Simulation of the Traffic Flow on US 101 Highway

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1. Introduction

The efficiency of the highway transportation system has a decisive impact on daily commuting or holiday traveling experience of people in urban or suburban areas, and therefore also influences their living qualities. The expansion of metro cities that exacerbates the in and out flows of commuting traffic urges an increasing number of highway construction, which requires a more comprehensive understanding of this system and more delicate, organized designs. Simulation approach is one of the most effective and intriguing ways to understand the traveling mechanism of the highway traffic system. By modelling the individual behavior of each traffic unit, the dynamics of traffic flow can be simulated as a group behavior in this system. The simulation results are mostly self-explanatory and the effect of key factors can be quantified by the corresponding dependent variable produced by the simulation. In this project, the efficiency of the transportation system is indexed by an average traveling time. In the past decade, researchers and scientists have proposed various theories and computational approaches to simulate the dynamics of this complicated system, stressing this issue from different perspectives. To deepen our understanding of this system and how key factors play out in it, our team proposes a discrete event simulation (DES) approach to simulate the dynamics of traffic flow in a selected segment of the highway 101, which is located in the city of Los Angeles and stretches around 2 miles in distance. The studied segment includes several exits and entries that acts as the inlets and the outlets of the traffic flow. Our project will mainly focus on studying two aspects that can potentially influence the transport efficiency of this system: the traffic flow from the highway entries and exits, and the behavior of each individual traffic unit. We will adopt a data-driven approach to characterize the statistics of the input and parameters in this model, while the output will also be validated by real-world data. The proposed simulation approach will also be employed to investigate the significance of each parameter in this model.

Numerous research has been dedicated to investigate the efficiency of traffic flow. A high spatial and temporal resolution is usually required to simulate a complex real-world traffic network, which raises the challenge to current computational power. Fortunately, event-driven queue-based simulation is found to be an effective tool for such a simulation task as it tremendously reduces the associated computational cost [1]. Nam and Drew devised an inductive model under the assumption of stochastic queueing theory and conversation of vehicle principle [2] that produces results matching real-world data. Dirk adopted a queueing-theoretical model to bring insights into congestion and travel time [3]. A queue-based light-weight dynamic traffic assignment package was developed by Xuesong to fully utilize traffic capacity. His model is indicated to be applicable to different real-word networks [4]. However, there is a lack of considering the lane change in all these models, which is a non-trivial component in real-word traffic flow and can incur unignorable effects in this network. In previous study, learning-based algorithms, including support vector machine, Bayesian filter and hidden Markov model, have been proved effective in predicting lane changes [5-8]. Schofield developed a camera-based automotive lane change aid system [9], which has been widely used on US highways. In this project, we applied the lane-changing model developed by Rickert, et al.[10] to explore and evaluate the impact of lane change in our event-driven queue-based model. The traffic efficiency is indexed by the average traveling time, which is a critical and fundamental criterion for measuring traffic efficiency [2,11-13]. Additionally, we aim at proposing optimal highway designs with the same amount of entry and exit ramps, which produce higher traffic efficiency.

2. Problem Statement

The traffic flow on a two-mile segment of US 101 highway (as shown in Fig. 1) is investigated in this paper. This segment contains a start point and five entry points, where vehicles enter the road, and an end point and two exit point, where vehicles leave the road. Hence, the whole segment is divided into eight sections with various length. Our model is a discrete event simulation (as shown in Fig. 2)--events associated with each vehicle includes entering the road, running on the road, lane-changing (optional) and leaving the road. For each entrance, there is a random car generator that generates a new car into the section that is after the entrance. For each car, it will have its ID, current time, entranceID, exitID, laneID, expected velocity, current velocity… For each lane, it will have its ID, speed limit, car capacity, car numbers...At each entrance and exit, there is a priority queue that process which car will move first based on their arrival time.

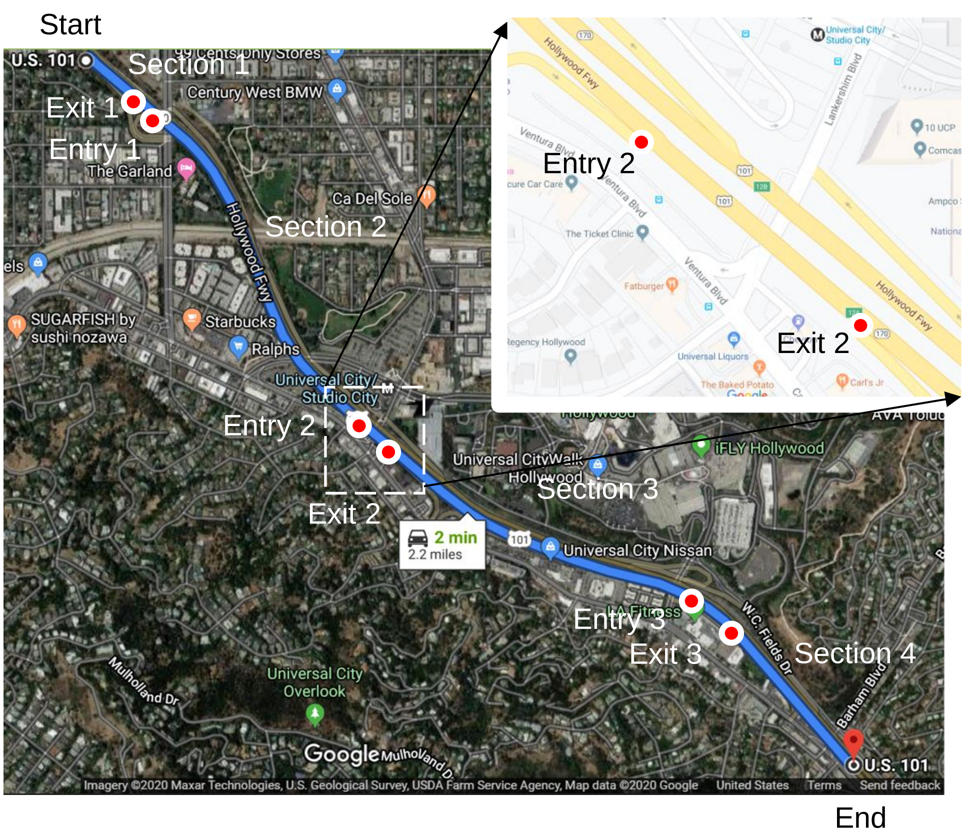

Figure 1. A 2.2-mile segment of US 101 highway (Google Map).

The traffic data for US 101 in Los Angeles, CA is collected from the Next Generation Simulation (NGSIM) Vehicle Trajectories and Support Data. The data between 7:45 am-8:00 am will be used. The probability distribution of the car entering the federal highway for each entrance will be generated based on the data. Besides, the total number of traffic flow, the distribution of the velocity with respect to the number of the car in a certain section of the highway will also be calculated. Apart from the data from NGSIM, the data collected by commercial APPS, Google

Map, will also be used to do the verification. The average travel time for a single car passing the part of the expressway that is studied from Google Map between 7:50-8:00 am over one week will be compared with the average travel time obtained from simulation.

3. Conceptual Model

In this study, we adopted a discrete event-oriented (DES) model for simulating the traffic flow on a specific segment of Highway 101. In this model, the traffic flow is driven by a list of events and the simulation time is viewed as continuous. To achieve this, a priority queue data structure, i.e., future event list (FEL), is used in the simulation engine to hold all unprocessed events. In each simulation loop, the event with the smallest time stamp would be removed and handled. State variables are updated when an event occurs. (events occur at irregular points in simulation time). The following assumptions are made:

1. The 2.2-mile segment of Highway 101 is divided into 4 sections, with the start, end and 3 pairs of entry/exit (Fig. 1). The distance between the paired entry and exit is neglected.
2. The presence of vehicles on the road follows independent and identical uniform distribution. Hence, vehicles are generated at end and three entries via random number generator with statistical parameters obtained from data.
3. If dense flow occurs at entries, much traffic at entry points may cause traffic congestion—the vehicles entering the road at entries need to yield to vehicles already on the road while they arrive at the intersection of entries at the same time. In light of this, we set such an condition that when the intersections are occupied by vehicles on the main road, incoming cars from queues have to wait until the intersection becomes clear.
4. The speed of the vehicles depends on the traffic density ahead. The relationship between the two is determined from the data.
5. The length of each section of the road is approximated based on the map, whereas the length of the vehicles is neglected.
6. The activity of changing lane is considered in the model and can take place at the specific nodes. Three nodes are set at the 2^{nd} and the 3^{rd} sections respectively (dividing each section into four intersections) for checking whether the vehicles need to change a lane on arrival at the intersections. The interval between each adjacent nodes is 0.2 mile. A two-lane model, referring to the work of Rickert, et al.[10],is used here for the lane-changing event. The lane-changing activity takes place for one car at one node if following criterions are fulfilled:
   (1) The driver is willing to change the lane. It is represented by generating a random number and compare it with a constant: Random() < 1
   (2) This car is too close to the car ahead of it. The distance between this car and the car ahead of it on this lane it is smaller than a constant distance L_1.
   (3) This car looks ahead to confirm it has enough room to change to another lane. The distance between this car and the car ahead of it on another lane is larger than a constant distance L_2.
   (4) This car looks back to confirm it has enough room to change to another lane. The distance between this car and the car behind it on another lane is larger than L_3.

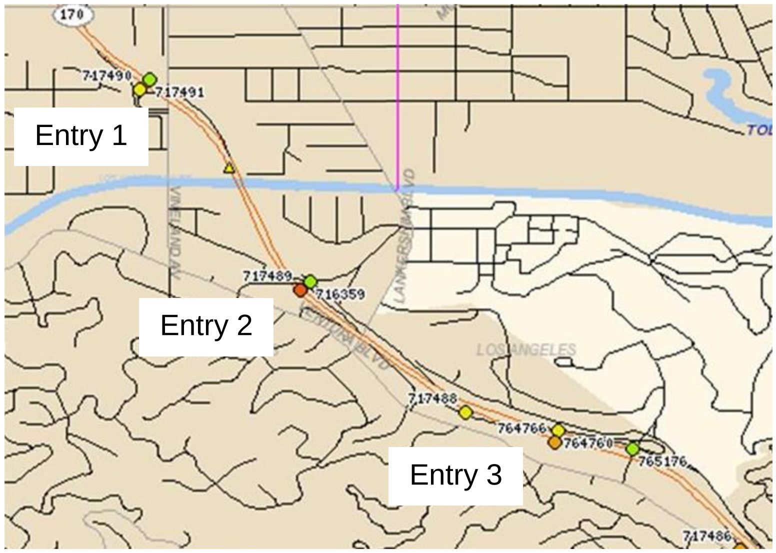

Figure 2. Traffic density at entries. (red, orange, yellow and green dots denote very heavy, heavy, normal and light traffic respectively).

Figure 3 depicts the “world view” of the simulation model, which consists of simulation application and simulation executive. The simulation application part contains the state variables, event procedures and I/O and user interface software. The simulation executive part contains the FEL, event processing loop and manages advances in simulation time.

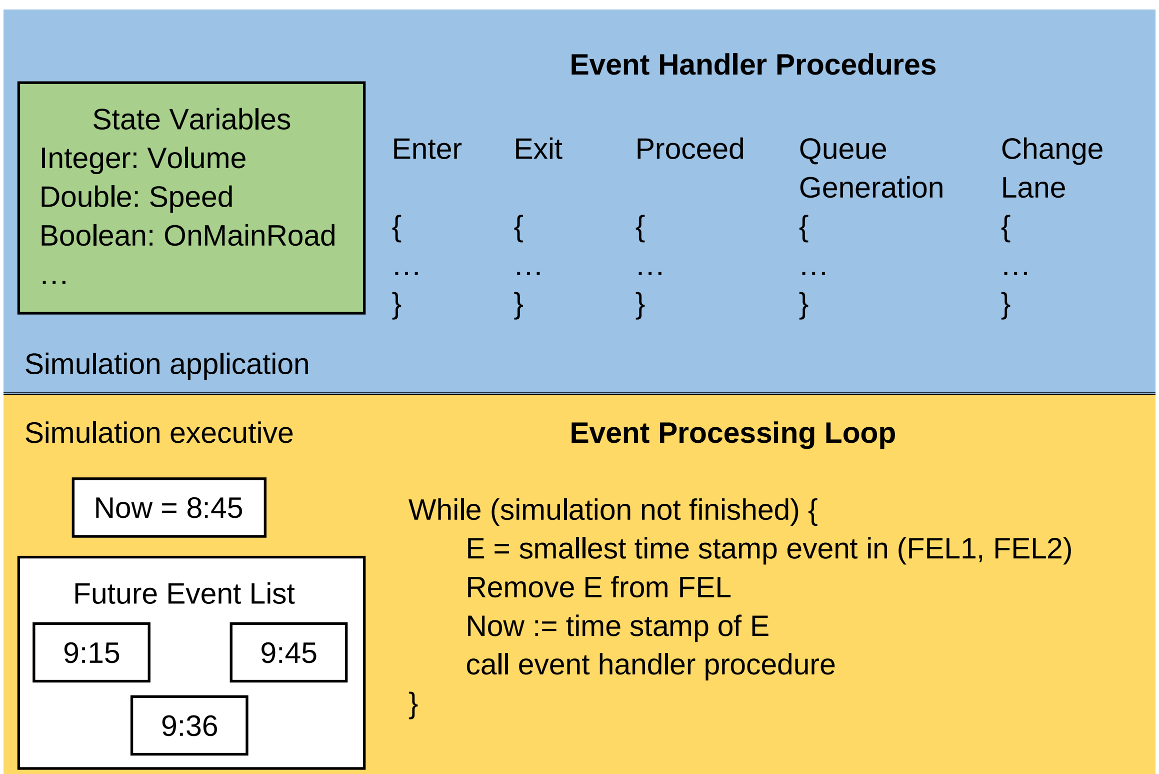

Figure 3. World view of the traffic flow simulation model.

There are five different types of events in the model, including Queue Generation, Enter, Exit, Proceed and Change Lane. The event Queue Generation handles the appearance of the vehicles in FEL and schedules Enter event. The Enter event manages the vehicles entering the start and entry points, and schedules the Proceed or Exit events depending on its entry point. The Exit event manages the vehicles exiting the end and exit points, and schedules the Enter event at next entry point or get released from the FEL depending on the vehicle variables. The Proceed event handles the vehicles reaching nodes, and schedule Changes Lane event or next Proceed or Exit event depending on whether the corresponding requirements are satisfied. The Change Lane event handles the vehicles changing lane at the nodes, and schedule the next Proceed or Exit event. Figure 4 documents the detailed procedures. The Queue Generation, Enter and Exit events are described in Fig. 4a and the events associated with the lane-changing activities are described in Fig. 4b. Notably, the lane-changing activities as shown in Fig. 4b only take place at section 2 and 3.

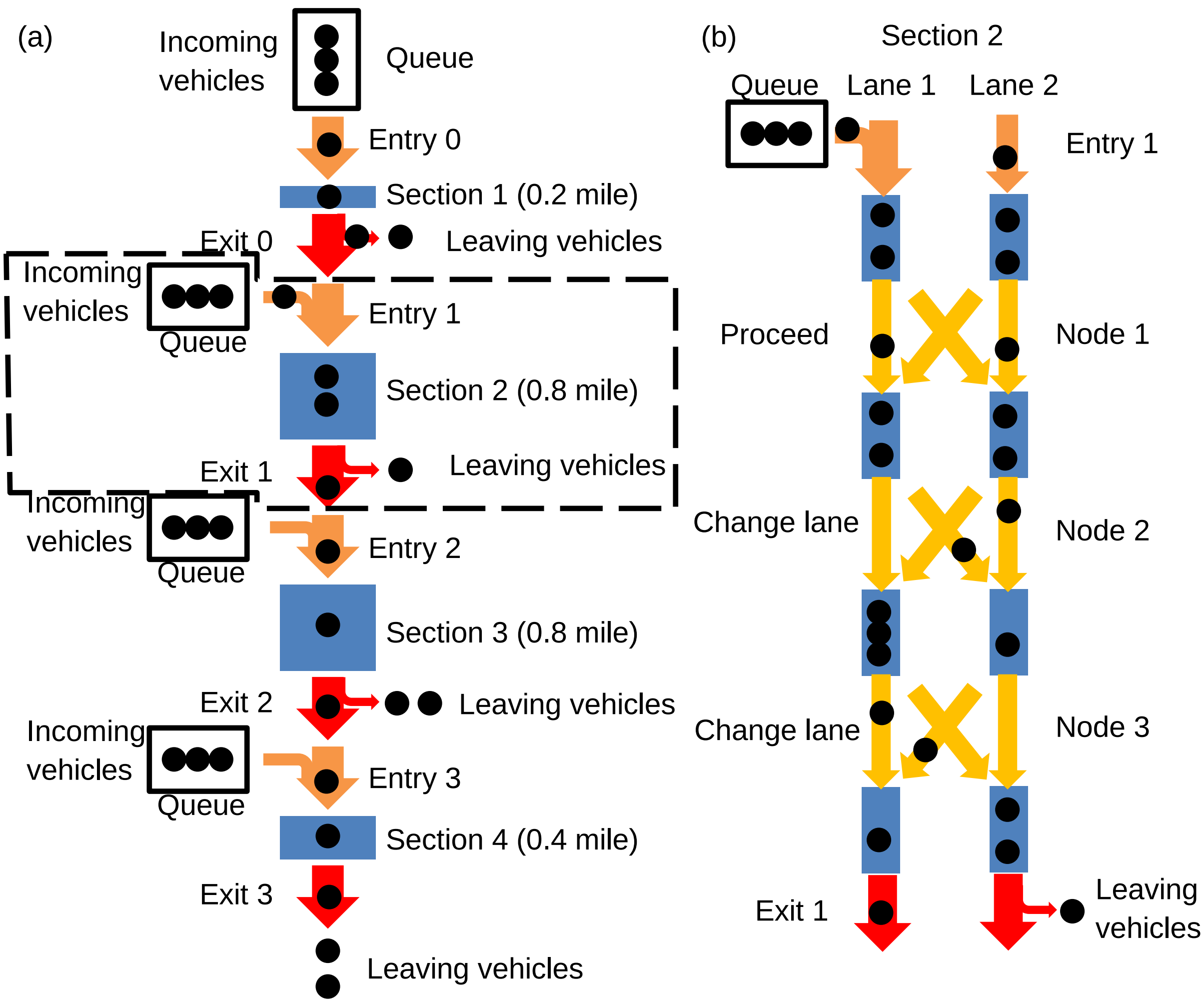

Figure 4. Traffic flow conceptual model: (a) global system and (b) example of the local system at section 2.

4. Processed Data

4.1 Vehicle Generation Function at Entry Based on Raw Data

We tracked the incoming vehicles at the Entry 2 over a 15-minute period based on our raw data. Figure 5 shows the relation between the amount of vehicles arriving at the entry and the time interval. This function is used in the random generator at the entry queue in the model.

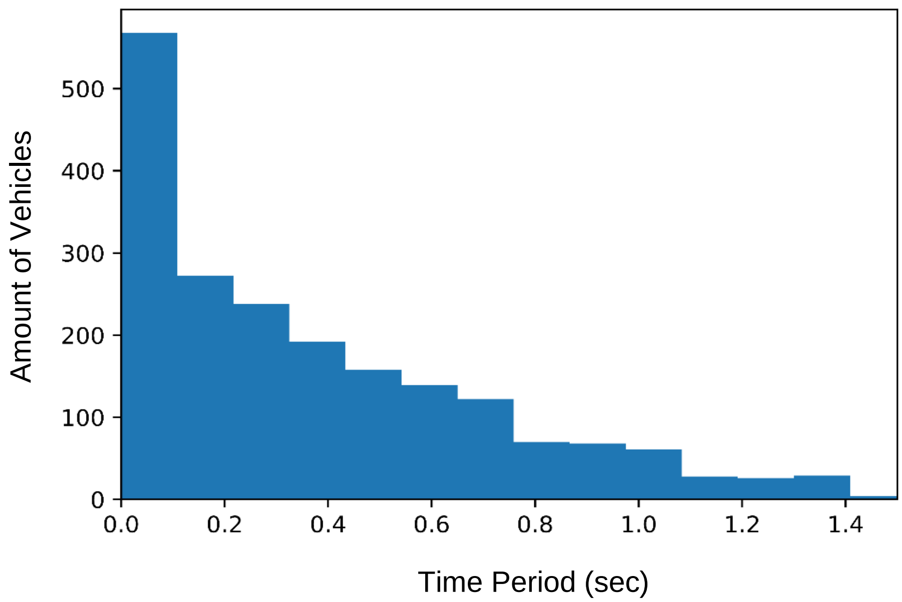

Figure 5. Distribution of vehicles' entering the road.

4.2 Relation between the Vehicle Average Speed and Traffic Volume

We tracked the average speed of the vehicles and the amount vehicles on the road at various time frames and plotted them as the Fig. 6. Then we conducted a regression to obtain the relation between the average speed of the vehicles and the amount vehicles on the road.

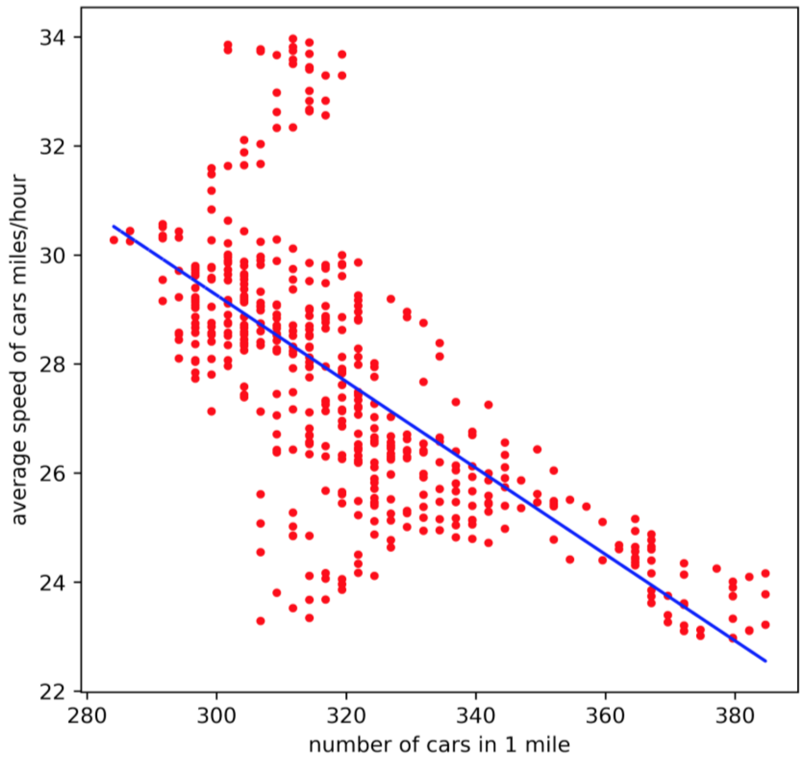

Figure 6. The vehicle average speed as a function of the amount of vehicle on the highway.

5. Verification

Figure 7 shows an example of the results from our model. We can see that the model can run according to the rules and assumptions based on our conceptual model. Specifically, the vehicle A_{4834} enters the road at entry 2 at 155.1 sec. However, it encountered a traffic congestion, which delayed its entry into the main road by 0.5 sec. Hence, our model is functional.

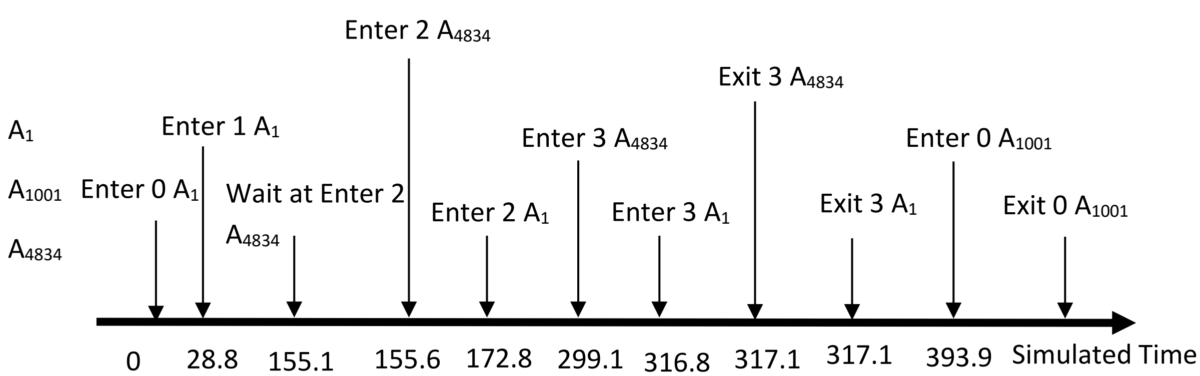

Figure 7. Example of the results produced by the model.

We verified our model by testing whether the event functions (enter, exit and change lane) and traffic characteristics (vehicles on ramps yielding to the vehicles on main road and the relation between the average velocity of vehicles and the traffic flow density) work as assumed in our conceptual model. The model simulates the road traffic over 15 min and the test has 5 repetition for each case.

5.1 Event Functions

5.1.1 Enter and Exit Events

The enter and exit events are the key functions that let the vehicles run onto and off the main road. Figure documents the statistic results of the amount of the in/out vehicles at each entry/exit. From the Fig. 8, we can see that the enter and exit events are fully functional. Firstly, the amount of vehicles entering each entry is approximately 2200, which matches the properties of vehicle generator. We set the fraction of vehicles exiting at exit at 30% and only vehicles on lane 0 can exit. At exit 0, the exit vehicles are approximately 15% of the incoming vehicles at entry 0, which is reasonable. The amount of exiting vehicles at exit 1 and 2 increases in that more vehicles are on the following sections of the road. Additionally, exit 3, denoting the main exit on the main road, keeps the majority of the vehicles, which makes sense as well. Hence, the Enter/Exit events and the random number generator for vehicles are fully functional.

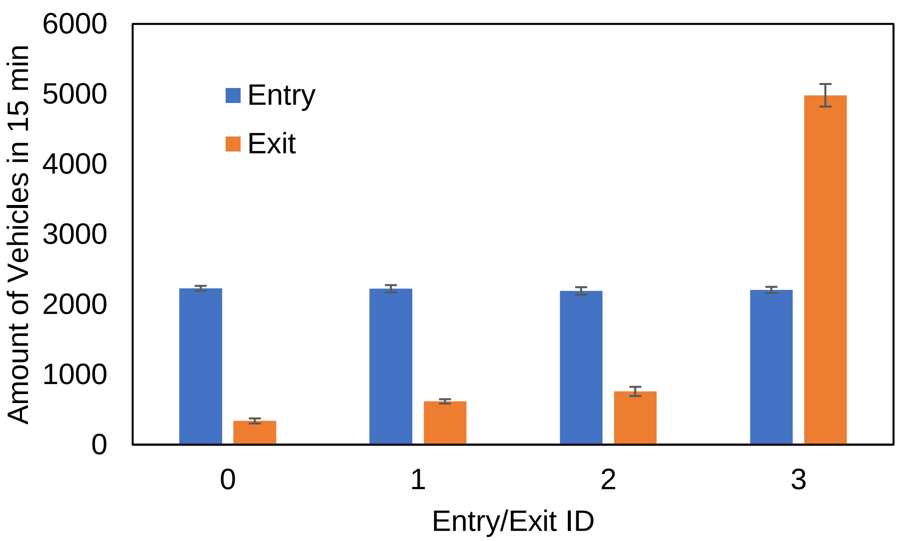

Figure 8. The amount of vehicles appearing at each entry or exit in the simulated 15 min. Error bars denote the confidence intervals.

5.1.2 Change Lane Events

A two-lane model incorporating four criteria for lane-changing [10] is adopted for the lane-changing event. Given that the distance between adjacent vehicles as a function of the difference between the time frames of the two vehicles passing the same location is definite, we modified the lane-changing criteria as following:

(i) Driver willingness: Random()<0.5;

(ii) $T_{\text{Front vehicle on the same lane}} - T_{\text{Current vehicle}} < 0.29$ sec;

(iii) $T_{\text{Front vehicle on the other lane}} - T_{\text{Current vehicle}} > 0.3$ sec;
(iv) $T_{\text{Current vehicle}} - T_{\text{Rear vehicle on the other lane}} < 0.3$ sec;
where T denotes the time frame when the vehicle passes the lane-changing check node. We picked randomly the vehicles which changed lanes in the simulation from five repetitions and checked the corresponding lane-changing criteria. Table 1 documents the lane-changing cases, the results of which satisfy with our criteria quite well.

Table 1. Verification of lane-changing criteria.

Car	Time frame when the vehicle passes the lane-changing node			
	$T_{\text{Current vehicle}}$	$T_{\text{Front, the same lane}}$	$T_{\text{Front, the other lane}}$	$T_{\text{Rear, the other lane}}$
1	1587.37	1587.20	1585.08	1592.96
2	1684.61	1684.97	1683.74	1684.91
3	689.14	688.93	687.87	695.17
4	1515.24	1515.12	1514.08	1521.25
5	551.80	551.67	549.82	557.82

5.2 Traffic Characteristics

5.1.1 Yielding Rule

Since we have multiple flow of traffic onto the main road, including the prior section of main road, and entry ramps, we need to enforce the top priority for the vehicles on the main road. In other words, the vehicles on the main road can run onto the next section when it reaches the entry point the same time as another vehicles on the entry ramp. To deal with this conflicts and set the priority, we developed a Yielding Rule for the vehicles on the entry ramp. When the vehicle on entry ramp conflicts with the vehicles on the main road, the entry time of the former one should be delayed by 0.5 sec every time until it does not conflict with vehicles on the main road in term of entry time. We picked randomly the vehicles which were delayed by the Yielding Rule at the entry ramp from five repetitions and checked the corresponding delay behaviors. Table 2 documents the delayed cases, the results of which satisfy with our Yielding Rule quite well. Notably, we captured a rare case (car 4 in Table 2) where the vehicle were delayed twice at the entry 3 ramp. This happened due to a quite heavy traffic.

Table 2. Verification of Yielding Rule.

Car	Time Frame of a	
	$T_{\text{Current vehicle}}$	$T_{\text{Front, the same lane}}$
1	587.80	588.30
2	380.63	1684.97
3	888.82	688.93
4	843.09	844.09
5	798.56	551.67

5.1.2 The Average Velocity of Vehicles as a Function of the Traffic Flow Density

We calculated the average velocity of the vehicles and the traffic flow density on the road at various time frames from the model (Fig. 9), which matches with the results obtained from measured data quite well (Fig. 6).

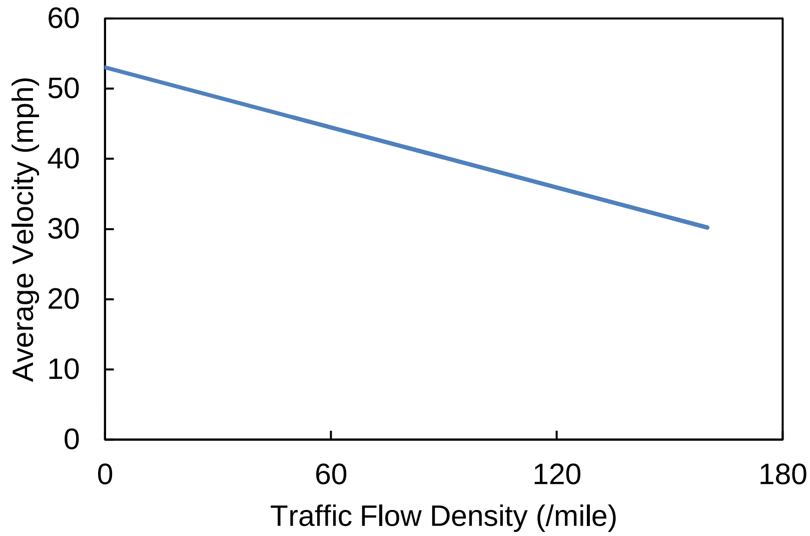

Figure 9. The vehicle average speed as a function of the amount of vehicle on the highway.

6. Validation

Validation of the model has been conducted in terms of the flow density, vehicle velocity history and average travel time.

6.1 Flow Density

Flow density is defined as the number of cars on the road, which is a significant parameter impacting car velocity and traffic condition. The car number pdf generated by our simulation is compared with that generated by data in Fig. 10. Two pdfs both show an increasing trend, followed by a decreasing after a peak around 125, indicating our simulation provides insight of characterizing the pattern of car number. The deviation between data and simulation is inevitable due to assumptions in our model.

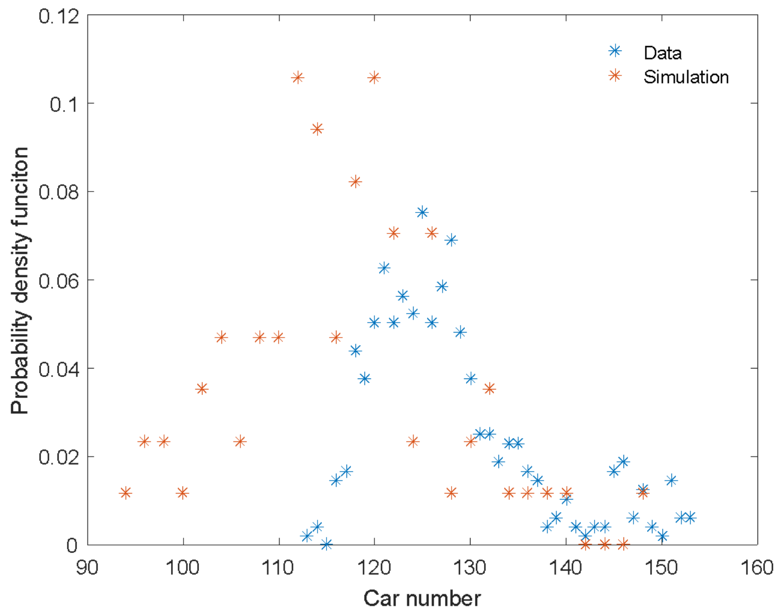

Figure 10. Comparison of probability density function (pdf) of car number between data and simulation

6.2 Vehicle Velocity History

We tracked a car traveling between two specific points to generate a velocity history. The velocity histories retrieved from data and simulation are compared in Fig. 11. Both velocity curves are changing between high limit (50 mile/hour) and low limit (20 mile/hour). Their changing trend may be different because traffic condition, i.e., congestion, lane changing, may occur and thus impact the car’s velocity. Our model is accurately predicting the velocity range of real world.

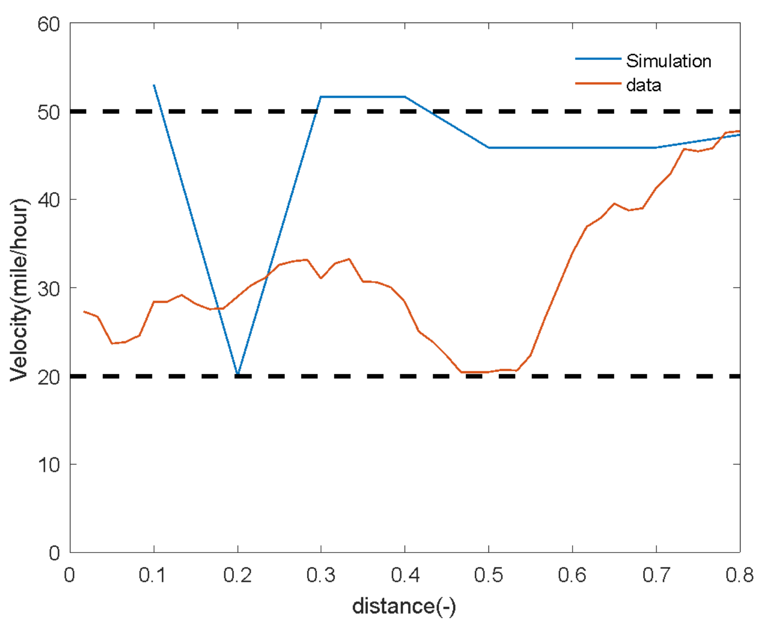

Figure 11. Car velocity history comparison between data and simulation.

6.3 Average Travel Time

The travel time for one specific car from one entrance to one exit from our simulation is compared with from google map. We simulated a light and heavy traffic respectively. The number of the car on the road is controlled by the car generator for entrances, i.e., smaller time span between cars for heavier traffic. According to Google map, the average travel time from Entrance 1 to Exit 3 varies during different time periods. Heavier traffic on weekdays leads to a longer travel time of about 6-12 minutes while it decreases to about 2 minutes on weekends, as shown in Fig. 12.

(a) (b)

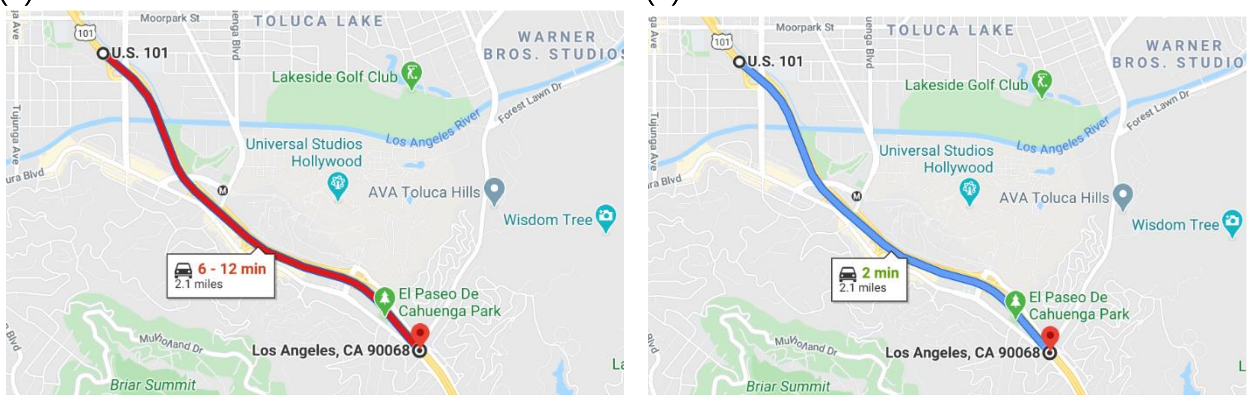

Figure 12. Travel time estimated from Google map (a) heavy traffic on weekdays (b) light traffic on weekends

In our simulation, the mean travel time for all the cars passing the road is 161s and 518s for the light and heavy traffic respectively. The comparison is shown in Table 3. Our simulated travel time is corresponding to the result of from Google map, indicating our model is applicable in predicting the traffic condition during normal and peak time.

Table 3. Comparison between Google Map and simulation estimation

	Light traffic	Heavy traffic
Google estimation	120s	360s – 720s
Simulation estimation	161s	518s

7. Results and Discussions

7.1 The effect of lane-changing criteria on the traffic efficiency

7.1.1 The importance of lane-changing

Figure 13 documents the amount of vehicles passing by the investigated segment of highway over 15 min with change-lane enabled or disabled at various traffic flow density (denoted by average travelling time). We can see that with the lane-changing introduced into the traffic rule, there is a pronounced increase in the amount of vehicles that can pass the segment. In other word, enabling changing lane on the highway can facilitate the smooth traveling on the road.

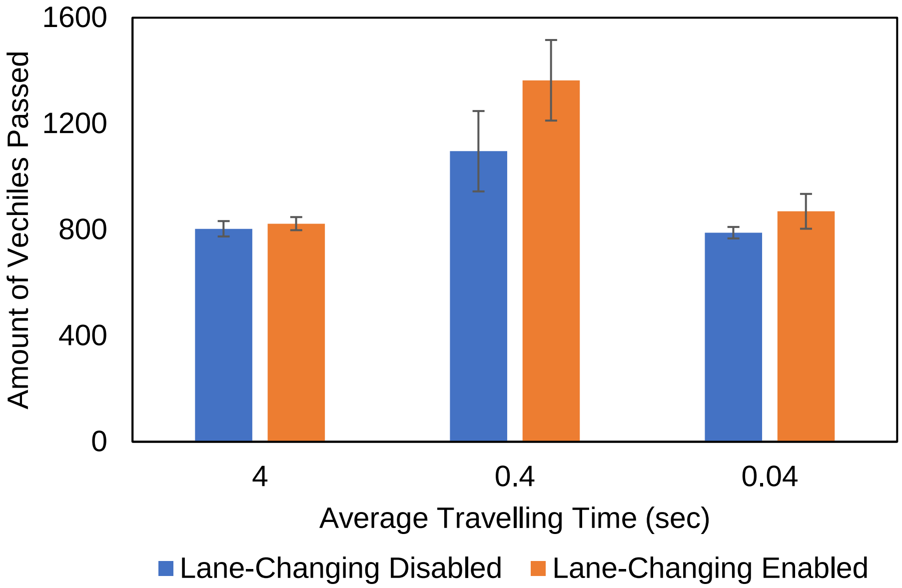

Figure 13. The importance of lane-changing in increasing the traffic flow efficiency. Error bars denote the confidence intervals.

7.1.2 Various lane-changing criteria parameters

After knowing the importance of enabling the lane-changing on the highway, we investigate the effect of the parameters of lane-changing criteria on the traffic flow efficiency, specifically, the threshold of difference between time frames when the vehicle and its surrounding vehicles passing the check node on road. We set the default value around 0.3 second, converted from the corresponding threshold for distance between vehicles in [5], as the mediocre threshold. Then, we set 0.1 sec and 1 sec as the radical and conservative threshold. From Fig. 14, we can see that increasing the threshold (being more conservative) is negative to the increasing of the traffic flow efficiency.

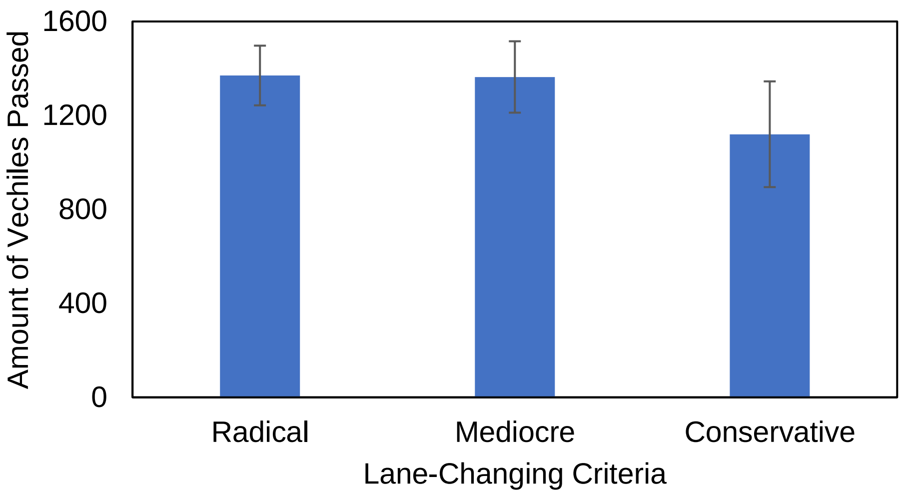

Figure 14. The effect of lane-changing criteria parameters on the traffic flow efficiency. Error bars denote the confidence intervals.

7.1.3 Various willingness level for lane-changing

Additionally, we varied the willingness level of the drivers for changing lane when they are able to. Figure 15. depicts the amount of the vehicles passing the segment of highway over 15 min as a function of the willingness level of the drivers for changing lane. Increasing the willingness level enhance the traffic efficiency as expected.

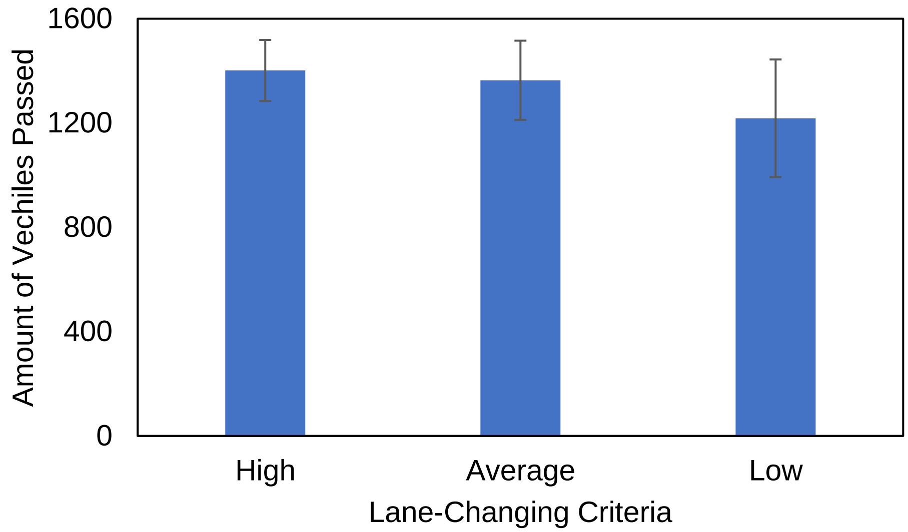

Figure 15. The effect of lane-changing willingness level on the traffic flow efficiency. Error bars denote the confidence intervals.

7.2 The effect of the locations of entry/exit on the traffic efficiency

In order to check the influence of the position of enter/exit on the efficiency of the road, different arrangements of the length of four sections are tested. The four section lengths are L1, L2, L3, L4 respectively. The total length L1+L2+L3+L4 are maintained the same. Four proposed arrangements as well as the original road settings are listed in the Table 4. The original road is long at the middle and short at the two ends. The second and third one is short at the beginning and long at the end. The fourth one is long at the beginning and short at the end. The last one is equal distributed. According to the results, the fourth arrangement, that is long at the beginning and short at the end, generates the best efficiency. The schematic arrangement is also shown in the Fig. 16. The fourth arrangement is the closer one to the design that separates the road into three sections, which means the less the enters/exits, the better the performance is.

Table4: Car finished at different arrangements of section length

L1/mile	L2/mile	L3/mile	L4/mile	#Car Finished
0.2	0.8	0.8	0.4	1435
0.2	0.6	0.7	0.7	1426
0.2	0.4	0.8	0.8	1468
0.9	0.9	0.2	0.2	1869
0.5	0.6	0.6	0.5	1409

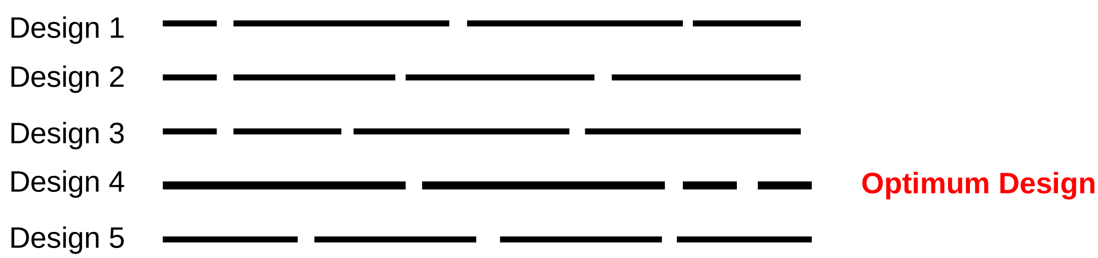

Figure 16. The schematic of different designs of entry/exit configuration.

8. Conclusions

In this project, we have developed software packages based on discrete event modeling to simulate the traffic flows on a segment of US 101 Highway in California. The model is verified to match our conceptual model via several test cases and validated by comparing with the actual data collected from real traffic situations. The model, resembling the real traffic, adopts the 2-lane model incorporating the lane-changing events. It has been found that enabling the lane-changing on the road can effectively increase the traffic efficiency at various traffic flow density. Furthermore, changing the parameters of the lane-changing criteria smaller has positive influence on increasing the traffic efficiency. However, increasing the willingness level for lane-changing of the drivers does enhance the traffic efficiency. Lastly, an optimal design of the entry/exit configuration over the segment of the highway under investigation has been proposed, which shows an increased traffic efficiency. Notably, the current model is not perfect in that the real highway has more than 2 lanes. In light of this, we may explore to simulate multiple lanes with more complicated lane-changing criteria via cellular automata (CA) model.

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