A Traffic Flow Simulation Model Based on the Desired Speed in Merging Sections on Freeways

Xing-ju WANG, Xiao-ming XI, Lin HUANG, Tao ZHANG

1. School of Traffic and Transportation, Shijiazhuang Tiedao University; Traffic Safety and Control Laboratory of Hebei Province, wangxingju@stdu.edu.cn
2. School of Traffic and Transportation, Shijiazhuang Tiedao University, xxm19871031@sina.com
3. Shijiazhuang Tiedao University, yispy@sjzri.edu.cn
4. School of Traffic and Transportation, Shijiazhuang Tiedao University, 595781171@qq.com

Abstract

In order to alleviate traffic congestions and environmental impact, developing a model to evaluate under various geometric and traffic conditions is desirable, which is the objective of this study. The car following model describes following behaviors that drivers follow each other in the traffic stream on only one lane. The lane change model is one of the essential components of any microscopic traffic flow simulation. To reproduce the traffic flow in two or more lanes, lane change model which explores lane change behaviors is represented. We develop a novel traffic simulation model consisting of car following model and lane change model based on the desired speed. Moreover, we propose a novel lane change model based on the driver’s lane change desire known as the psychological constraints and lane change abilities of road known as physical conditions. Numerical simulations are given in this paper to demonstrate the traffic flow simulation model, such as reproducing pinned localized clusters and homogeneous congested traffic and phase transitions by java. Moreover, a sensitivity analysis is conducted. In addition, the relationship between model parameters and input flow variable are discussed. It is shown that when traffic flow rate of mainline is less, the effectiveness of acceleration lane length is good, and vice versa.

Keywords: Traffic Flow Simulation, Jam, Localized Clusters, Homogeneous Congestion, Phase Transitions

1. Introduction

Increasing dependence on car-based travel has led to the daily occurrence of recurrent and nonrecurrent freeway congestions not only in the China but also around the world [1]. Congestions on freeways form when the demand exceeds capacity. Recurrent congestion reduces substantially the available infrastructure capacity at rush hour, i.e., at the time this capacity is most urgently needed, causing delays, increasing environmental pollution, and reducing traffic safety. Similar effects are observed in the frequent case of nonrecurrent congestion caused by traffic incidents such as crashes, disabled vehicles, adverse weather conditions, work zones, special events and other temporary disruptions to the freeway transportation system [2-4]. Therefore, a dynamic traffic flow simulation model on freeways which is applied to emulate state of traffic flow is needed [5-7].

This paper proposes a micro model for describing the traffic flow in a merging section on freeways. This traffic flow simulation model consists of Intelligent Driver Model introduced by Treiber and Helbing [8] and lane change model presented by this study. Congestion on freeways generally exhibits distinct patterns according to temporal variations in traffic flow. Two typical congestion patterns are localized cluster and homogeneous congestion. The localized cluster is the jam occurring at a certain location on freeways and the homogeneous congestion shows the phenomenon that the jam spreads to the upstream from some point. This simulation model is applied to reproduce the observed traffic congestions.
2. Micro-simulation Model

2.1 Car following model

In a micro-simulation model, a modeled fundamental behavior is the “car following” which adjusts the driver’s characteristics: the distance between two adjacent cars, the relative speed, adjacent cars, the relative speed, etc. In 1953, Pipes proposed the following basic differential equation model for car following behavior \[9\]: It is assumed that the delay of time the vehicle responds to the speed difference is so small that it can be neglected. To remove this drawback, Chandler introduced a reactive delay time \( T \) \[10\]. Based on the rationale that the acceleration of the following car is also influenced by its speed and the distance between the vehicles, Gazis, Herman and Rothery proposed the general type of car following model \[11\]. Newell proposed the following model in which the acceleration is propositional to an exponential function of the distance between the vehicles, based on the measurement result \[12\]. Although the above modifications have improved the reality of car following model, they have the following two drawbacks. When the proceeding vehicle does not exist (equivalently, the distance to the preceding car approaches infinity, the acceleration is 0, independent of the speed and the speed difference). This implies that a car will maintain an initial speed if there is not a preceding car. When the speed difference is 0, the acceleration is 0, independent of the distance between two cars at all. This implies the unrealistic phenomenon that the following car will not apply the brake even when the distance to the preceding car approaches 0, and will not accelerate even if the distance is very long. To solve the above-mentioned problems, Treiber and Helbing introduced the Intelligent Driver Model, in which a desired speed and a shortest distance between cars are introduced.

2.2 Lane change model

To simulate driver’s behavior in the merging section on freeways and the merging behavior in the weave section, etc. the lane change model is needed \[13\]. We propose a new lane change model in which driver’s behavior is described by equation systems with judgment functions. We focus on a vehicle approaching to a confluence point and describe its behavior with several variables: the relative speed between the vehicle and vehicles on the first lane, the locations of both the main line cars and the on-ramp cars, Driver's judgment functions for changing his lane and driver’s desired speed. The driver's judgment function for the free merging is different from the judgment function for the forced merging. A free merging implies that a car on ramp can merge into the main line with no influence and vehicles on the main line are not interfered. The forced merging occurs when cars on the main line decelerate or accelerate by inflows from the ramp and the drivers are compelled to change their behaviors. As shown in Figure 1, the lane change model with driver's judgment function is expressed as follows:

\[
h = x_f - x_c - L + (v_f - v_c)u + (-A + B)u^2 / 2 + \delta \frac{(v_{df} - v_f)}{v_{df}} S + \frac{(v_{dc} - v_f)}{v_{dc}} S \geq S
\]

Figure 1. Lane change behavior

\( x_f, x_c \) are the locations of the vehicle on the on-ramp and the location of the main line, respectively. \( v_f \) is the speed of the following car. \( v_{df} \) and \( v_{dc} \) are the minimum speeds that the following car can get if there is no influence and the emergency stopping, respectively. \( S \) is the shortest distance between the vehicles. \( \delta \) is a judgment function for changing the lane, \( \delta = 1 \) or \( \delta = 0 \) depending on the drivers’ judgment.
where $h$, $g$ = judgment function; $x$ = distance from reference point; $v$ = speed; $L$ = length of a vehicle; $t$ = the judgment time; $v_0$ = desired speed, subject to normal distribution; $\delta, \zeta, \theta, \xi$ $(\delta, \zeta, \theta, \xi \in [0,1])$ = adjustment coefficient; $A$ = rapid acceleration with upper bound $e$; and $B$ = rapid deceleration with upper bound $d$. Parameters $A$ and $B$ are associated with vehicle $c$’s judgment functions for lane change and decide the free merging or the forced merging. Since vehicle $c$ judges to accelerate or decelerate to merge into the main line, two events are mutually exclusive.

The function $h$ judges whether vehicle $c$ accelerates or decelerates to merge according to given space and speed conditions between vehicles $f$ and $c$. Similarly, the function $g$ is applied to judge in the relationship between vehicles $c$ and $b$.

If both $A$ and $B$ take 0, the distance between two vehicles $f$ and $b$ is large enough for vehicle $c$ to be accommodated to enter into the main line, then the free merging occurs (no acceleration or deceleration behavior is required for vehicle $c$). Conversely, in the case of the forced merging, we need to examine whether the solution of Inequality equations (1) to (4) exists. If $A$ and $B$ are mutually exclusive, then the following two conditions (I) and (II) are got:

(I) When a rapid brake event $B$ does not exist, then $B=0$ and only an event $A$ could happen;

(II) When a rapid acceleration event $A$ does not exist, then $A=0$ and only an event $B$ is approved. The lane changing behavior of vehicle $c$ could happen when a solution for (I) or (II) exists.

3. Data and Measures

In this section, in order to verify the correctness and the effectiveness of traffic flow simulation model in the merging sections on freeways, we make a traffic simulation program for the merging sections on freeways by Java. Traffic simulations reproduce the various patterns of congestion in the merging sections on freeways. Congestion in the merging sections on freeways generally exhibits distinct patterns according to the variation of traffic flow [14, 15]. Two typical congestions are localized cluster and homogeneous congested traffic [16]. The localized cluster is the jam occurring at a certain location on freeways. And the homogeneous congestion is the phenomenon that the jam spreads to the upstream from some point. The simulations are carried on to verify whether the traffic simulation model can reproduce the traffic congestion in merging sections mentioned above.

In our simulation, we set main line length on freeways to 1000m, ramp length to 200m, and length in merging sections of mainline and ramp to 100m. As shown in Table 1, Table 2 and Table 3, three combinations of traffic flows on main line and ramp are listed as follows:
### Table 1. Traffic inflows of the free merging and the forced merging

<table>
<thead>
<tr>
<th>Case</th>
<th>Group number</th>
<th>Traffic flow rate on the mainline (pcu/h)</th>
<th>Traffic flow rate on the ramp (pcu/h)</th>
<th>Total (pcu/h)</th>
</tr>
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<tbody>
<tr>
<td></td>
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<td>Traffic flow rate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
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<td>5</td>
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<tr>
<td></td>
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<td>1200</td>
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### Table 2. Parameters of sensitivity analysis

<table>
<thead>
<tr>
<th>Case</th>
<th>Acceleration lane length (m)</th>
<th>Traffic flow rate on the mainline (pcu/h)</th>
<th>Traffic flow rate on the ramp (pcu/h)</th>
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<tbody>
<tr>
<td>D</td>
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<td>1000</td>
<td>800</td>
</tr>
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<td>E</td>
<td>10 100</td>
<td>1000</td>
<td>1200</td>
</tr>
<tr>
<td>F</td>
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<td>1800</td>
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</tr>
<tr>
<td>G</td>
<td>10 100</td>
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<td>1200</td>
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</tbody>
</table>

### Table 3. Traffic inflows of phase transitions

<table>
<thead>
<tr>
<th>Case</th>
<th>Group number</th>
<th>Traffic flow rate on ramp (pcu/h)</th>
<th>Traffic flow rate of lane 1 on the mainline (pcu/h)</th>
<th>Traffic flow rate of lane 2 on the mainline (pcu/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
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<td>1100</td>
<td>1300</td>
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<td>1400</td>
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</table>
4. Results and discussions

4.1 Free Emerging

![Figure 2. Relationships between density and time for free merging](image)

![Figure 3. Relationships between speed and time for free merging](image)

Parameters of free emerging are shown as in Table 1-A. In Figure 2, the horizontal axis represents time, and the vertical axis is the density. According to relationships between density and time, the density is around 5 pcu /km, actually with no change. The relationship between speed and time in Figure 3 illustrates that the mean speed is around 30m /s, approaching to the theoretical upper bound 33m/s. When the total traffic volume is below 1300pcu/h for 5 simulation results, there is almost no congestion. In other words, merging vehicles can adjust their speed in conducting merging execution with no influence of traffic flows on the main line.

4.2 Forced Merging

Frequent lane-changing behaviors of merging vehicles cause the congestion in the mainline on freeways. According to the variation of traffic flow, the congestion generally exhibits two distinct patterns of localized cluster and homogeneous congested traffic. 10 times simulations have been experimented to reproduce the congestions.

(1) Localized Clusters

Parameters of traffic flow simulations for pinned localized clusters are set as shown in Table 1-B. And Figure 4, the 3D graph of localized clusters, presents that the average speed is around 20m/s and instability of traffic flow in merging sections does not expand along with the space axis. Conversely, the congestion instability expands along with the time axis. Moreover, the average speed observed decreases to about 10m/s and oscillates around it, and that there is no distinct change in density.
(2) Homogeneous Congestion

Parameters of traffic flow simulations for homogeneous congestion are shown as in Table 1-C. The simulation results are presented in Figure 5. The traffic phenomenon can be described as follows:

① Congestion expands along with the space axis and causes the decrease of the average speed of traffic flows in merging sections.

② According to the relationship between density and speed, density increases as time goes on. This means that congestion expands along with time axis.

③ The average speed decreases to 3 m/s. The similar decrease also performs in Table 1-B, while Table 1-C shows the space spread phenomenon with three factors of traffic flow, speed and density.

④ As is shown in the 3D graph of the homogeneous congestion, congestions expand along with both the space and time axis.

Characteristics of homogeneous congestion above-mentioned reproduce in these simulations.
4.3 Analysis the effectiveness of acceleration lane length

Simulation results are shown to analysis the effectiveness of acceleration lane length by our Micro-simulation model. Various combinations of traffic flows of the main line and the ramp are given. Table 2 presents the set of parameters.

Case D in Table 2 describes traffic flow rates of the main line and ramp are both small. The results of the simulation are shown in Figure 6. In Figure 6, the horizontal axis is the time, and the vertical axis is the speed. Since the traffic flow rate is not large, the average speed in the main line falls into 15 m/s when the length of the acceleration lane is 10 m. However, the average speed runs at about 30 m/s when the length of acceleration lane is 100 m. If the acceleration lane is longer, the effectiveness of reducing congestions is more obvious.

Case E in Table 2 presents that the traffic flow rate of the ramp is large while the traffic flow rate in the main line is little. As shown in Figure 7 the average speed in the main line falls into 10 m/s when the length of the acceleration lane is 10 m or 100 m. The average speeds on the ramp falls into about 2 m/s with a 10-m acceleration lane. The average speed on the ramp with a 100-m acceleration lane is obviously observed to be about 17 m/s, and the congestions of the ramp are not generated. The acceleration lane extension is greatly effective.

Case F in Table 2 shows that the traffic flow rate in the main line is large, while the traffic flow rate on ramp is little. The results of the simulation are shown in Figure 8. The average speed in the main line decreases to about 5 m/s when the acceleration lane is 10 m or 100 m long. The average speed on the ramp gets about 2 m/s with both 10-m and 100-m acceleration lanes. In this case, the congestions on the ramp are generated. Moreover, a 100-m acceleration lane has smaller generation time of congestions comparing with a 10-m acceleration lane. In addition, Case G in Table 2 explores that there are a lot of traffic flow rates in both the main lane and ramp. The same results as shown in Figure 9 are observed. There is not the effectiveness of the acceleration lane extension when the traffic flow rate in the main line is large.
4.4 Phase Transitions

Case H in Table 3 presents free merging behaviors in merging section on freeways, and the simulations reproduce the phase transitions of traffic flows called the Synchronized flow-wide moving jam (S-J) when the parameters settings of 1150 pcu/h on ramp, 1800 pcu/h on lane 1 of main line and 1400 pcu/h on lane 2 of main line. Curves of phase transitions are shown in Figure 10. The left of phase transitions point is the synchronized flow, and the right is wide moving jam. In the initial stage of simulations, congestions firstly occur on the main lane 1 on highways, and as time goes on, lane 2 goes into congestion state that density and speed are homogeneous and synchronized.

5. Conclusions

According to earlier traffic flow theories, traffic flow can be defined as either “free” or “congested”. However, in the congestions, the homogeneous congestion phenomenon is observed, and a sequence of different localized clusters also appears. In addition, the phase transitions of traffic flows called the Synchronized flow-wide moving jam are also observed on freeways. To alleviate traffic congestions, developing a dynamic traffic flow simulation model is desirable. A traffic flow simulation model consisting of IDM and lane change model based on desired speed is developed in this study, which provides a useful tool to simulate car movements based on driver’s behaviors, calculate the average speeds and estimate the density. According to a specified time interval, this model is applied to conduct a sensitivity analysis of acceleration lane to demonstrate effectiveness of acceleration lane extension for alleviating traffic congestions.

As discussed in the simulations, the complex merging behaviors in the merging section on freeways are reappeared by using the traffic simulation model. Numerical simulations are given to reproduce pinned localized clusters and homogeneous congested traffic. Moreover, phase transitions...
transitions of traffic flows called the Synchronized flow-wide moving jam are reproduced by using this simulation model when the parameters settings of 1150 pcu/h on ramp, 1800 pcu/h on lane 1 of main line and 1400 pcu/h on lane 2 of main line. In the initial stage of simulations, congestions firstly occurs on main lane 1 on highways, and as time goes on, lane 2 goes into congestion state that density and speed are homogeneous and synchronized. In addition, the sensitivity analysis is conducted to demonstrate relationships among traffic flow parameters. The results indicate that the effectiveness of acceleration lane length is good when traffic flow rate of mainline is less, and vice versa.

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7. References


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