh/km/lane. There may also be no evident effect on safety when the density is more than 90 veh/km/lane because this represents the state of congestion, even though there are more lane changes when the proportion of micro-cars is higher.

5.3 Number of decelerations

The number of deceleration events has a maximum of approximately 430/veh/km when the micro-car proportion is 0% in dense traffic. In Fig. 12, the deceleration count on the highway increases positively with the addition of vehicles except in the no-micro-car traffic being at a density of 143 veh/km/lane (this means that the vehicles are completely stationary because all cells are occupied). When density is greater than 57 veh/km/lane, higher proportions of micro-cars will result in fewer decelerations. The explanation for this is that, with a certain density, the lower the proportion of micro-cars, the lesser the available space on the road; hence, the more congested the traffic becomes, the more decelerations occur.

However, in a free flow on a highway, the number of decelerations in traffic with micro-cars is higher than one without them (Fig. 12b). Both micro-cars and conventional vehicles in mixed traffic exhibit more decelerations per vehicle per kilometer than conventional vehicles do in a purely conventional traffic. In examining the reason for this, first, it should be noted that deceleration results from stochastic braking or limited space (proximity of another vehicle). Because all vehicles have the same stochastic braking probability under all conditions on the highway, the other factors that influence the number of decelerations has to be considered. At low densities, all vehicles can drive at their desired speed; however, in mixed traffic, the desired speed of micro-cars is lower than that of conventional vehicles. That is, they move through a shorter distance over a given time period than conventional vehicles do. For micro-cars, the shorter the distance driven, the greater the number of decelerations per vehicle per kilometer; this is because the number of decelerations per vehicle per kilometer equals the deceleration count divided by the distance travelled by each vehicle. For conventional vehicles, the micro-cars travelling at speeds lower than that desired pose as obstacles, which compel conventional vehicles to decelerate or change lanes to maintain a higher speed. Even when conventional vehicles change lanes, they may be hindered by micro-cars in the new lane; eventually, they have to decelerate. Hence, the more micro-cars present in the system, the higher the probability that conventional vehicles will be hindered. At the same time, the conventional vehicles will have lower average speeds because of their frequent decelerations. Finally, the shorter distances driven by conventional vehicles because of lower speeds and the greater number of decelerations increase their number of decelerations per vehicle per kilometer in mixed traffic.

The curves drawn separately for micro-cars or conventional vehicles are all considerably similar to the curves for all vehicles in the same scenario. The three lines with the same micro-car rate are practically superposed when the density is higher than 50 veh/km/lane. This means that the difference in the number of decelerations between micro-cars and conventional vehicles at higher densities can be ignored. On the other hand, when the density is lower than 50 veh/km/lane, although there may be differences, the three separate curves remain considerably similar. Whether micro-cars or conventional vehicles exhibit more decelerations per vehicle per kilometer depends on whichever controls between the shorter travel distance and the position as an obstacle of micro-cars. When traffic density and micro-car proportion are both low, micro-cars have slightly more decelerations per kilometer than conventional vehicles; in this case, the shorter driving distance controls. When traffic density is low and micro-car proportion is high, conventional vehicles decelerate more frequently per kilometer than micro-cars do; in this case, the micro-car nature as an obstacle controls.

Because vehicle mass and size are significant factors that impact safety, as reviewed in Section 2.3, decelerations are classified into three types: a conventional vehicle decelerates at the rear of another conventional vehicle, a micro-car decelerates at the rear of another micro-car, and one type of vehicle decelerates at the rear of another type of vehicle. These three types of decelerations are calculated per vehicle per kilometer for the analysis of safety. Because the deceleration between micro-cars and conventional vehicles is probably more hazardous, the analysis of this type is analyzed here. The number of decelerations between a conventional vehicle and micro-car or between a micro-car and conventional vehicle (NDCMMC) do not have a linear relationship with the micro-car proportion (Fig. A5). In the congested regime, a lesser NDMCCM follows a higher micro-car proportion. However, in the free flow regime, mixed flow, which has considerably more of one type of vehicle and substantially less of another type of vehicle (micro-car proportions are 20% and 80%) has more NDMCCMs on the highway; on the arterial road, the difference is not evident.

Figure 12 demonstrates that when there are more vehicles on the road, more decelerations occur, whereas the greater number of micro-cars than other vehicles results in fewer decelerations in congested traffic. With two significantly different characteristics, similar trends can be observed in the arterial road: one is that mixed traffic exhibits fewer decelerations per kilometer than traffic without micro-cars for the whole range of vehicle densities and for any micro-car proportion, and the other is that the rising gradient of the curves is less steep than that for the highway. It can be concluded that the number of decelerations for conventional vehicles and micro-cars evolves from similar values at different micro-car proportions to similar values as traffic density rises, especially when congestion begins. That is, more micro-cars may lead to more collisions during free flow on highways, whereas they may reduce crashes on arterial roads and in congested traffic on highways from the perspective of number of decelerations. If vehicle mass and size are considered, drivers and passengers may be more at risk when an accident occurs in a mixed flow with a huge difference between the numbers of the two types of vehicles.

5.4 Coefficient of speed variation

The coefficient of speed variation (C_v) is used to analyze the effect of speed variation on safety. A higher coefficient of speed variation is associated with a greater risk of collisions (Taylor et al., 2000; Boonsiripant et al., 2007; Mattar-Habib et al., 2008). The aforementioned coefficient, C_v, is calculated with the following equation:

$$C_v = SD/V \tag{13}$$

where *SD* is the standard deviation of speed and *V* is the mean speed.

The speed of all vehicles on both the highway and arterial road in each unit time of over 1 h is obtained as a sample; thereafter, C_v is computed for the sample. The highway case results are shown in Fig. 13. The value of C_v remains small when the vehicle density is less than the critical (with a traffic density of less than 21 veh/km/lane in the no-micro-car case and 28 veh/km/lane with micro-cars). It rises rapidly until a density of 50 veh/km/lane is reached; thereafter, it continues to gradually increase until it reaches a density of 114 veh/km/lane. It then grows rapidly up to the maximum traffic density, especially for the no-micro-car case. This is attributed to the sharp decrease in the average speed. All the curves have the same trends as the density increases; for a given density, the values are similar. When the vehicle density is less than 21 veh/km/lane, the traffic without micro-cars exhibits the lowest C_v; this indicates that a mixed-flow that contains micro-cars may be more hazardous than conventional traffic from the perspective of coefficient of speed variation. The reason can be found if the calculation of C_v is checked: the mean speed, *V*, sharply decreases after the introduction of micro-cars (Fig. 5) because the speed limit of micro-cars is considerably lower than that of conventional vehicles (60 and 100 km/h for micro-cars and conventional vehicles, respectively); consequently, this leads to the increase in C_v of free-flow traffic with micro-cars. As the vehicle density increases, a higher proportion of micro-cars results in a lower C_v (ignoring the sharp fall in the non-micro-car curve when the traffic flow is 0);

however, this has an insignificant impact on safety considering that the average speed is low. The situation for the arterial road shown in Fig. 14 is similar except that the superiority of non-micro-car flow is not evident even when the traffic density is less than 21 veh/km/lane, and the curves are more concentrated than those in Fig. 13 for densities ranging from 7 to 90 veh/km/lane. The average speeds of the two types of vehicles (Fig. 15) approximate each other except when the density is less than 14 veh/km/lane on the highway. For the arterial road, the curves are practically identical across the entire range of vehicle densities. The reason for this is that, they cannot reach their maximum when traffic becomes congested although conventional cars have higher maximum speeds than micro-cars. Further, on the arterial road, both conventional cars and micro-cars are unable to travel at their highest speeds even in free flow because of the presence of traffic signals. Figures 13, 14, and 15 demonstrate that free flow traffic with micro-cars has a higher coefficient of speed variation than when there are no micro-cars. Additionally, a higher proportion of micro-cars yield a lower coefficient of speed variation. In stop-and-go and jammed traffic, a lower C_v is associated with more micro-cars. Thus, it can be concluded that the presence of micro-cars may increase the number of crashes in free flow on highways; however, this number may decrease or may have no evident negative safety effect on arterial roads from the perspective of coefficient of speed variation.

6 Environmental Analysis

Vehicle-specific power (VSP) is defined as the instantaneous power per unit mass of a vehicle and is a core parameter of Motor Vehicle Emission Simulator (MOVES) (Koupal et al., 2002). This parameter is considerably useful in emission modeling, analysis of remote sensing data, and analysis of chassis dynamometer data because it captures the dependence of light-duty vehicle emissions on driving conditions; it is directly specified in emissions certification cycles. MOVES provides the HC, CO, and NO_x emission rates in different operating modes (VSP combining speed ranges) and vehicles of different ages. The average vehicle age in the United States is 11.4 years based on a study by a research firm (R.L. Polk and Co.) in 2013; in New Zealand, the averages are 13.35 in 2012 and 13.53 years in 2013 (Environmental Health Indicators New Zealand, 2014). The emission rates (Appendix A) of vehicles aged 10–14 years are obtained to calculate total emissions of the three types of gaseous discharges with respect to time. To simplify calculations, a typical micro-car (the famous Smart Fortwo 2012), weighing 750 kg, is assumed; the hypothetical conventional car used is the Toyota Camry 2012, weighing 1490 kg. The VSP of each vehicle per second is calculated by using the following equations as proposed by Jimenez–Palacios (1999):

$$\mathrm{VSP} = \mathrm{v} \cdot (\mathrm{a} \cdot (1+\varepsilon) + \mathrm{g} \cdot \mathrm{grade} + \mathrm{g} \cdot \mathrm{C_R}) + \frac{1}{2}\rho \frac{C_D \cdot A_F}{m} v^3 \tag{14}$$

where v and a are vehicle speed (in m/s) and acceleration (in m/s^2), respectively; ε (assumed as 0.1) is a mass factor that accounts for rotational masses; g is the gravitational acceleration (9.8 m/s^2); grade is the road gradient in degrees (assumed as 0°); C_R is the rolling resistance of radial tires in the range 0.008–0.013 for a majority of on-road passenger car tires (assumed as 0.013 here); ρ is the ambient air density (1.207 kg/m^3 at 20 °C= 68 °F); C_D is the aerodynamic drag coefficient (assumed as 0.3); A_F is the front area of vehicle (in m^2) calculated by Eq. 15; m is the vehicle mass (in kg).

$$\mathrm{A_F} = (\mathrm{H} - \mathrm{GC}) \cdot \mathrm{W} \cdot 0.93 \tag{15}$$

where H, GC, and W are vehicle height, ground clearance, and width, respectively.

Using the set values for all parameters above, the following expressions are derived for conventional cars (Eq. 16) and for micro-cars (Eq. 17):

$$\mathrm{VSP} = \mathrm{v} \cdot (\mathrm{a} \cdot 1.1 + 0.1275) + 2.735 \cdot 10^{-4} \cdot v^3 \tag{16}$$

$$\mathrm{VSP} = \mathrm{v} \cdot (\mathrm{a} \cdot 1.1 + 0.1275) + 4.987 \cdot 10^{-4} \cdot v^3 \tag{17}$$

The HC emission results on the highway are shown in Fig. 16. All curves have an "S" shape: each curve first increases to a peak, decreases, and then increases again. The HC emission is considerably lower in the no-micro-car case than in all cases with micro-cars when the density is less than 30 veh/km/lane, i.e., in free flow; however, the amount is greater than all other cases when the density ranges from 43 to 71 veh/km/lane. After dropping to a minimum of 100 veh/km/lane, the density rapidly increases up to the maximum. This demonstrates that congestion results in more emissions. In traffic with micro-cars, a higher micro-car proportion generally means lower amounts of emissions, except at densities ranging from 71 to 143 veh/km/lane when all emissions are considerably similar. On the arterial road, the "S" shape remains visible (Fig. 17). The no-micro-car case exhibits more amounts of emissions in all traffic flow phases. The emission amounts of CO are similar to those of HC, except that there is no sharp increase as the peak density is approached. The NO_x emission is more similar to those of CO than HC. It can be concluded that traffic with micro-cars generates more emissions on the highway in free flow, but generates lesser emissions on the arterial road.

7 Conclusions and Future research

In preparation for the expected more extensive use of micro-cars on city roads, we have analyzed the impact of micro-cars on safety and environment. This is an area that has not been previously investigated although other studies have examined the impact of micro-cars on congestion. We opted to use the TCA model as the basis of our analysis. The TCA model adopted is more exhaustive than that of our earlier research (Mu and Yamamoto, 2012); the vehicles were afforded more realistic accelerations and decelerations, as well as more speed choices. The model is sufficiently elaborate such that we are able to obtain the number of lane changes, the number of decelerations, the speed distribution, and the instantaneous power per unit mass (VSP) from the simulations. Using these results, we conducted safety and environmental analyses of the introduction of micro-cars into traffic. Based on the results, the following conclusions are drawn:

(1) In terms of lane-changing as a characteristic of traffic flow associated with safety, traffic consisting exclusively of micro-cars or exclusively of conventional cars usually results in less frequent lane-changing. In mixed flow, the more micro-cars there are in free flow on the highway, the less frequent lane-changing is. In contrast, in congested flow, the presence of more micro-cars results in more frequent lane-changing. Micro-cars might have a negative influence on traffic safety when traffic density is less than 30 veh/km/lane, i.e., in free flow on the highway; however, they do not have any evident influence on the arterial road at those densities. This implies that the use of micro-cars on the highway might be dangerous because of the higher lane-changing frequency.

(2) The number of decelerations can also be considered as a possible index of safety: the more the number of micro-cars on a highway, the fewer the instances of deceleration. This is especially the case when the traffic density is more than 57 veh/km/lane. However, the presence of more micro-cars in free flow on the highway results in more decelerations. Mixed flow, in which vehicles significantly vary in size or mass, may have more severe damage risk after accidents; as the difference between the proportions of the aforementioned vehicles increases, the greater the risk. The introduction of micro-cars does not lead to more decelerations in both free flow and congested traffic on arterial roads. The deceleration for every proportion of micro-cars is approximately the same when the traffic density is lower than 57 veh/km/lane on both highway and arterial road. Considering the number of decelerations as a possible index of safety, it is demonstrated that micro-cars do not introduce any hazards to arterial road traffic, but pose as hazards in free flow traffic on a highway.

(3) Considering speed variation as another characteristic of traffic flow associated with safety, the coefficient of speed variation becomes smaller as the proportion of micro-cars increases (both on highways and arterial roads). This is particularly true when there are more than 28 veh/km/lane; this distinction is clearer on highways. However, traffic with no micro-cars exhibits the lowest C_v in free flow; this indicates that there might be a safety disadvantage in using micro-cars on the highway.

(4) The analysis of emissions based on the VSP shows that the introduction of micro-cars will result in more HC, NO, and NO_x emissions under free flow conditions on the highway, but fewer emissions in other cases. Thus, the use of micro-cars on the highway is also shown to be disadvantageous from an emission point-of-view. In contrast, the introduction of micro-cars results in a positive effect on arterial roads with respect to emissions.

Briefly, mixed flows of conventional cars and micro-cars on the highway might result in a negative effect on safety based on the number of lane changes, number of decelerations, and coefficient of variation of speed in free flow. On the other hand, a higher proportion of micro-cars might be safer than a lower micro-car proportion on both highways and arterial roads. Moreover, micro-cars might have a positive effect or no negative influence on safety in arterial roads if it is evaluated by analyzing the changes in the three characteristics of traffic flow that have been shown to be associated with safety. If only accident severity is considered, the risk of severe damage may be significantly higher with the introduction of micro-cars in free flow where the average speeds are high; consequently, micro-cars may suffer more considerable damage because of their small size and lighter mass. On the contrary, the risk in congested flow may only change slightly because vehicle speeds are low. The introduction of micro-cars has an evident positive influence on the environment in terms of HC, CO, and NO_x emissions on arterial roads, but a negative effect on highways in free flow.

This study is the first attempt to analyze the effects of micro-cars on certain traffic flow characteristics, particularly with regard to safety and emissions. The results are highly dependent on the specific assumptions introduced in the simulation framework in Chapter 3, and some of them might be considered controversial;

therefore, the results should be evaluated accordingly. Several traffic flow characteristics that have been shown to be associated with safety have been analyzed as a function of the proportion of micro-cars in the traffic stream. However, there are several other potential factors that can influence safety; one such factor is the size differential of vehicles that may result in increased accident rates or increased accident severity. Micro-cars may have higher (or lower) accident rates because roads are designed primarily for conventional vehicles; such a design can influence factors that are related to safety, such as the driver's eye level. The foregoing is a limitation of this research, and more aspects related to traffic safety could be explored in future research. The TCA model can be refined by establishing more detailed rules that more realistically simulate actual traffic flow; these rules can include different lane-changing rules for free and congested flows, different lane-changing rules for flow while entering and leaving the intersection, and step-by-step deceleration of vehicles for stopping in front of a red light. Moreover, the use of some other minute simulation models, such as the car following model, can be attempted; thereafter, the simulation results of two models can be compared. Furthermore, considering that this study only analyzed one road segment, an investigation of network-wide effects would be an appropriate focus of future research.

Acknowledgements

This research was supported by the Environment Research and Technology Development Fund (E-1003) of the Ministry of the Environment, Japan. The authors appreciate the assistance and suggestions of Prof. Takayuki Morikawa of the Institute of Innovation for Future Society, Nagoya University. The authors express their gratitude to the anonymous reviewers for their valuable comments and suggestions to improve the quality of the paper.

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Appendix A. Sensitivity analysis of brake probability and lane-changing probability on the number of decelerations and speed variations

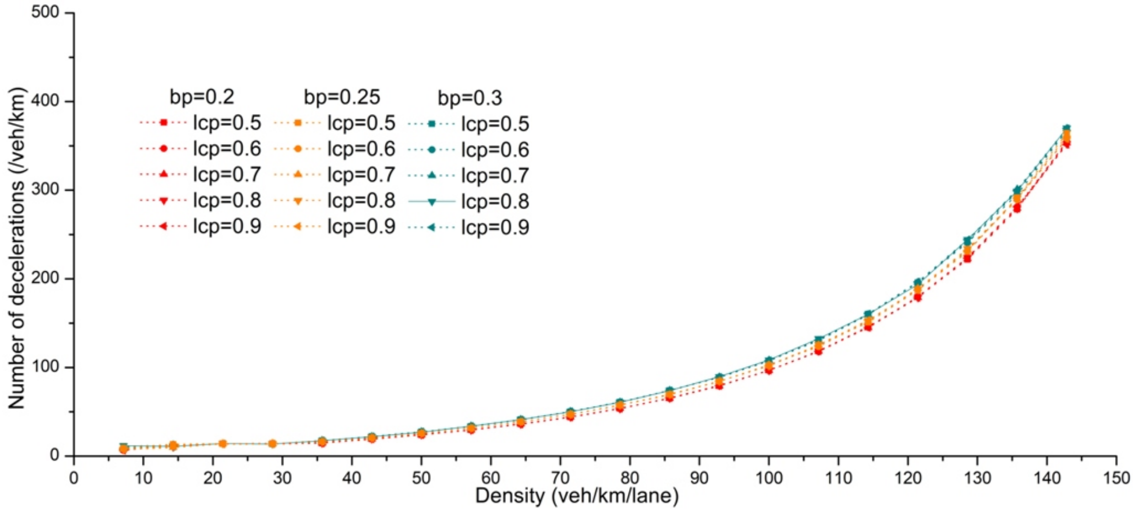


Fig. A1. Number of decelerations by density, brake probability, and lane-changing probability when the proportion of micro-cars on the highway is 20%

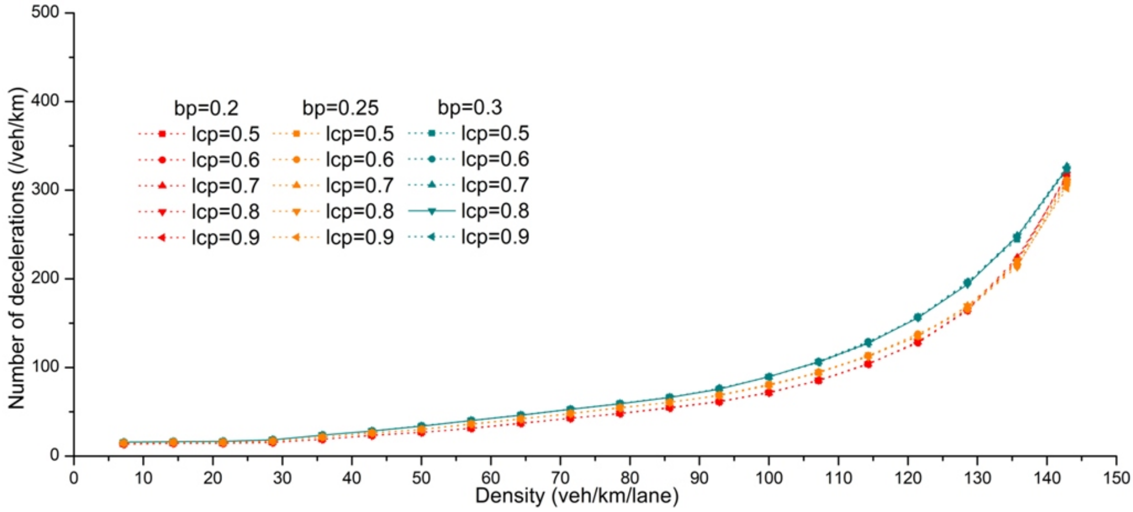


Fig. A2 Number of decelerations by density, brake probability, and lane-changing probability when the proportion of micro-cars on the arterial road is 20%

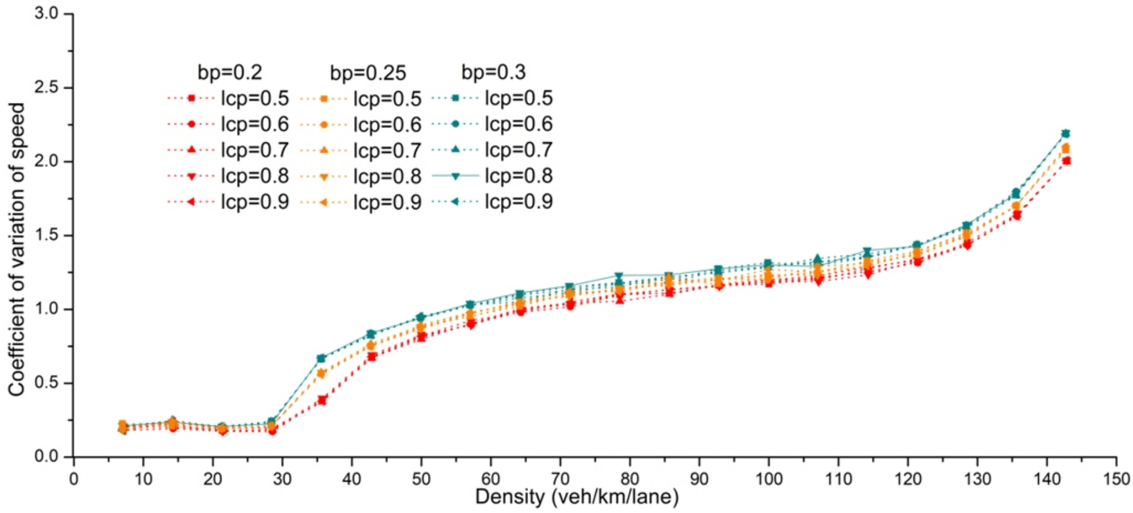


Fig. A3 Coefficient of speed variation by density, brake probability, and lane-changing probability when the proportion of micro-cars on the highway is 20%

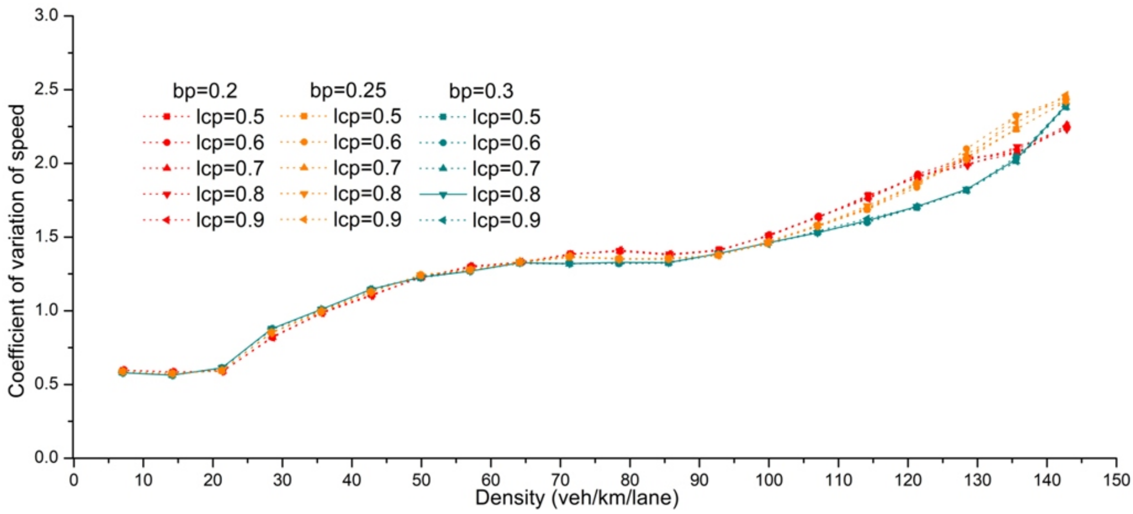
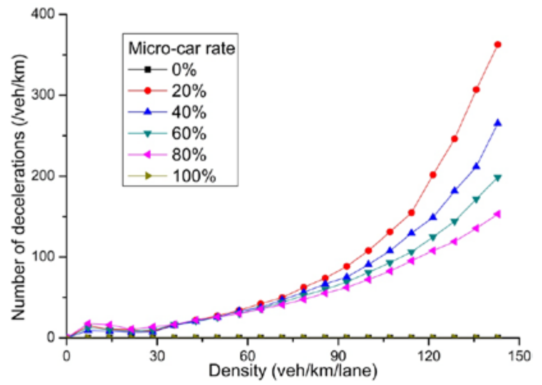
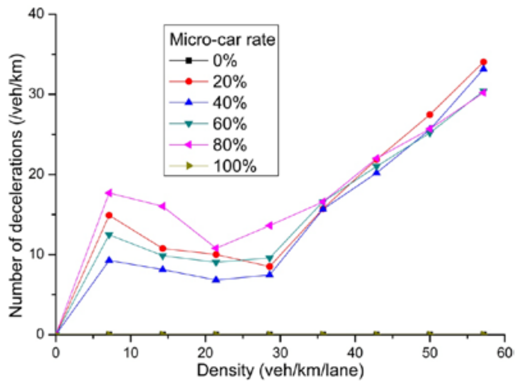


Fig. A4 Coefficient of speed variation by density, brake probability, and lane-changing probability when the proportion of micro-cars on the arterial road is 20%



a) For densities from 0 to 143 veh/km/lane



b) For densities from 0 to 57 veh/km/lane for a clear demonstration

Fig. A5 Number of decelerations per vehicle per kilometer by density and micro-car rate, for conventional vehicle and micro-car or micro-car and conventional vehicle combination on highway

Appendix B. Operating mode and emission rates used in MOVES

Table B1 Operating mode table for MOVES (opModeID is the ID of operating mode defined in MOVES; e.g., opModeID12 corresponds to a VSP higher than 0 kW/t and lower than 3 kW/t and to a speed higher than 1 m/h and lower than 25 m/h; brakeRate3Sec means the acceleration in 3 s)

opModeID	VSPLower (kW/t)	VSPUpper	speedLower (m/h)	speedUpper	brakeRate1Sec (m/s^2)	brakeRate3Sec
0				1	−2	−1
1			−1	25		
11		0	1	25		
12	0	3	1	25		
13	3	6	1	25		
14	6	9	1	25		
15	9	12	1	25		
16	12		1	50		
21		0	25	50		
22	0	3	25	50		
23	3	6	25	50		

24	6	9	25	50		
25	9	12	25	50		
27	12	18	25	50		
28	18	24	25	50		
29	24	30	25	50		
30	30		25	50		
33		6	50			
35	6	12	50			
37	12	18	50			
38	18	24	50			
39	24	30	50			
40	30		50			

Table B2 Emission rates of HC, CO, and NO_x for each operating mode

opModeID	HC (g/h)	CO (g/h)	NO_x (g/h)
0	0.484446	9.2158	0.222823
1	0.117507	1.59115	0.094427
11	0.330409	31.6836	0.330385
12	0.253183	51.726	0.504378
13	0.478528	47.6904	1.18074
14	0.650919	68.4272	2.08459
15	0.90743	99.2254	3.69458
16	1.44949	167.425	7.7051
21	0.494589	41.2956	0.65336
22	0.454222	54.7143	1.06122
23	0.489698	70.3645	1.60433
24	0.934452	102.86	2.70398
25	0.930953	116.737	3.79215
27	1.47119	175.313	5.97117
28	9.93093	364.087	21.9762
29	17.6316	771.078	38.5844
30	29.1088	2708.19	50.7629
33	0.47511	31.0054	1.39253
35	0.659775	52.9424	3.8415
37	0.845444	77.9303	5.36807
38	6.70603	333.71	18.6602
39	9.73741	352.118	27.7778
40	12.7312	1034.86	34.9857

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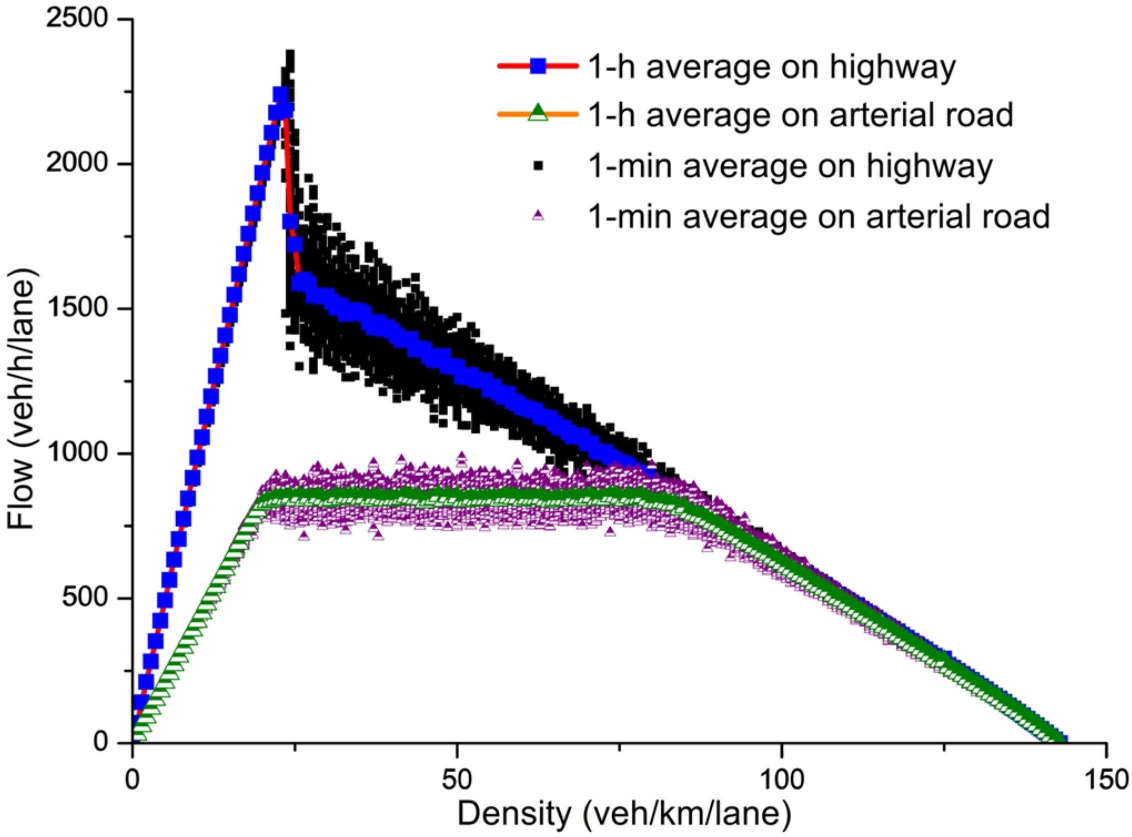


Fig. 1 Fundamental flow-density diagrams without micro-cars on highway and arterial road. Black squares and purple triangles are short-term averages taken over 60 simulation steps and thus mimic the 1-min averages on highway and arterial road, respectively. Blue squares linked with red lines and green triangles are the 1-h averages on highway and arterial road, respectively.

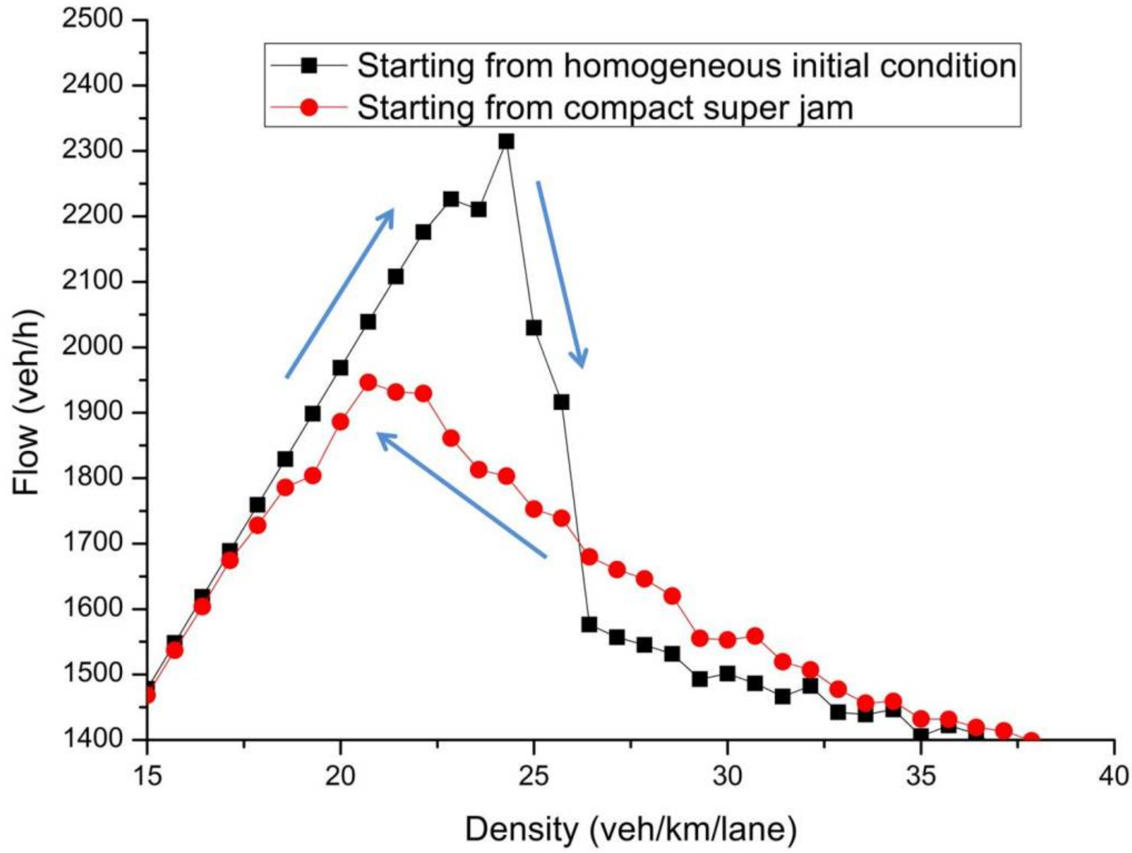


Fig. 2 Branched fundamental diagram for no lane-changing case without micro-car on highway

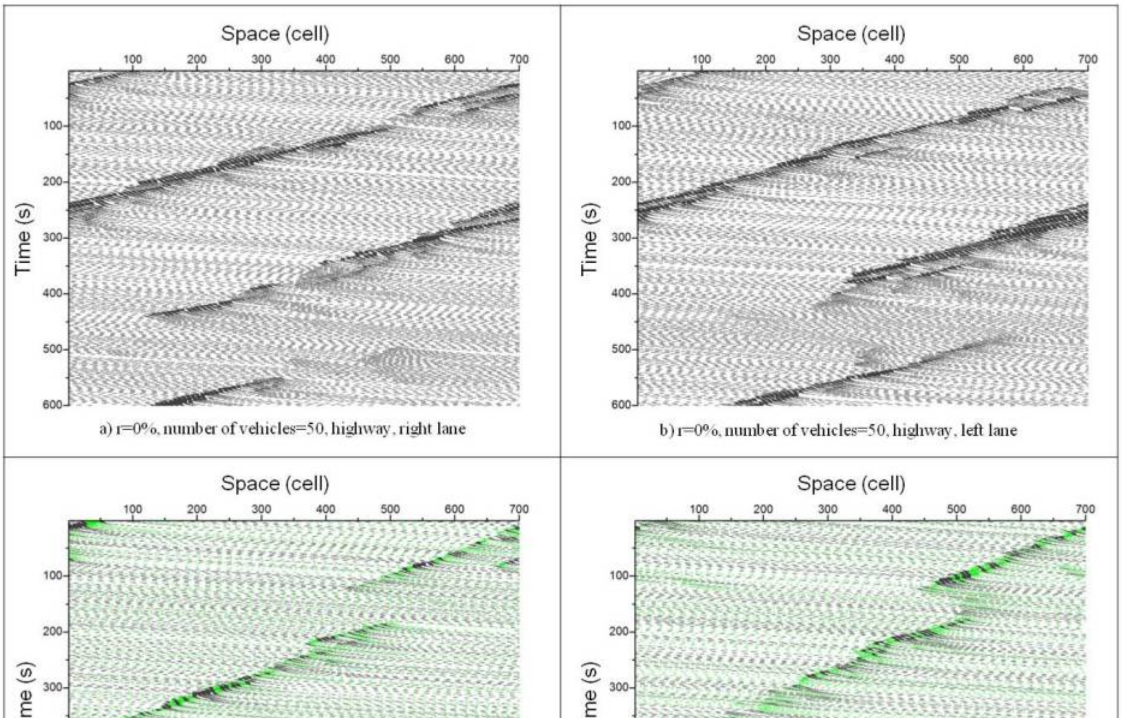


Fig. 3 Time-space plots for 50 vehicles on highway (50 vehicles on the two lane 700-m road; in the standard density unit, this is equivalent to 50×1000/700/2 = approximately 36 veh/km/lane). Cells occupied by a conventional car are represented by dark gray dots, whereas micro-cars are represented by green dots. Each illustrated lattice shows 700 1-m horizontal cells and the final 600 simulated time steps (s) in the vertical direction. Vehicles are driven from left to right and increasing time is downward.

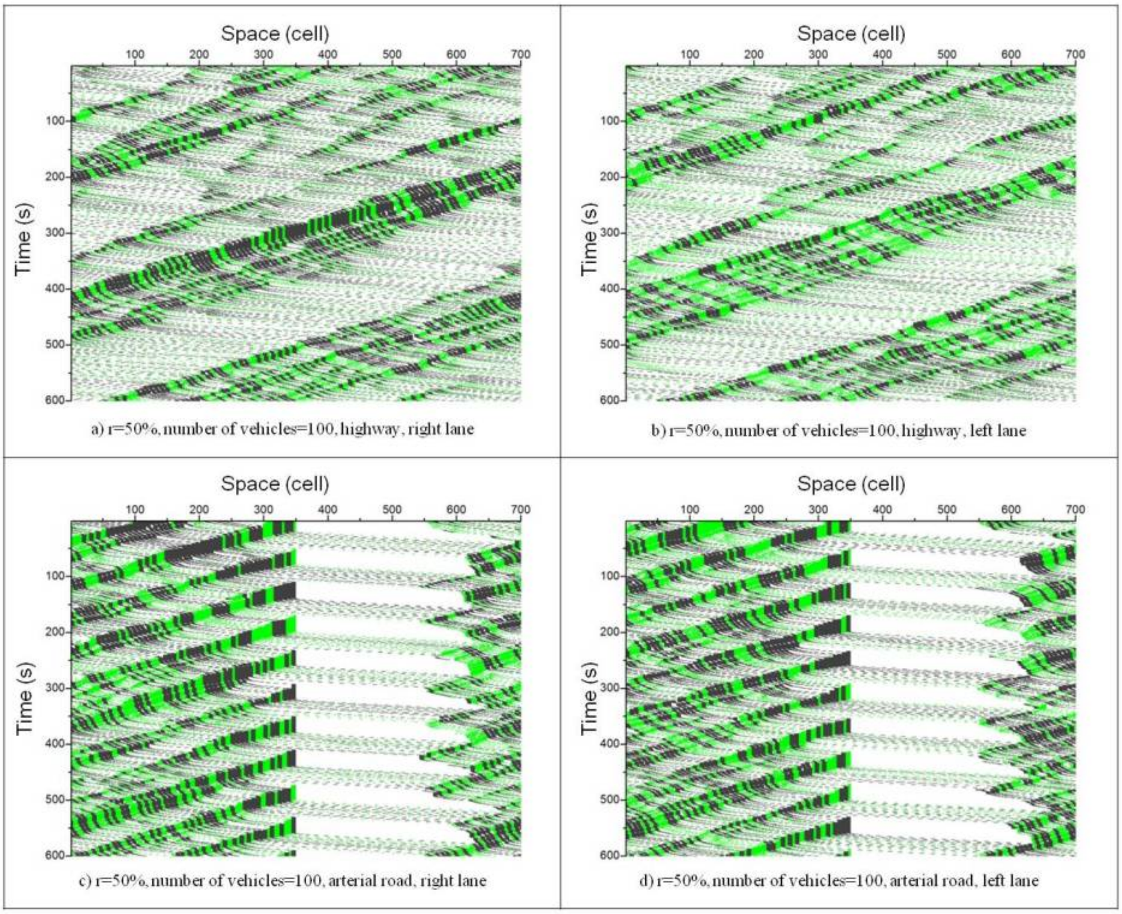


Fig. 4 Time-space plots for 100 vehicles with a 50% micro-car rate

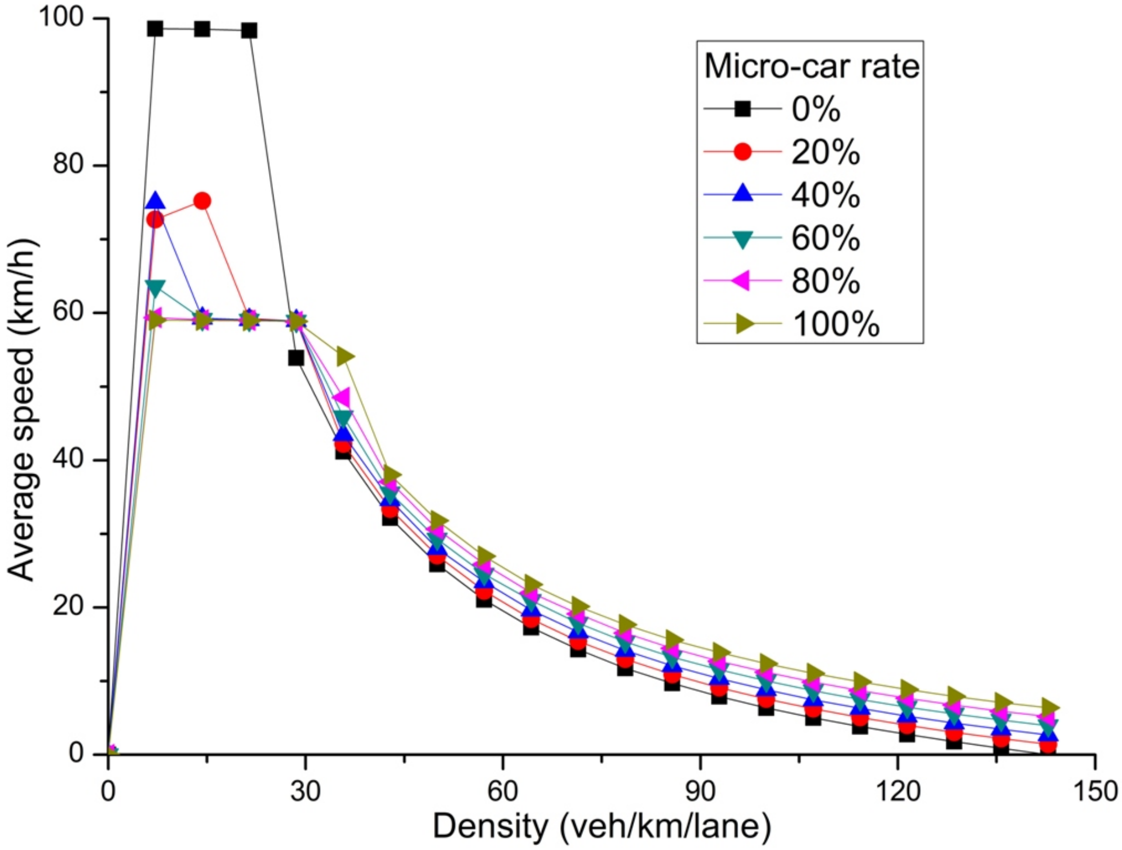


Fig. 5 Average speed–density fundamental diagrams by micro-car rate on highway

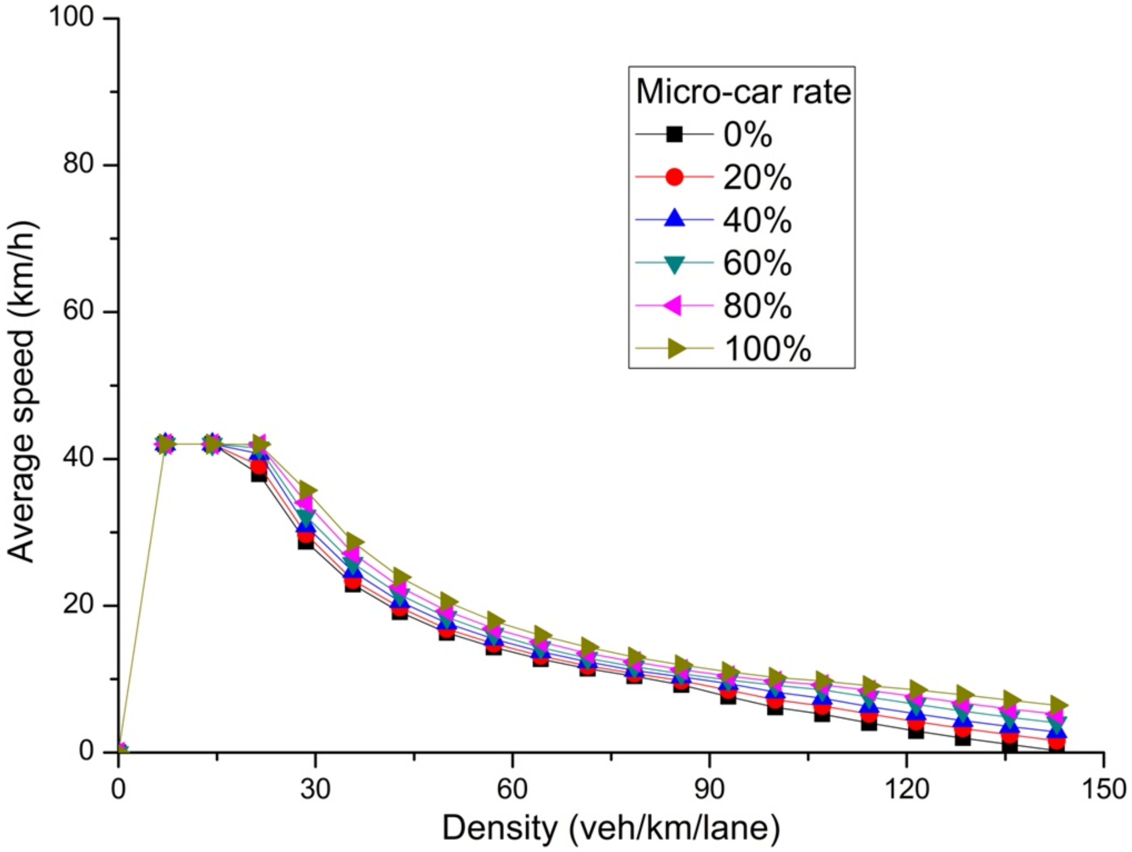


Fig. 6 Average speed–density fundamental diagrams by micro-car rate on arterial road

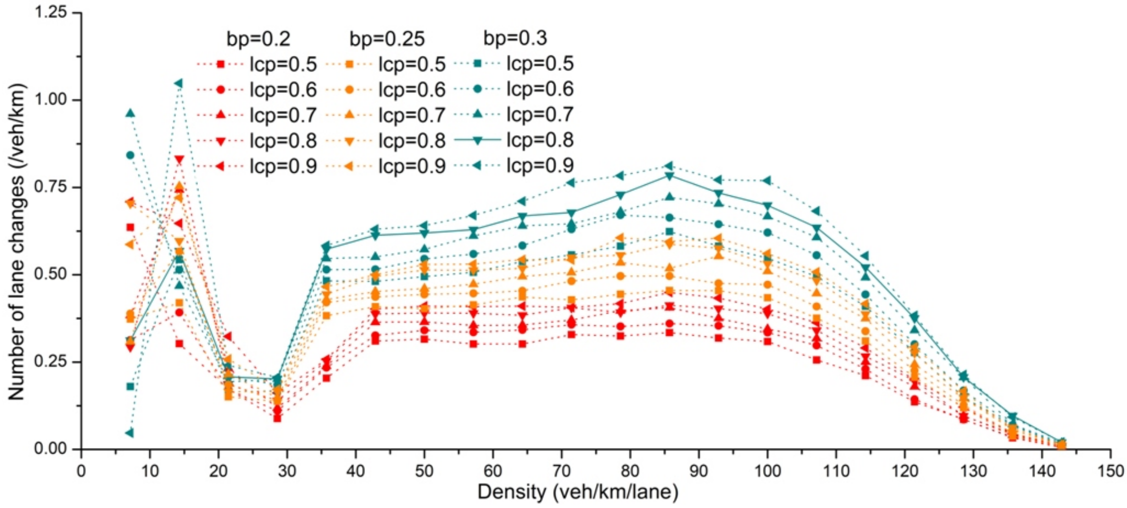


Fig. 7 Number of lane changes per vehicle per kilometer by density, brake probability, and lane-changing probability when the proportion of micro-cars on the highway is 20% (three sets of data with lane-changing probabilities of 0.5, 0.6, 0.7, 0.8, and 0.9; brake probabilities are 0.2 (red solid line and symbol), 0.25 (orange dash line and symbol), and 0.3 (dark cyan dot line and symbol); bp denotes the brake probability, and lcp denotes lane-changing probability)

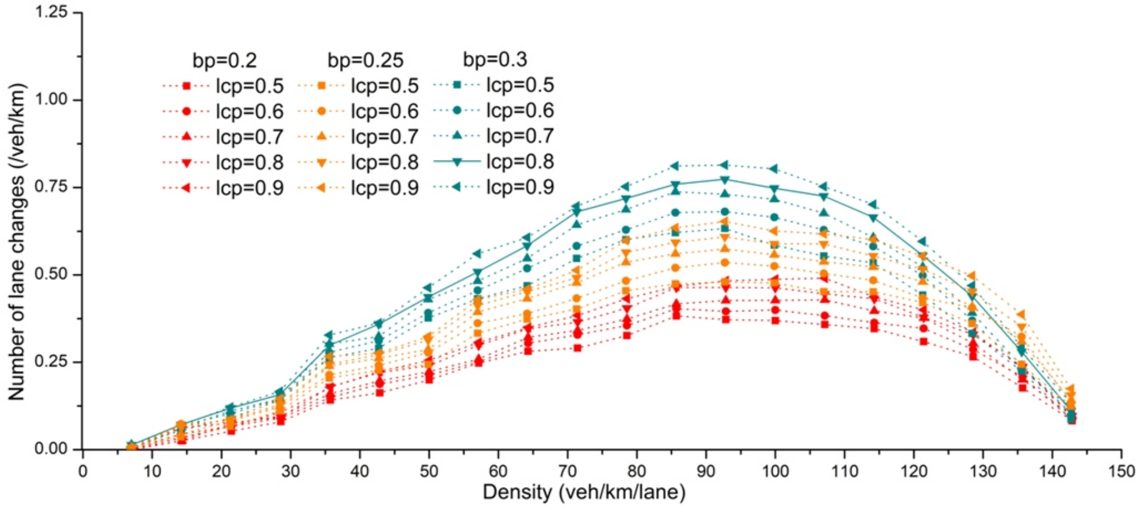


Fig. 8 Number of lane changes per vehicle per kilometer by density, brake probability, and lane-changing probability when the proportion of micro-cars on the arterial road is 20%

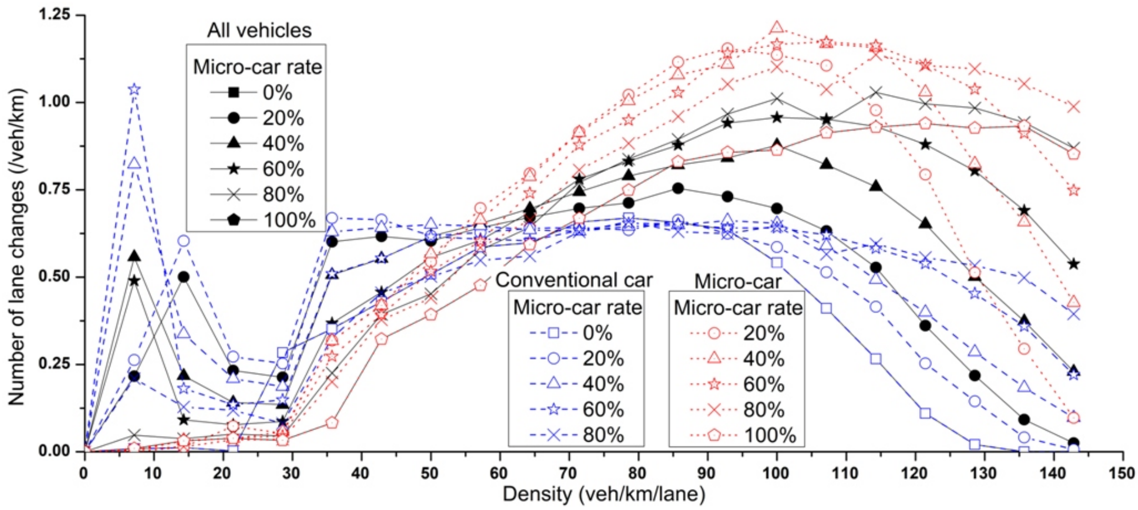


Fig. 9 Number of lane changes per vehicle per kilometer by density, vehicle type, and micro-car rate on highway (three sets of data for each micro-car rate are shown: all vehicles (black line and symbol), only micro-cars (red

line and symbol), and only conventional vehicles (blue line and symbol). Traffic will be stationary if there are 200 vehicles in a fully conventional vehicle traffic (equivalent to a density of approximately 143 veh/km/lane). Thus, the maximum density in traffic for all cases is set as 143 veh/km/lane for better comparison. The maximum density can rise to 250 veh/km/lane when only a micro-car traffic flow is present).

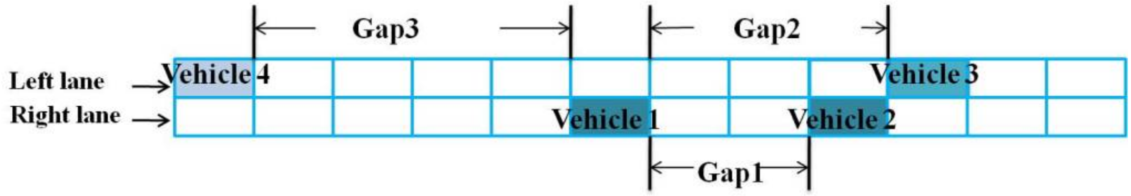


Fig. 10 Example of lane-changing situation

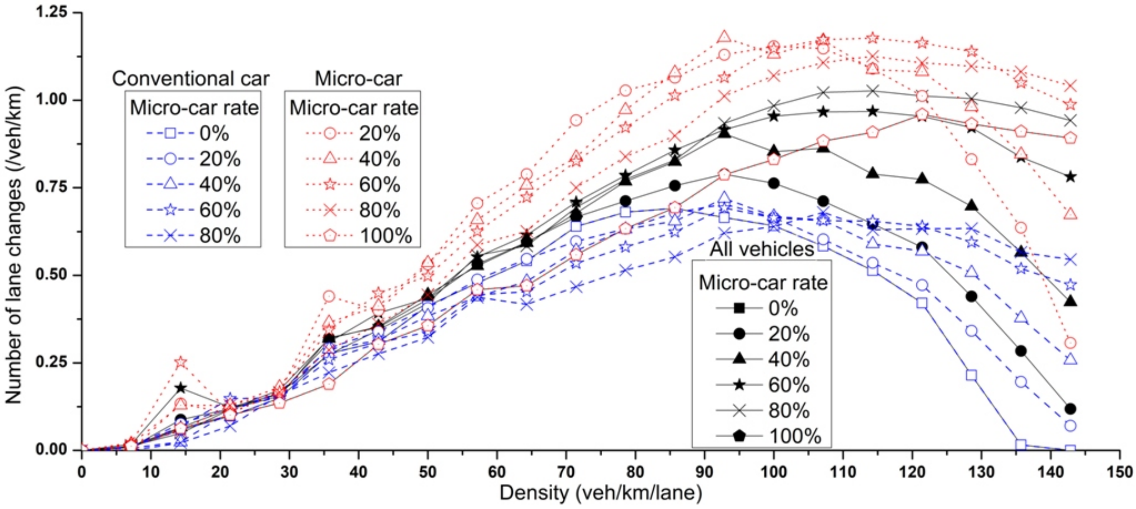
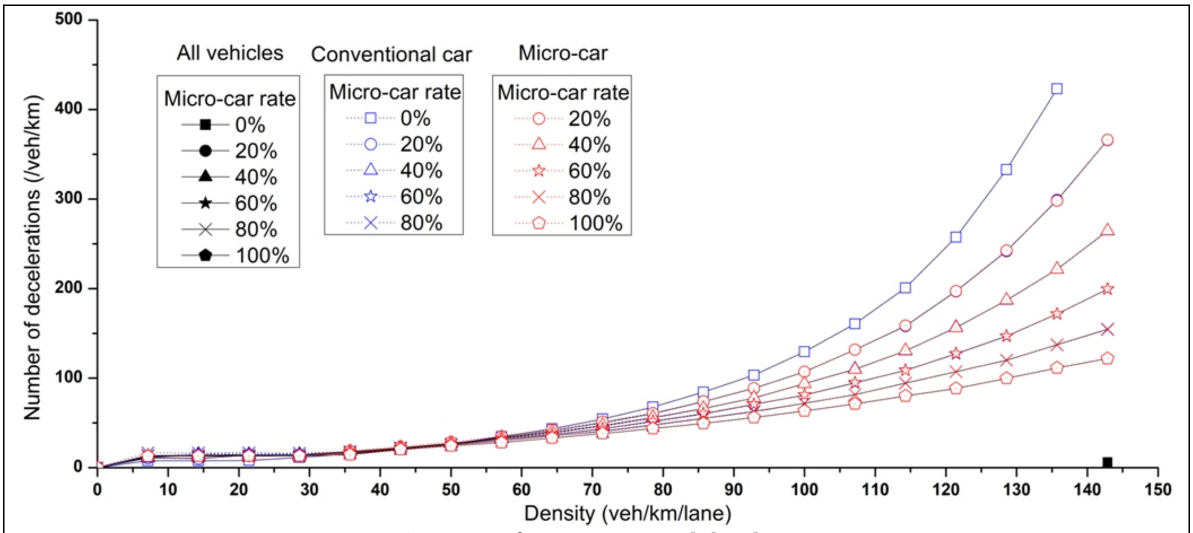
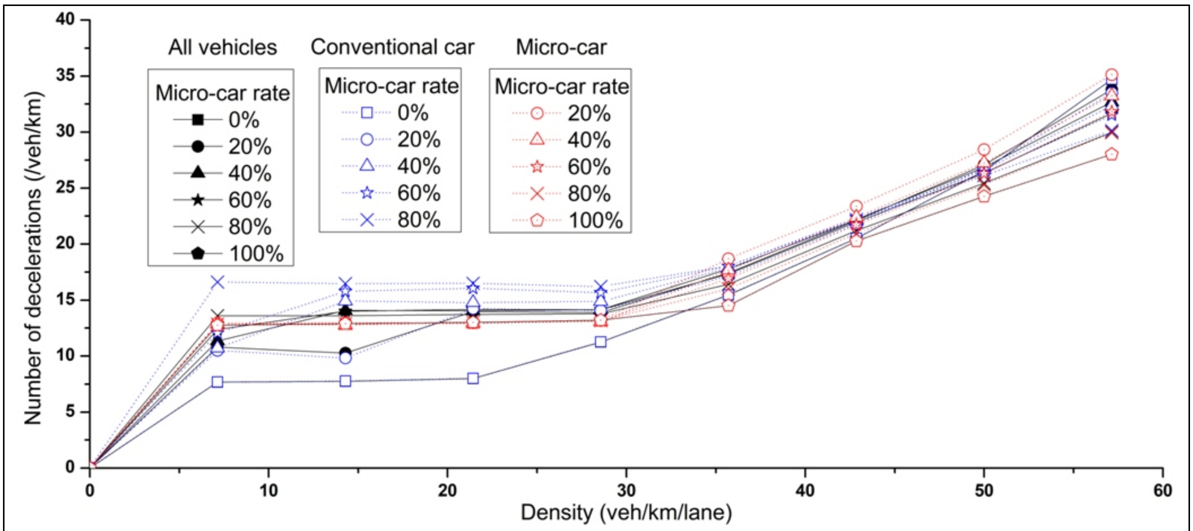


Fig. 11 Number of lane changes per vehicle per kilometer by density, vehicle type, and micro-car rate on arterial road



a) Density from 0 to 143 veh/km/lane



b) Density from 0 to 57 veh/km/lane for a clear demonstration

Fig. 12 Number of decelerations per vehicle per kilometer by density, vehicle type, and micro-car rate on highway

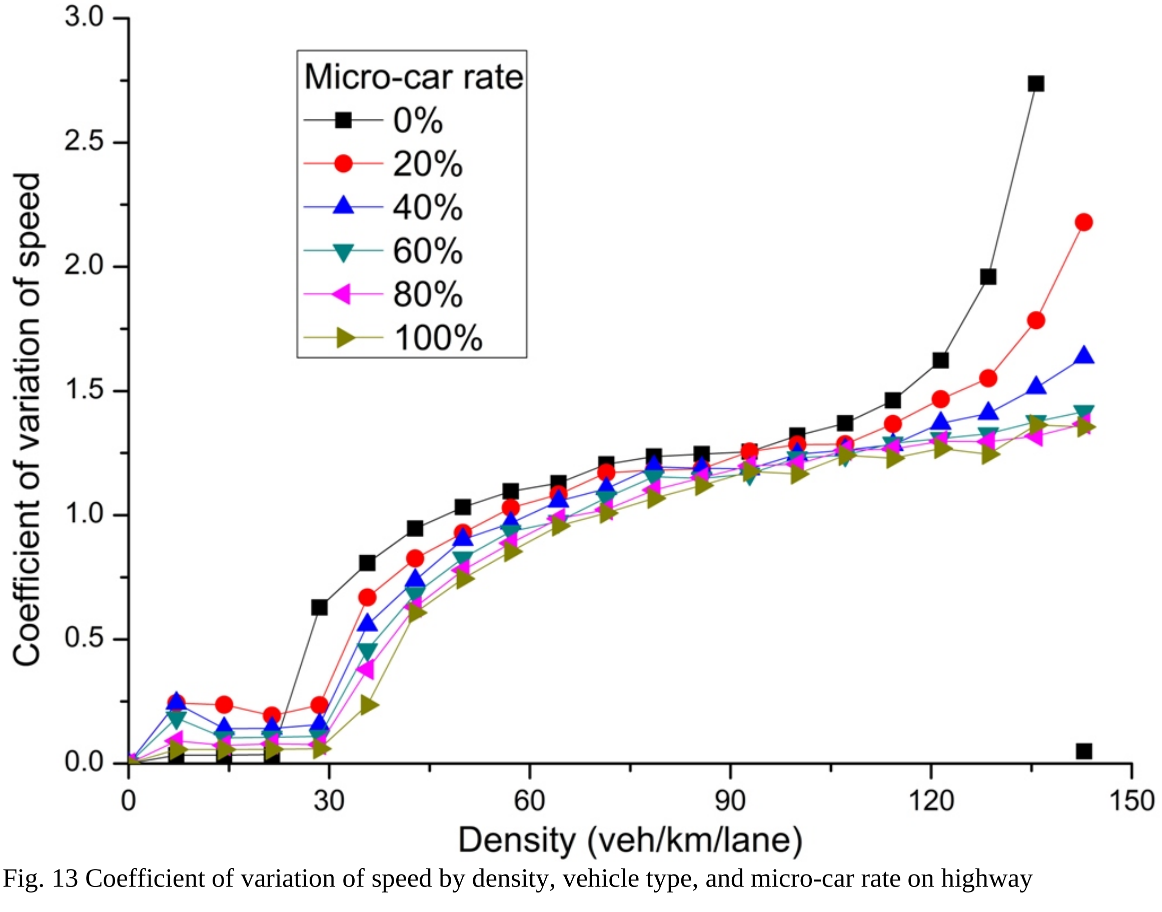


Fig. 13 Coefficient of variation of speed by density, vehicle type, and micro-car rate on highway

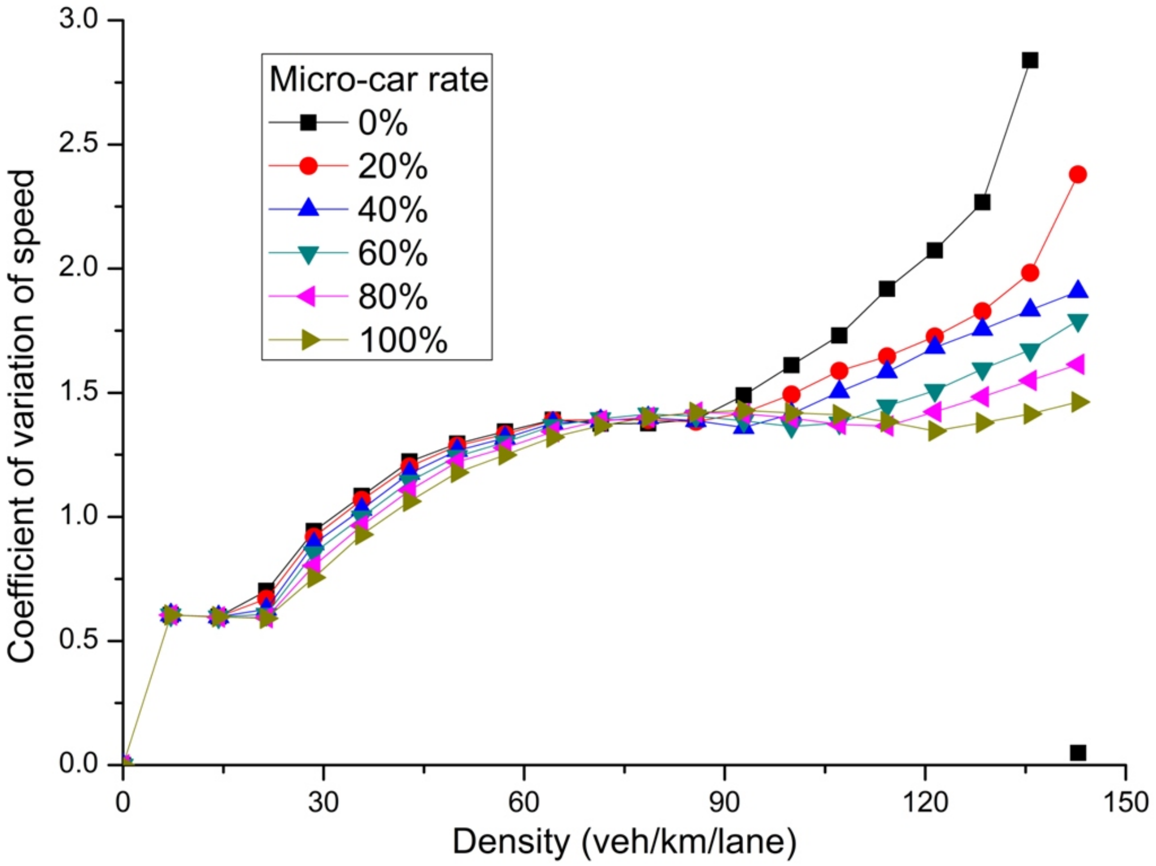
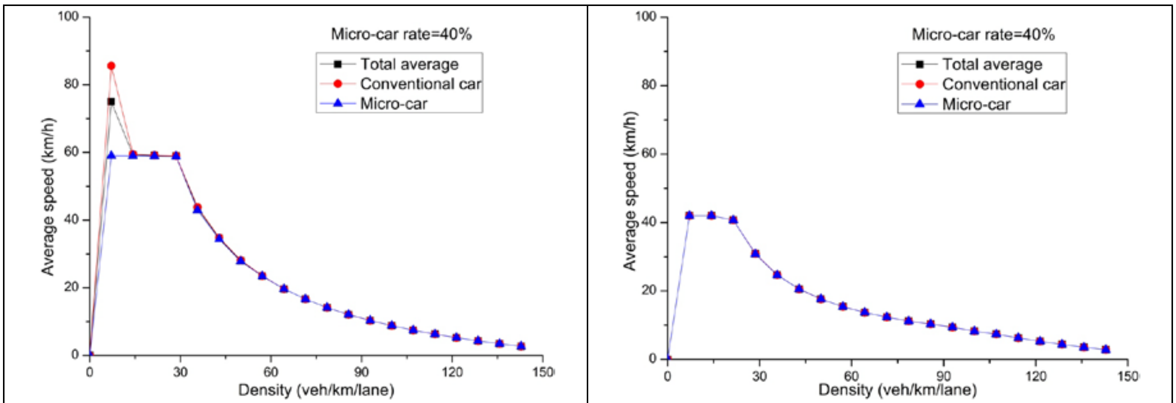


Fig. 14 Coefficient of variation of speed by density, vehicle type, and micro-car rate on arterial road



a) On highway
b) On arterial road

Fig. 15 Average speed difference between conventional cars and micro-cars when the proportion of micro-cars is 40%

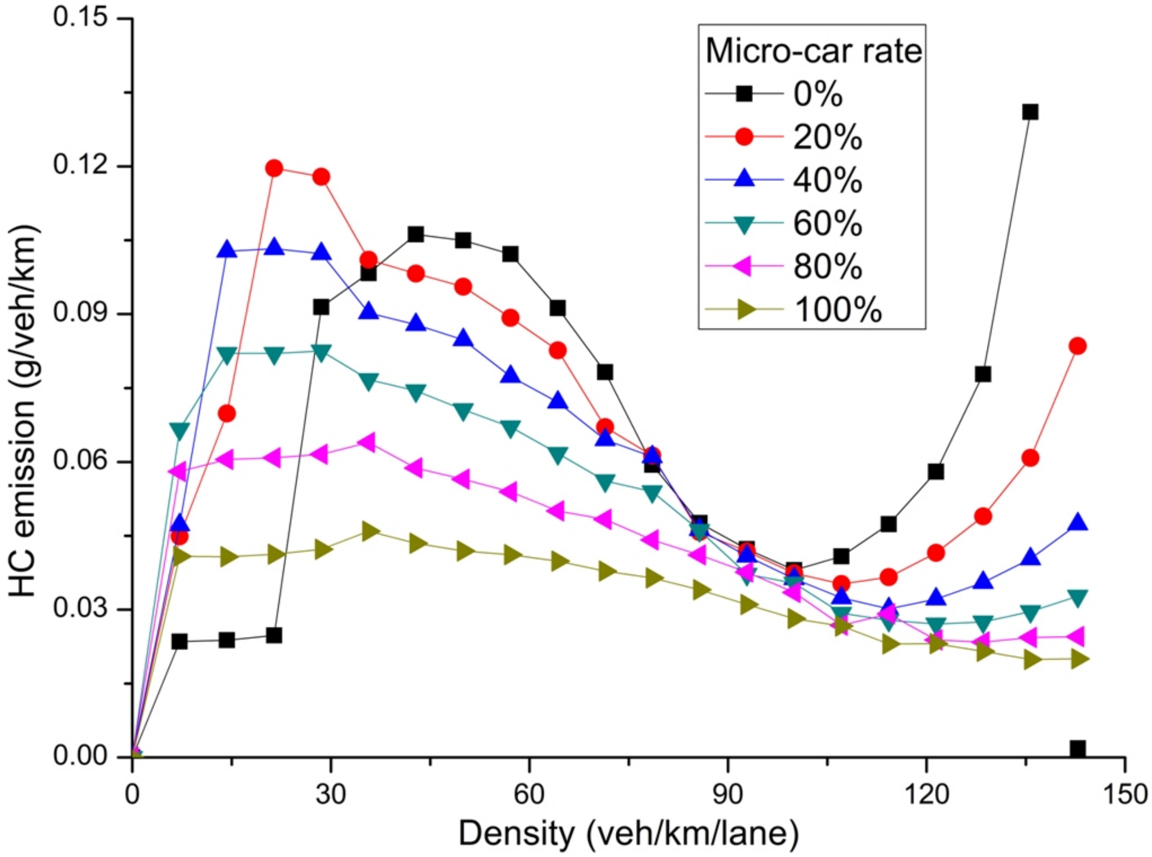


Fig. 16 HC emissions by density and micro-car rate on a highway

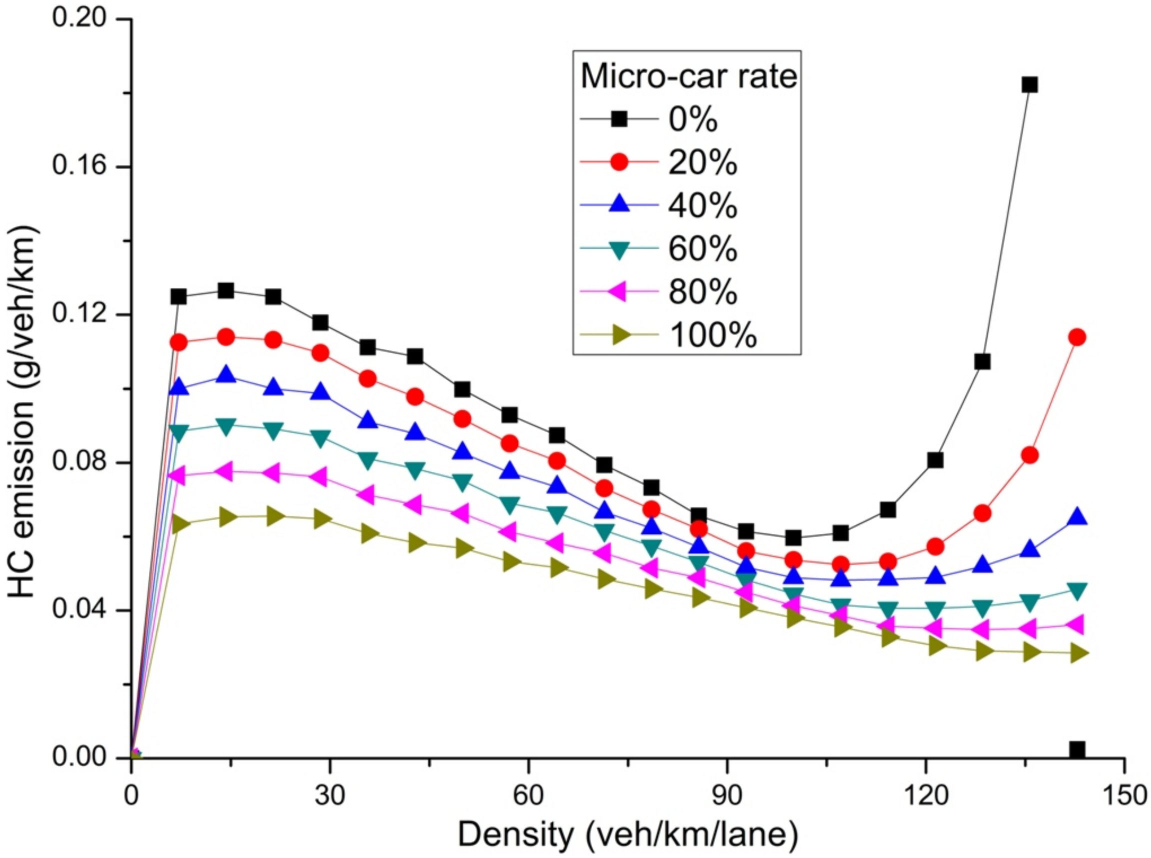


Fig. 17 HC emissions by density and micro-car rate on an arterial road