Evaluation of Freeway Traffic Management and Control Measures Based on SUMO

Fujian Wang\textsuperscript{1*}, Yixiao Lu\textsuperscript{1}, Hongliang Dai\textsuperscript{2} and Haihang Han\textsuperscript{2}

\textsuperscript{1}Institute of Intelligent Transportation System, College of Civil Engineering and Architecture, Zhejiang University, Hangzhou, China
\textsuperscript{2}Zhejiang Scientific Research Institute of Transport, Hangzhou, China
Email: ciewfj@zju.edu.cn

Abstract. With the rapid increase of freeway traffic volume, traffic congestion has become a normal phenomenon, through scientific freeway management and control measures, the traffic efficiency of the whole road can be effectively improved and the congestion problem can be alleviated. Therefore, this paper takes Shaoxing section of Shanghai-Hangzhou-Ningbo Freeway as the research object, puts forward three active traffic control measures, and uses the traffic simulation software SUMO to simulate and evaluate the effect of the freeway control measures. The results show that emergency lane control measure, ramp metering control measure, and variable speed limit control measure can effectively reduce the delay of freeway in the congested section, and improve road capacity. In this paper, the study of freeway management and control measures under congestion conditions, provides relevant decision support and theoretical guidance for freeway management.

Keywords. Traffic congestion, Simulation software SUMO, Freeway management.

1. Introduction
Freeway operation management is faced with the problems of low monitoring coverage density, low level of intelligent management and control, lack of early intervention and control. Traffic congestion and traffic accidents not only lead to the decline of freeway service level, but also seriously affect the safety of freeway. With the development of intelligent and automatic high-tech, the freeway management and control measures will be more consummate. This will effectively improve the efficiency of the entire road system and alleviate congestion.

At present, there are many researches on freeway management and control measures at home and abroad. Among them, ramp metering (RM), variable speed limit control (VSL) and route guidance (RG) are considered as most effective measures to alleviate freeway traffic congestion [1]. Ramp metering refers to the number of vehicles released into the ramp by preset control ratio [2]. Variable speed limit control is to achieve the goal of stable traffic flow by limiting the driving speed. According to the real-time traffic status of the road network, route guidance is to provide the best driving route for the driver through calculation and optimization for the purpose of balancing the road network system and reducing the travel time of vehicles [3]. In addition to the above-mentioned common management and control means, nowadays, emergency lane management and control, merge point management and control, and other means have become freeway management and control strategies under congestion conditions.

Active management measure is an important support of traffic system management. Therefore, with the help of the traffic simulation software SUMO, this paper studies and evaluates the freeway...
management and control means through computer simulation [4], and studies their impacts on the traffic flow of freeway. In addition, it can improve the level of highway active management, alleviate traffic congestion and improve traffic safety.

2. Basic Simulation Settings

2.1. SUMO
SUMO is an open source, highly portable, microscopic and continuous traffic simulation package designed to handle large networks [5]. Since 2001, the SUMO package has been used in the context of several national and international research projects. The applications included: traffic lights evaluation, route choice and re-routing, evaluation of traffic surveillance methods, simulation of vehicular communications, and traffic forecast.

2.2. Road Layout
In this study, Shaoxing section of Shanghai-Hangzhou-Ningbo Freeway is taken as the research object. The simulation road map is obtained from the Open Street Map (OSM), the OSM map file is generated, and then use SUMO's own convert tool to generate the net.xml file, and then modify the road network file according to the actual road network situation, input the road network file into SUMO, and get the simulation road section as shown in figure 1. The vehicle entrance and exit points from left to right are Keqiao Toll Station, Qixian Hub, Shaoxing Toll Station, Guzhu Hub and Shangyu Toll Station.

![Figure 1. SUMO simulation scenario of Shaoxing section of Shanghai-Hangzhou-Ningbo Freeway.](image)

In the simulation scenario, detectors are set up on the road section to detect traffic flow parameters, such as traffic volume, speed, delay and other data. The locations of the detectors on the road section is shown in figure 2.

![Figure 2. Detector locations.](image)

In figure 2, cross-section detectors are set at different positions of the road section, which are represented by points A, B and C. The detector at position C is used to calibrate the real behavior of the simulated traffic on the main lane, and the detector at position B is used to calibrate the real
behavior of the simulated traffic on the ramp lane, and the detector at position A is used to detect the real traffic behavior after the ramp vehicles merge into the main lane.

2.3. Traffic Composition
According to the data of eight checkpoint detectors along Keqiao-Shangyu road section in Shaoxing, and the data of three toll stations' entrances and exits, the input of traffic flow in the simulation scenario is determined. In the simulation scenario of freeway management and control measures, the traffic flow data are taken from the morning peak data of September 2-6, 2019, and the traffic flow is composed of two different vehicle types: conventional vehicle (CV) and heavy goods vehicle (HGV), in which HGV accounts for about 25%.

3. Simulation Scenario Settings

3.1. Freeway Management and Control Measures
According to the situation of freeway congestion, the following three kinds of freeway management and control measures are put forward:

(1) Emergency lane control. The applicable conditions are as follows: when the traffic flow of a certain section is large, and a lot of vehicles leave the freeway through the front hub or off-ramp. Meanwhile, there will be vehicles running right in the left lane continuously, which will greatly increase the risk of scraping accidents while affecting the traffic order on the main line. At this time, the emergency lane is opened so that vehicles can use the emergency lane to ease the congestion on the main line. The specific measures are as follows: in the road section, by using the road information board or adding the warning board to define the starting point and end point of the opening emergency lane. In case of congestion, the freeway command and dispatching center will issue control instructions for borrowing emergency lane, and the road information board and warning board will prompt the control informations at the start and end points respectively: "vehicles driving out in front can take the emergency lane", "stop using the emergency lane, please drive back to the original lane".

(2) Ramp metering control. On-ramp control is more commonly used. The applicable conditions are that there are more vehicles on the on-ramp, causing congestion on the main line, and there is enough parking space on the on-ramp. The specific measures are as follows: setting signal at the ramp exit, allowing a certain number of vehicles to enter the main line at fixed time, thus limiting the traffic volume from the on-ramp into the main line of the freeway, so as to make the traffic volume on the main line evenly distributed, alleviate even eliminate the traffic congestion on the main line, and make full use of the traffic capacity of the main line.

(3) Variable speed limit control. The applicable condition is that the traffic flow of freeway is unstable and the vehicles stop and go in the queue. The specific measures include: implement speed limit control measure within the congestion section by controlling the variable speed limit signs on the roadside, and publish real-time speed limit information to limit the driver to pass through the congested section at a lower speed, so as to achieve the purpose of stabilizing the overall traffic flow.

With the use of SUMO, the overall operation states of freeway after different control measures are simulated. In the simulation model, the corresponding detectors shown in figure 2 are set up to obtain the traffic volume, average speed, main line travel time, ramp queuing length, ramp delay time and other data as evaluation indicators. The simulation results are compared with those results without control measures, in order to evaluate the effects of above freeway management and control measures.

3.2. Parameter Setting
By calibrating the parameters of car following model and lane changing model, the traffic flow of SUMO simulation can be closer to the real traffic flow state. SUMO provides many car following models, in this study, carFollowing-IDM model is used. The IDM model is the simplest complete and accident-free model producing realistic acceleration profiles and a plausible behavior in essentially all single-lane traffic situations. Its main parameters are as
follows: accel, decel, sigma, tau and so on. Similarly, SUMO provides three lane changing models, and in this study, we used the SL2015 model as the lane changing model, which considers lane changing as a continuous process, and takes into account the angle, lateral velocity, acceleration and other information of lane changing, which is mostly used in micro simulation. The main parameters of lane changing model include lcStrategic and lcCooperative.

The meanings of the main parameters are as follows:
1. accel: the acceleration ability of vehicles(m/s²).
2. decel: the deceleration ability of vehicles(m/s²).
3. tau: the driver's desired/minimum time headway(s).
4. sigma: the driver imperfection, 0 denotes perfect driving, range [0-1].
5. aSL(actionStepLength): the interval length for which vehicle performs its decision logic (acceleration and lane-changing) (s).
6. speedFactor: The vehicles expected multiplicator for lane speed limits.
7. speedDev: The deviation of the speedFactor.
8. lcS (lcStrategic): the eagerness for performing strategic lane changing. Higher values result in earlier lane-changing, range [0-inf).
9. lcC(lcCooperative): the willingness for performing cooperative lane changing. Lower values result in reduced cooperation, range [0-1].

Finally, the parameter settings of conventional vehicles (CV) and heavy goods vehicles (HGV) are shown in table 1 [6].

|        | accel | decel | tau  | sigma | aSL  | speedFactor | speedDev | lcS  | lcC  |
|--------|-------|-------|------|-------|------|-------------|----------|------|------|
| CV     | 2.0   | 4.0   | 1.07 | 0.5   | 0.7  | 1.03        | 0.123    | 0.8  | 0.6  |
| HGV    | 2.0   | 4.0   | 1.21 | 0.5   | 0.7  | 0.91        | 0.115    | 1.0  | 0.6  |

### 4. Simulation Result

#### 4.1. Calibration Result
First of all, we verify the authenticity of the simulation scenario. The data from 9:00-10:00 on September 2, 2019 is selected to verify the accuracy of model parameter calibration. The simulation without any control measures is compared with the real situation of the freeway to verify the consistency of the simulation scenario and the real traffic flow situation. After inspection, the traffic flow situation of the simulation scenario is basically consistent with the real situation of the freeway, with an average relative error of 1.57%. The results are shown in table 2.

|                     | Actual value(veh/h) | Simulation value(veh/h) | Error |
|---------------------|---------------------|-------------------------|-------|
| Exit of Keqiao Toll Station | 1090                | 1064                    | 2.4%  |
| Entrance of Keqiao Toll Station | 930                | 930                    | 0%    |
| Keqiao Toll Station to Qixian Hub | 2557               | 2600                    | 1.68% |
| Qixian Hub to Shaoxing Toll Station | 3458               | 3667                    | 6%    |
| Exit of Shaoxing Toll Station | 965                | 957                    | 0.83% |
| Entrance of Shaoxing Toll Station | 1044               | 1044                    | 0%    |
| Shaoxing Toll Station to Guzhu Hub | 1586               | 1581                    | 0.32% |
| Guzhu Hub to Shangyu Toll Station | 1287               | 1229                    | 4.5%  |
| Exit of Shangyu Toll Station | 96                | 96                     | 0%    |
| Entrance of Shangyu Toll Station | 301                | 301                    | 0%    |
4.2. Evaluation of Freeway Management and Control Measures

4.2.1. Emergency Lane Control Measure. The section at the exit of Keqiao Toll Station is selected as the research object. The traffic volume of this section is large, and there are many vehicles entering the off-ramp. At this time, The emergency lane control measure is taken to allow vehicles to use the emergency lane. Figure 3 shows the traffic flow operation state without emergency lane control measure. Vehicles are congested in the upstream section of the off-ramp. Figure 4 shows the traffic flow operation state after emergency lane control measure is taken, and the congestion situation has been significantly alleviated.

![Figure 3. Simulation scenario without emergency lane control measure.](image1)

![Figure 4. Simulation scenario with emergency lane control measure.](image2)

The delay time, the traffic volume, the average speed and other evaluation indexes in SUMO are selected to analyze the changes of road traffic conditions after the implementation of emergency lane control measure. See table 3 for comparative analysis of simulation data of the control measure.

| Parameter                  | No control measures | Take control measures |
|----------------------------|---------------------|-----------------------|
| Average delay time(s)      | 11.24               | 5.18                  |
| Traffic volume(veh/h)      | 3665                | 4419                  |
| Average speed of main line(km/h) | 89.7               | 98.1                  |

Through the analysis of the simulation results, it is found that after the emergency lane management and control measure is taken, the traffic congestion is alleviated, the average speed of vehicles is increased by 9.4%, the average delay time of vehicles is reduced by 53.9%, and the traffic volume is increased by 20.6%. Therefore, emergency lane management and control measure can effectively alleviate the congestion of freeway and improve the road capacity.

4.2.2. Ramp Metering Control Measure. The on-ramp of Shaoxing Toll Station is selected as the research object, where the traffic volume is large and congestion often occurs in the merge area. The traffic volume entering the main line is limited by setting signal at the end of the on-ramp, with 30 seconds red light and 30 seconds green light. Figure 5 shows the traffic flow operation state without ramp metering measures. The vehicles run in a low speed in the main line. Figure 6 shows the traffic flow operation state after ramp metering measures are taken. Although the number of queues at the on-ramp increases, the traffic flow operation state has been improved significantly. The simulation results are shown in table 4.
Table 4. Simulation results of ramp metering measure.

| Parameter                        | No control measures | Take control measures |
|----------------------------------|---------------------|-----------------------|
| Average delay time (s)           | 4.62                | 2.02                  |
| Traffic volume (veh/h)           | 4324                | 4512                  |
| Average speed of main line (km/h)| 89.44               | 96.92                 |
| Standard deviation of speed (km/h)| 12.12              | 9.22                  |

Figure 5. Simulation scenario without ramp metering measure.  
Figure 6. Simulation scenario with ramp metering measure.

According to the simulation results, the ramp metering control can effectively improve the average speed of the main line and alleviate traffic congestion. The average delay time of vehicles is reduced by 56.2%, and the average speed is increased by 8.4%.

4.2.3. Variable Speed Limit Control Measure. Taking the section between Keqiao Toll Station and Qixian Hub as the research object, the vehicles in this section often stop and go in the queue. By limiting the speed, the driver can pass through the congested section at a lower speed, so as to stabilize the overall traffic flow. When the speed limit control measures are not taken, the original speed limit value is 120km/h of this section, and in simulation scene, the new speed limit values of the road section are 100km/h, 80km/h and 60km/h, respectively.

When the speed limit is 100km/h, the simulation results are shown in table 5.

Table 5. Simulation results of variable speed control (speed limit: 100km/h).

| Parameter                        | No control measures | Take control measures |
|----------------------------------|---------------------|-----------------------|
| Average delay time (s)           | 11.24               | 3.69                  |
| Traffic volume (veh/h)           | 4165                | 4226                  |
| Average speed of main line (km/h)| 70.99               | 80.32                 |
| Standard deviation of speed (km/h)| 7.51               | 5.04                  |

When the speed limit is 80km/h, the simulation results are shown in table 6.


Table 6. Simulation results of variable speed control (speed limit: 80km/h).

| Parameter                          | No control measures | Take control measures |
|------------------------------------|---------------------|-----------------------|
| Average delay time(s)              | 11.24               | 0.79                  |
| Traffic volume(veh/h)              | 4165                | 4380                  |
| Average speed of main line(km/h)   | 70.99               | 75.36                 |
| Standard deviation of speed(km/h)  | 7.51                | 2.94                  |

When the speed limit is 60km/h, the simulation results are shown in table 7.

Table 7. Simulation results of variable speed control (speed limit: 60km/h).

| Parameter                          | No control measures | Take control measures |
|------------------------------------|---------------------|-----------------------|
| Average delay time(s)              | 11.24               | 1.26                  |
| Traffic volume(veh/h)              | 4165                | 4355                  |
| Average speed of main line(km/h)   | 70.99               | 52.92                 |
| Standard deviation of speed(km/h)  | 7.51                | 2.67                  |

According to the simulation results, speed control measures in congested road sections can effectively reduce the dispersion of speed, reduce vehicle delay and increase the capacity of the road section. In this simulation scenario, when the speed limit is 80km/h, the control effect is the best. There is basically no delay, the traffic volume is increased by 5.2%, and the speed dispersion is reduced by 60.9%.

5. Conclusion
In this study, firstly, the traffic flow data are collected and processed, and the model parameters are set to build the basic freeway simulation model in SUMO. Then the difference between the simulated traffic flow state without management and control measures and the actual traffic flow is tested. The results show that the simulation scenario is comparatively close to the actual scenario.

Then, the simulation experiments of freeway management and control measures are carried out. The data analysis shows that emergency lane control, ramp metering control and variable speed control measures can effectively reduce the delay of freeway in congested road sections, improve the vehicle operation speed and increase the capacity of the road section, among which the effect of emergency lane control measure is relatively remarkable.

6. Acknowledgments
This work was supported by Science and technology plan project of Zhejiang Provincial Transportation Department [grant number 2019047].

References
[1] Wang X, Qiu T Z, Niu L, Zhang R and Wang L 2016 A micro-simulation study on proactive coordinated ramp metering for relieving freeway congestion Canadian Journal of Civil Engineering 43 599-608
[2] Pasquale C, Sacone S, Siri S and De Schutter B 2017 A multi-class model-based control scheme for reducing congestion and emissions in freeway networks by combining ramp metering and route guidance Transportation Research 80 384-408
[3] Zuo L, Zhang N, He Y G and Zhou T T 2017 Research on dynamic route guidance and navigation system based on multi information feedback Proc. of 2017 Int. Conf. on Sensing, Diagnostics,
Prognostics, and Control (SDPC) Eds C Li and Oliveira J V (Danvers: Conference Publishing Services(CPS)) 421-424

[4] Krajzewicz D, Brockfeld E, Mikat J, Ringel J, Rössel C, Tuchscheerer W, Wagner P and Wösler R 2005 Simulation of modern traffic lights control systems using the open source traffic simulation SUMO Proc. of the 3rd Industrial Simulation Conference 2005 Eds J Krüger, A Lisounkin and G Schreck (Berlin, EUROISIS-ETI) 299-302

[5] German Aerospace Center 2020 SUMO User Documentation Available at https://sumo.dlr.de/docs/

[6] Richter G, Grohmann L, Nitsche P and Lenz G 2019 Anticipating automated vehicle presence and the effects on interactions with conventional traffic and infrastructure Proc. of SUMO User Conference 2019 (EPiC Series in Computing) Eds. M Weber, L Bieker-Walz, R Hilbrich and M Behrisch (Manchester, EasyChair) 62 230-243