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2017

MCM/ICM

Summary Sheet

(Your team's summary should be included as the first page of your electronic submission.)

Type a summary of your results on this page. Do not include the name of your school, advisor, or team members on this page.

The Design of Toll Station's Fan-in Area

Summary

We aim to devise a system which includes four specific models to evaluate the performance (including traffic carrying capacity,risk of accident and the cost of tollbooths) of the toll station's 'fan-in' area.

The dimension measuring model is built to calculate the size of the fan-in area.It's based on acceleration and rate of transition can describe the performance in different situation.The shape and size of 'fan in' area is very significant to generate a satisfying performance. The length of area should be long enough to support vehicles to speed up,and unnecessary length will also lead to a waste of money(road construction).We used the transition rate to prove that concave part may help to improve security of the area according to calculation.Our advice is to mix part of concave boundary with convex one and convex part should still be major.

The queuing theory model is able to confirm the number of tollbooths and lanes.

The car following model is built to achieve the safety distance.

The traffic condition simulation model is set and realized by Java and MATAB to simulate performance of the traffic.It's a simultaneous dynamic simulation of the situation in 'fan in' area based on continuous speed,driving direction and coordinate.Due to the continuous parameters in the model,the simulation is more accurate than other ways like cell machine,which is based on discrete grid.The step time in the simulation can reach 0.01s which can simulate the delay time from the happen of an emergency to the movement to change vehicle's state, sufficiently.The fundamental unit in simulation is a single vehicle.It is able to check surroundings,respond to it and run in the area.The program puts vehicles in the areas,checks the statement and then simulates the situation.The result shows if system can distribute vehicles to certain lances,the performance will be improved a lot.

In the heavy traffic,the simulation shows the risk of accident will increase,but our scheme is still applicable.If there are some self-driving cars added into 'fan-in' area,their fast reaction and correct decision will help to improve the performance.As for different types of tollbooths,the result shows that high proportion of ETC booths enhances the traffic carrying capacity.But too many ETC booths may become a hidden trouble in traffic problem more or less.

Eventually we evaluate the model by repeatability test and sensitivity analysis.

Key words:traffic management,simulation,tollbooths design,risk evaluation

Contents

1.Introduction

1.1 Background

Ever since the 1950s, the United States has finished the construction of 88,000 kilometers of highways, about half of the world's total highways quantity.This makes America the country which contains the most highways in the world.Thus it can be seen,in modern society,traffic conditions of the highways determine the overall traffic level of a country.So, the planning of various facilities on the highway becomes particularly important. Barrier tolls are the bottleneck of freeway traffic flow, and the capacity of toll station directly affects the traffic capacity of highway, which generally restricts the traffic condition of highway.Moreover, with the further development of highway-net and the rapid development of automobile industry, the demand of materials and personnel transportation is increasing day by day. The traffic flow of expressway is still growing rapidly. Mainly reflected as:first, the rapid development of private cars, which leads to the increase of small and medium-sized cars.The growth of tourism during holiday is also very fast.Second, the demand of cross-regional transport grows a lot, large tonnage transport vehicles increased; The third is overloading, the number of overloading vehicles has reduced, at the same time, social traffic demand has increased significantly. The rapid growth of the volume of traffic, has resulted in serious traffic jam in many places, therefore the existing toll station mode can not meet the recent needs.

At present,the main forms of payment which most of toll stations use are: conventional tollbooths,exact-change tollbooths, and electronic toll collection booths .Electronic toll collection booths have the characteristic of time-saving and there is no need for it to stop.But the popularity of ETC is still low compared with the other two methods. Most of the highway toll stations changed some of the conventional tollbooths and exact-change tollbooths into electronic toll collection booths which forms a type of hybrid highway toll station. Based on this type of toll station ,designers need to pay attention to the allocation of different types of toll booths, it must be ensured that toll booths should achieve the highest utilization rate in the peak hours . Moreover, since the number of toll booths in a enclosed type toll station tends to be larger than the number of exports, clogging tends to occur in the fan-in areas.Thus the shape, size and merging parttern of the zone become the essential factors which determine the traffic capacity of the toll stations.

1.2 Our Work

The problems require us to plan the fan-in area which located between the tollbooths and the exits.We should design its shape, size, and emerging pattern to achieve the optimal traffic conditions. What’s more examine whether such a scheme is still applicable under different roads conditions, vehicle types and payment methods. When we are processing the project,the factors should be considered contains: traffic flow, traffic accident prevention and road construction costs.How to realize lager traffic flow and lower the probabilities of traffic accidents with the minimum cost is the main issue that must be considered carefully.

First of all, this area is divided into three main parts: tollbooths part, acceleration part and exit part. In order to determine the shape and size of the area,width of the tollbooths part,exit part and acceleration part should be calculated out.The relevant factors include the distance required for the vehicles to reach the minimum speed permitted by the highway, the construction funds, vehicles’ driving methods and so on. The data calculated from multiple factors are more accurate and comprehensive.In order to ensure the safety of vehicles traveling in the region,we should also analyze how to maintain the distance and speed in the region to lower the probabilities of the occurrences of traffic accidents.Based on the considerations above, draw up the layout of the tollbooths, determine their quantities and types ,also the merging pattern. Then programming to simulate the regional traffic condition.

Secondly, changing the number of vehicles passing through the toll station in the simulation program to reflect the crowding degree of the road, and using the simulation program to observe the emerging pattern of the exit under different congestion conditions. At the same time, with more existences of autonomous (self-driving) vehicles on the road, this may affect the efficiency of merging and security, therefore we add some autonomous vehicles to the simulation program,in order to analyze the security level of the area.In that way,the effect of the scheme can be presented.

Finally, complete the establishment,test and analyzation of the scheme.The final judgment should be done ,so that we can analyze its advantages and disadvantages.

1.3 Symbol Description

v_p :The minimum speed allowed by the highway.

l_{ri} :（$i=1、2$）The length of the acceleration zone.

d_{ri} :（$i=1、2$）The total width of the tollbooths and exits.

a :The minimum acceleration of the vehicle.

P_r :The size of the designed area.

K_r :Transition rate of the designed area.

S :Minimum safety distance between vehicles.

Q :The traffic capacity of the road.

$E(\lambda)$:The predicted number of vehicle collisions.

x_i :Collision coefficient.

γ_i :Coordination factors.

β :The factor of traffic collision capacity.

V :The maximum traffic flu.

C :The maximum traffic capacity.

2.Models

2.1 Establishment

2.1.1 Assumptions

The following assumptions are listed to simplify this model.

• All the vehicles reach the exports should accelerate to the minimum velocity permitted by highways.

• The initial speed of the cars start from the conventional tollbooths and exact-change tollbooths is 0.

• There is no reaction time of autonomous (self-driving) vehicles,but they still need braking time.

2.1.2 Basic Structure Of The Area

According to analysis of the problem,when designing the shape,size,and merging pattern of the area following the toll barrier in which cars fan-in from toll booth egress lanes down to lanes of traffic,there are three significant factors to consider including accident prevention ,throughput and cost of tollbooths.According to those factors,the working model of the designed area presents like this: Code the exports from 1 to 3,the signal lights determine whether the cars through the tollbooths should pass or not.The signal lights also determine which export should the cars come through.If the signal lights show the cars to go,the cars will accelerate in the fan-in area and then enter the assigned export.It should be noted that, cars which are showed to enter the same export,should keep a safe distance between each other.In order to prevent the rear-end accident.

Considering that vehicles do not need to stop when passing the ETC lane , we set the ETC dedicated lane. Build the sign to call driver’s attention to keep distance between each cars, rather than take coercive measures to intercept the vehicles.Regarding to the number of ETC dedicated lanes, we found some informations from references[1]:

(1) When ETC usage rate is 30%, configure one or two ETC dedicated lane , the overall service level is higher than the present situation. When the traffic flux is lower than 1100vph, it is better to configure an ETC dedicated lane. When the traffic flux is higher than 1100vph,the configuration of two ETC dedicated lane is more appropriate. it is better to configure two ETC dedicated lanes.

(2) When ETC usage rate is 40%, configure one or two ETC dedicated lane , the overall service level is higher than the present situation. When the traffic flux is lower than 1200vph, the configuration of an ETC dedicated lane is wise; when the traffic is higher than 1200vph, the configuration of two ETC dedicated lane is more appropriate.it is better to configure two ETC dedicated lanes.

(3)When ETC usage rate is 50%, configure one or two or three ETC dedicated lane , the overall service level is higher than the present situation. When the traffic flux is lower than 1300vph, the configuration of an ETC dedicated lane is wise; when the traffic is higher than 1300vph, the configuration of two ETC dedicated lane is more appropriate.it is better to configure two ETC dedicated lanes.

(4)When ETC usage rate is 60%, configure one or two or three ETC dedicated lane , the overall service level is higher than the present situation. When the traffic flux is lower than

1400vph, the configuration of an ETC dedicated lane is wise; when the traffic is higher than 1400vph, the configuration of two ETC dedicated lane is more appropriate.it is better to configure two ETC dedicated lanes.

(5)When ETC usage rate is70%, configure one or two ETC dedicated lane , the overall service level is higher than the present situation. Whatever the traffic flux is,the configuration of two ETC dedicated lane is more appropriate.it is better to configure two ETC dedicated lanes.

Sum up these five cases , a single direction with two ETC dedicated lane is more widely applicable, so in our scheme it is better to configure two ETC dedicated lanes.

2.1.3 Size Of The Area

Length of the fan-in area should be longer enough to support cars' acceleration[2].At the same time,land and road construction costs lots of money and unnecessary distance of the area will lead to a huge waste.Here we can model from analysis:the road length of fan-in area , is mainly determined by the distance which allow vehicles to speed up from rest to lowest required speed on the highway:

$$\begin{cases} v_p = at \\ l_{r1} = \frac{1}{2}at^2 \end{cases}$$

The distribution of minimum speed which is permitted on highway in United States is shown in Figure 1:

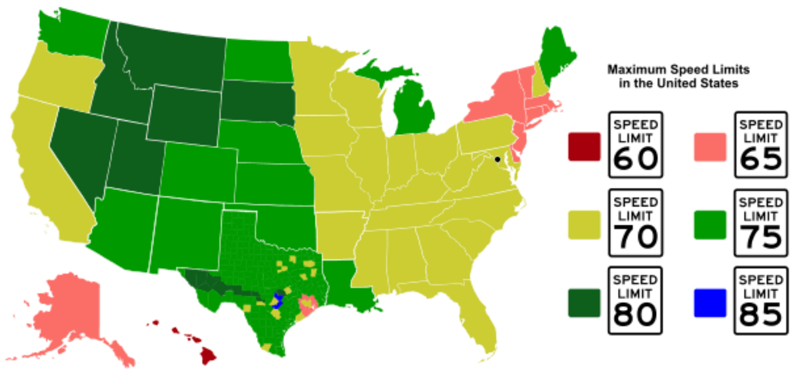

Figure 1 :Maximum Speed Limits in the United States. (From Wikipedia)

As the figure showed us, the region of which speed limit is 70km / h is the most widespread, so we take v_p = 70km/h for calculation. The Table 1 shows the acceleration of different cars:

Table 1:The Acceleration Time of Different Types of Cars

TYPE	Times needed to accelerate to 100km/h(s)
Porsche Turbo S 3.8T	2.98
Audi V10 performance	3.41
Land Rover 3.0 V6 SC Vogue SE	6.62
Santana 230TST DSG	8.83
Honda XR-V 1.5L Lxi CVT	10.09

Citroen C4 PICASSO	10.57
Jetta 1.6L	12.36

According to the analysis of actual situation ,accelerated length depend on the acceleration of vehicles.In order to make all the vehicles gain the allowed speed through the accelerated area ,we take the minimum acceleration for calculation.When $a = 2m/s^2$,calculations indicate that $l_{r1} = 94.5m$.

As for the actual highway, the most common type is the two-directions six-lane highway, which owns three one-direction exits[3]. In the premise of three exports , utilizing the queuing theory to build the model. It is a remarkable fact that the velocity follows the Gaussian distribution:

$$F(x) = \int_{-\infty}^{x} \frac{1}{\sqrt{2\pi}} e^{-\frac{t^2}{2}} dt$$

The arriving cars follow the Poisson's distribution:

$$P_n(t) = \frac{e^{-\lambda t}(\lambda t)^n}{n!}$$

Supposing that there are S tollbooths, every tollbooths are independent from each other, so they follow the Queue Discipline. According to the Queuing Theory, it can be concluded that the scheme is the most efficient when S equals 8.Based on the ordinary geometric size of highway toll station,this scheme uses some geometrical parameters :the width of conventional tollbooths is 3.2 m,the width of electronic toll collection booths is 3.6 m, and the width of one common lane is 3.75 m.We set eight tollbooths match three exports for calculation,The total width of the tollbooths part is $d_{r1} = 26.4m$,and the width of export part is $d_{r2} = 11.25$m .We assume that K_r refers to the rate of transition.The equation is :

$$K_r = \frac{d_{r1} - d_{r2}}{l_r}$$

If the transition rate is too small ,the length of the acceleration zone is too big, the scale increases, so the investment also increases ; If the transition rate is too big,the traffic flows will focus on the central lane,therefore the peripheral lane can't be used sufficiently.Even the normal traffic while the peak hours might be affected.The transition rate of the main square should be 1/5 to 1/7, generally not less than 1/10. In our scheme,we take $K_r = \frac{1}{6}$ for calculation:

$$l_{r2} = \frac{d_{r1} - d_{r2}}{K_r}$$

Calculation indicates that the minimum length of the acceleration area $l_{r2} = 90.9m$,now we get

l_{r1} and l_{r2},the weight factors of them are determined by their impacts on l_r.Establish the equation:

$$l_r = 60\% l_{r1} + 40\% l_{r2}$$

Calculation indicates the optimal length of the acceleration area $l_r = 93.06m$ .Assuming that the size of the region is P_r, then we can establish the equation:

$$P_r = \sqrt{\left(\frac{d_{r1} - d_{r2}}{2}\right)^2 + l_r^2}$$

Calculation indicates that the size of the region $P_r = 93.36m$.

2.1.4 Shape Of The Area

Figure 2 shows the structure of the fan-in area :

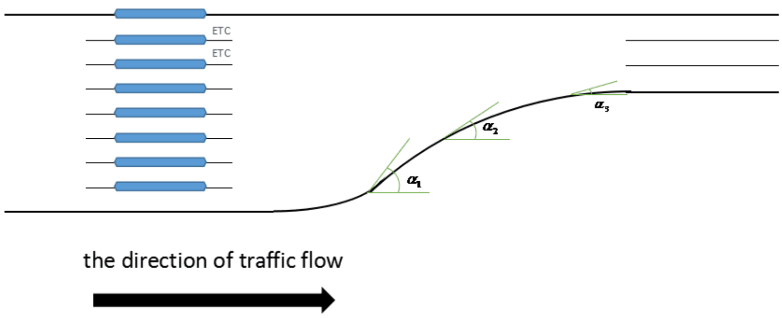

Figure 2:Schematic Diagram of The Fan-in Area

As shown in the Figure 2, α_1 α_2 α_3 respectively refers to the angle change of fan-in area in beginning,middle and ending section of the road.In our scheme, we use convex structure in the beginning and middle section of the fan-in area.For the reason that the speed of the vehicles in these sections are generally low, make the rate of transition bigger than 1,so that the area can contain more vehicles into the export. On the contrary ,we use the concave structure at the end of the fan-in area. This design can make the rate of transition lower than 1/10, so the high-speed vehicles could merge safely. What's more,considering that many two-directions lanes are closely near or quarantined by the green belt and other obstacles,we ignore the design of the left side here(to see towards the direction of traffic flow).

2.1.5 Emerging Pattern Of The Area

While we are designing the traffic mode in this area ,it should also be taken into consideration that 'when should the signal lights show available for the next vehicle' and 'which export should the vehicles pass ' .In order to solve these questions,a dynamic distributed method of cars is adopted to realize flexible distribution of traffic routes, which can alleviate the traffic congestion at the exit and increase the traffic volume [4].The programming details are :

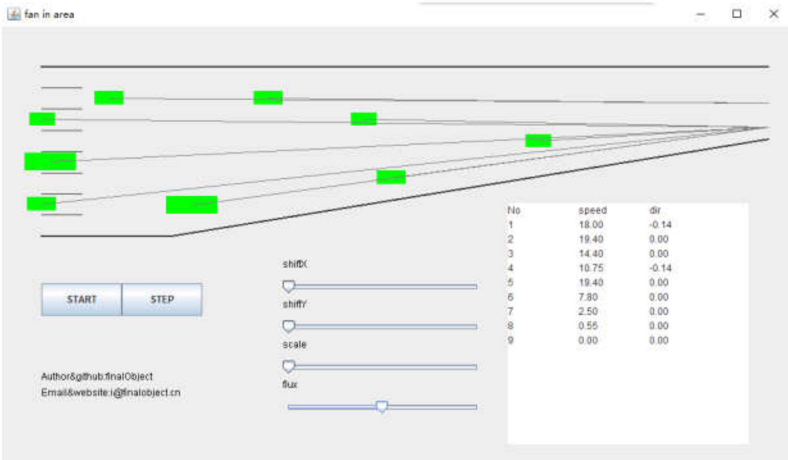

Figure 3:Interface of Program

In emerging pattern,here is an simulation to simulate the situation and the dynamic change in fan-in area.

The simulation is coded by finalObject(Xiaobo Hu) on Java based on Java basic tools and all codes are available on https://github.com/finalObject/simulationOfFanInAreaMCM.

In program,the simulation of vehicle's position,speed and driving direction are continuous.Because of that,the simulation is surely more accurate than other ways like cell machine,which is based on discrete grid.The elementary unit in the program is Car.Car's parameters includes size,maximum acceleration,speed,driving direction and so on.Characteristic of car's drive will also be covered in car's parameters including reaction time,the chance to change lanes and safe distance.A set of cars run on the 'fan in' area,which is determined by the size of tollbooths and lances.

There are many matches of parameters to simulate and next result will be based on this match:

Table 2:Process of Program

number of ETC tollbooths = 2	range of vehicle's driving direction = 120°
number of normal tollbooths = 6	width of lanes = 3.75m
width of ETC tollbooths = 3.6m	number of lanes =3
width of normal tollbooths = 3.2m	

Three different types of of vehicles:

Table 3:Size of Different Types of Cars

	Maximum acceleration(m/s^2)	Width(m)	Length(m)
Car 1	5.5	2	4
Car 2	3	2.2	4.5
Car 3	2.5	2.8	8

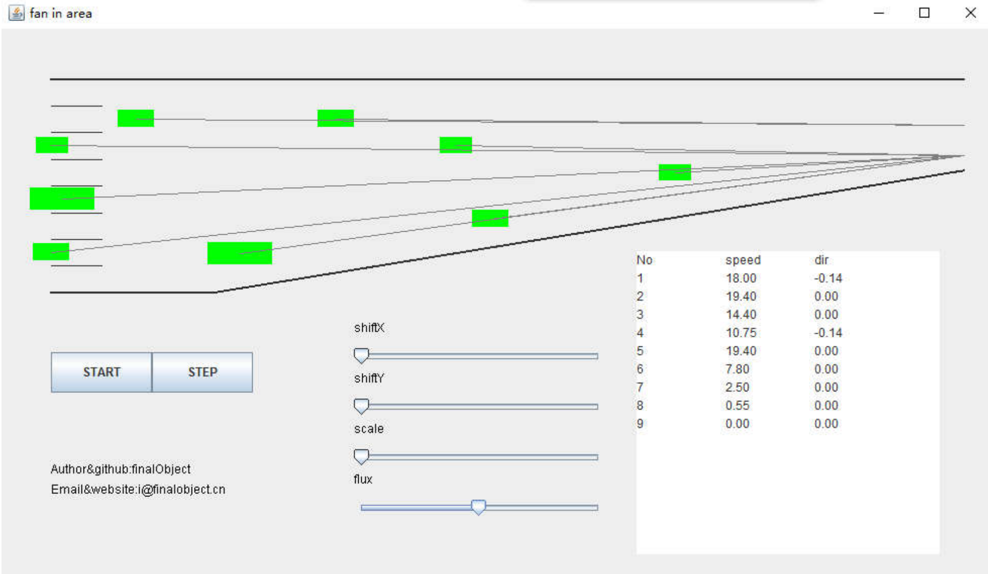

Figure 4:User Interaction Interface

In program,it consider vehicle and its driver as a whole.It will be check situation with the border of area,other cars and its target position,then it change acceleration to adjust its speed and driving direction after a reaction time.Of course,some vehicle like to change target,the lanes,as it likes,which has to be taken into consideration.This is how the simulation works.

2.2 Safety Assessment

2.2.1 Safe Distance

From the safety point of view, in the fan-in area ,the space between each cars should be limited,so that traffic accident could be prevented[5].To deal with this problem,a car-following model based on the minimum safety distance is established. The Car Following model is established direct at the guide vehicle A which keep stationary state,uniform motion state or uniformly retarded state.Assuming that the interval between two vehicles A and B is S ,they are driving towards the same direction on the same road at the speed of v_A and v_B .The initial relative velocity between these cars $v_e = v_A = v_B - \frac{a_{B\max} t_p^2}{2t_B}$, S_A and S_B refer to the driving distance of vehicle A and vehicle B .The maximum acceleration of them are written as $a_{A\max}$ and $a_{B\max}$.

(1) The guide vehicle keeps stationary state.

When the current guide car A is static, $v_A = 0$ also $S_A = 0$, driver’s reaction and braking time t_z . the minimum distance between the guide vehicle and the following vehicle l (rank from 2m to 5m).We can get the equation of the minimum safety distance between A and B:

$$S = v_B(t_z + \frac{t_B}{2}) + \frac{v_B^2}{2a_{B\max}} + l$$

(2) The guide vehicle driving at a constant speed

Since the process of vehicles' movement,when the guide vehicle is at a constant speed state, the guided vehicle's speed is obviously higher than the former. Further more the relative speed is big, after a certain time, It may occurs rear-end accident. Therefore when the distance between cars has almost reached the safe distance, the guide vehicle should slow down to ensure the safety of each other. Due to the guide vehicle A has been in a uniform state of motion, when the following vehicle B keep moving with the same speed , we can make sure the Car-following is safe . Then:

$$S_A = v_A(t_z + \frac{v_B - v_A}{a_{B\max}} + t_p)$$

$$S_B = v_B(t_z + \frac{t_p}{2}) + \frac{v_B^2 - v_A^2}{2a_{B\max}}$$

The equation of the minimum safety distance between A and B :

$$S = v_e(t_z + \frac{t_p}{2}) + \frac{v_e^2}{2a_{B\max}} + l$$

When the relative velocity between these cars v_e is too small,after t_p ,the speed of the following vehicle may be the same with the guide vehicle .For this moment, $v_A = v_B - \frac{a_{B\max} t_p^2}{2t_B}$. The equation of the minimum safety distance between A and B :

$$S = v_e(t_p + t_B) - \frac{a_{B\max} t_B^2}{6} + l$$

(3) The guide vehicle keeps uniformly retarded state

In the process of traveling,it is a risk that the speed of the guide vehicle is lower than the speed of the following vehicle, because the guide vehicle is ready to drive in the course of driving, so there is no delay for the uniform deceleration, the reaction time t_z is negligible. The difference between a guide vehicle and a following vehicle is that the following vehicle slows down before the vehicle starts to decelerate and there is a delay in time t_z .All in all,The equation of the minimum safety distance between A and B :

$$S = v_B t_z + \frac{v_A t_p}{2} + \frac{v_B^2}{2a_{B\max}} - \frac{v_A^2}{2a_{A\max}} + l$$

If $v_A = v_B$,The equation changes as:

$$S = v_B t_z + \frac{v_B^2}{2}\left(\frac{1}{a_{B\max}} - \frac{1}{a_{A\max}}\right) + l$$

2.2.2 Crash Prediction

Crash prediction model is a effective model for analyzing the condition of roads[6].It can predict the rate of crashing and asses the safety level of the road.The expression is:

$$E(\lambda) = \alpha Q^{\beta} e^{\sum \gamma_i x_i}$$

Q refers to the traffic flux, $E(\lambda)$ is the estimated number of crashes, x_i is a risk factor, γ_i refers to the corresponding coefficient and β refers to the effect of traffic flux on crashes.In the practical problem,traffic flux Q is in random variation.The random arrival vehicles follow Poisson distribution:

$$P_n(t) = \frac{e^{-\lambda t}(\lambda t)^n}{n!}$$

λ represent mathematical expectation of traffic flux Q and we can obtain the equation:

$$E(\lambda) = \alpha \lambda^{\beta_1} e^{\sum \gamma_i x_i}$$

Other parameters such as risk factor and the effect of traffic flux on crashes can be changed in some ways.In our scheme,we keep the safety space between contiguous cars and reduce the risk factor.In this way,the predicted number of crashes changed as:

$$E(\lambda) = \alpha \lambda^{\beta_2} e^{\sum \gamma_i x_i}$$

$\beta_1 > \beta_2$,the number of crashes reduced effectively.In summary,it is safer when the vehicles keep the safety distance between each other.

2.3 Result Analysis

2.3.1 Based On Funds

As a result for all the calculation above,we can get the parameters of the designed area,as the chart shown below:

l_r	93.06m
d_{r1}	26.4m
d_{r2}	11.25m
P_r	93.36m
S	12m

Table 4:the parameters of the designed area

From the references,we could get the picture of CrossBay Toll,the other toll station in America:

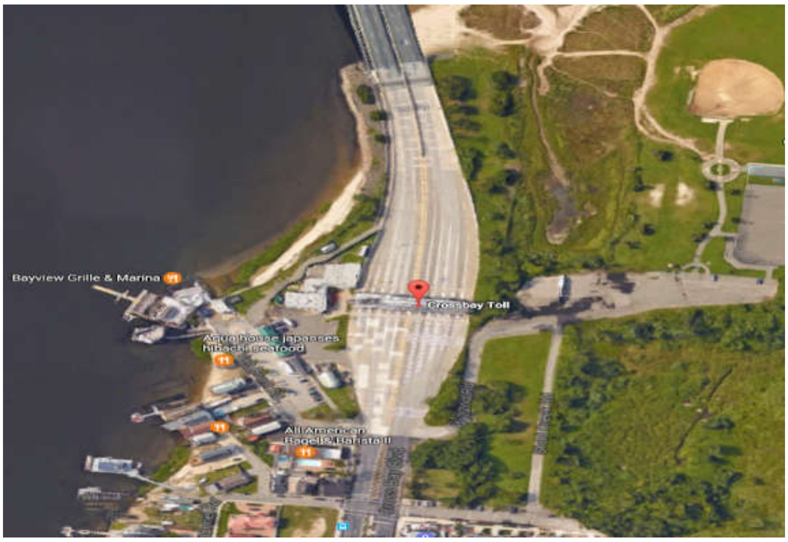

Figure 5:The Picture of CrossBay Toll.(From Google Map)

The parameters of CrossBay Toll:

Table 5:parameters of CrossBay Toll

l_r	195m
d_{r1}	30.97m
d_{r2}	12.87m

Compared with the parameters of our designed area, we can see that the width of CrossBay Toll's tollbooths region and exit road region is roughly the same with ours, but CrossBay Toll’s acceleration area is too long, so the project is very large, cost Large amount of funds.our scheme can remedy its shortcomings.Meet the actual needs on the basement of saving money.

2.3.2 Based On Traffic Flux

In order to measure the capacity of the program to improve the state of traffic at highway toll stations,we use the notion of saturation.

The saturation index is the ratio of the maximum traffic flux to the maximum capacity, that is, the degree of balance between the demand and supply of the surrounding road traffic[7]. As the level of road service, crowded degree are affected by a number of factors, the saturation is always used as the main index for measuring, the equation is as follows:

$$q = V / C$$

V The maximum traffic flux

C The maximum traffic capacity

According to the 《Capacity Manual》, there are six levels of traffic saturation, as shown in the following table:

LOS	V/C Ratio
A ,B&C	<0.77
D	0.78-0.85
E	0.86-1.00
F	>1.00

Table 6:Levels of Traffic Saturation

Levels higher than E-level are identified as congestion.

In addition, according to the prepared program simulation ,it can be obtained that in the case of different total traffic flux, the increment of traffic flux per hour in this area .As shown in the following Table 7 and Figure 6:

Table 7:Increase of vehicle number

vehicle flux(per hour)	900	1300	1700	2100	2500	2900
Increase of vehicle number in the area per hour	0	0	2	10	65	133

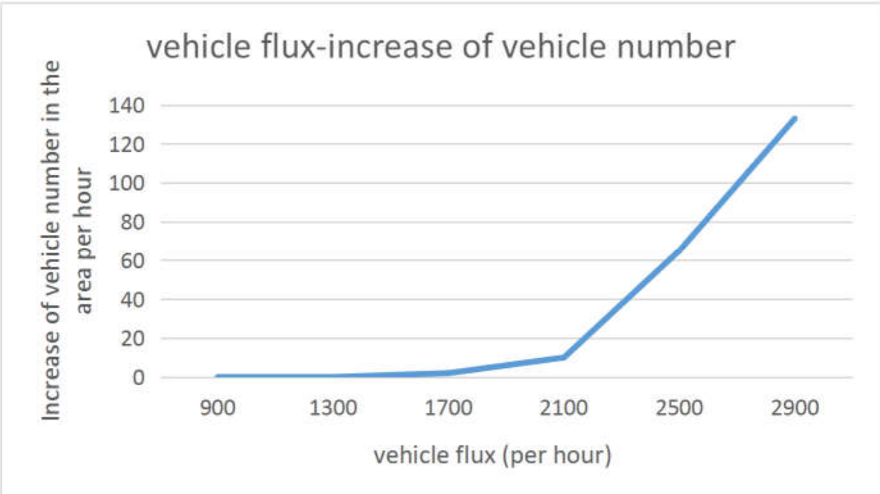

Figure 6:Vehicle Flux-increase of Vehicle Number

When vehicle flux is blew 2100,there is no stress for fan-in area,where vehicle flux was increased to 2500,the area became crowed.But flux is 2900 per hour,it will be blocking!

2.3.3 Based On Accident Incidence Rate

Simulated by the program,here are some results When vehicle flux is 1500 per hour:

Table 8:Risk of Accident

Chance of changing lanes	1%	3%	5%	10%	15%	20%
Risk of accident	0.000 001%	0.000 001%	0.00 0003%	0.000 009%	0.00 0023%	0.00 0088%

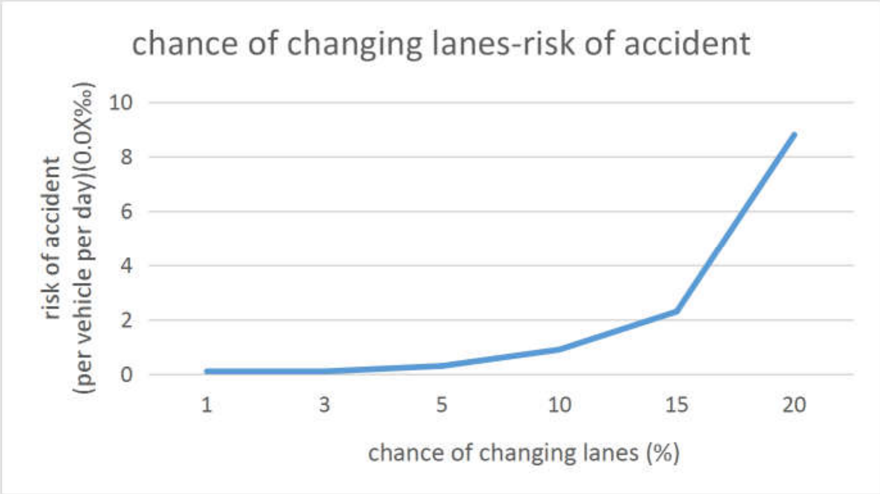

Figure 7:Chance of Changing Lanes-risk of Accident

It's clear that when chance of changing lanes is smaller than 10%,the risk is smaller than 0.00001%,which means it is very safe.So the safety of this area can be guaranteed.

2.4 Additional Advice

Whats' more ,there is a daring advice for emerging pattern!According to the result,we can get conclusion that choosing lances blindly is a major reason to increase the risk of accident.If the tollbooth can give vehicle advise or order to set a certain lance as target,the condition will be improved.The tips from tollbooths is based on condition of lanes,can distribute vehicle to lanes dynamically.

Dynamic distribution is coded by finalObject(Xiaobo Hu) on MATLAB based on MATLAB basic tools and all codes are available on https://github.com/finalObject/mergeAfterToll.

Table 9:Increase of vehicle number

vehicle flux(per hour)	1300	1700	2100	2500	2900	3300
Increase of vehicle number in the area per hour	0	0	0	15	102	141

According to the simulation,no stress vehicle flux has been increase from 2100 per hour to 2500 per hour,which means it does help to increase the area's carrying capacity in some way.

3. Model Extension

3.1 Solution In Light And Heavy Traffic

The greater the traffic flux in the toll station is,the traffic condition inside the toll station is more complex.And greater traffic pressure will be given to this area. In order to study the feasibility of the scheme when the traffic of the toll station is congested or unobstructed. We use the program to simulate the traffic merging pattern in this area, and the simulation result is shown as follows[8].

vehicle flux(per hour)	900	1300	1700	2100	2500	2900
Increase of vehicle number in the area per hour	0	0	2	10	65	133

Table 10:Increase of Vehicle Number in The Area Per Hour

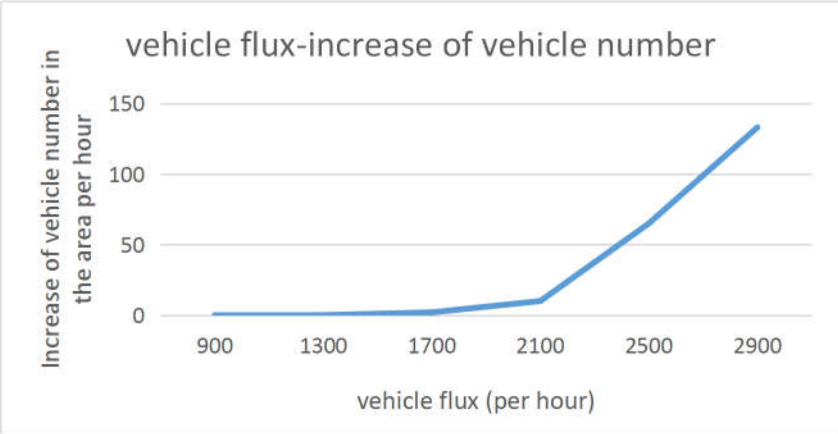

Figure 8:Vehicle Flux-increase of Vehicle Number

Ignore the different reaction time of different people,we take 0.4s as the reaction time,here.Through the simulation of different traffic flux, When the traffic flux rank from 900vph to 2100vph, increase of vehicle number in the area per hour is slow,so the road is not in a crowded state. When the traffic flux exceeds 2100vph, there are some vehicles waiting in line in the fan-in area.When the traffic flux is greater than 2500vph, the traffic condition of this area is very crowded. When the traffic flux reaches 2900vph, the vehicles continued to gather in the fan-in area , resulting in traffic congestion.

When Chance of changing lanes is 5% per.

Table 11:Risk of Accident

Vehicle flux (per hour)	900	1200	1500	1800	2100	2400
Risk of accident	0.0000005%	0.0000008%	0.000003%	0.00002%	0.000033%	0.00015%

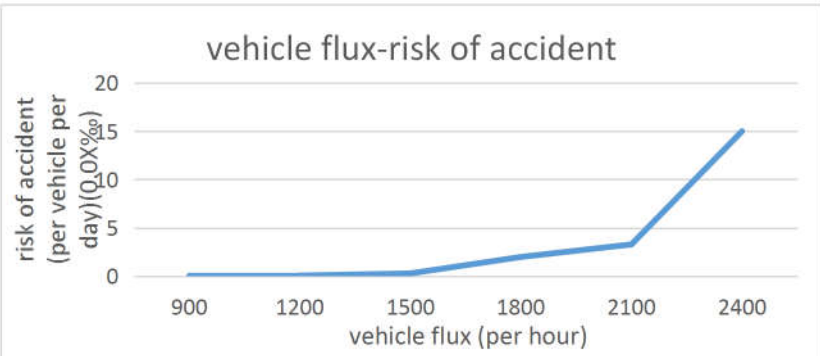

Figure 9:Vehicle Flux-risk of Accident

It can be seen that,the risk of accident will increase as vehicle flux increase.In the area we designed,when the vehicle flux is below 1500vph,the probability of a car accident is kept below 0.0000008%;when the flux is greater than 1500vph, the probability of a car accident increased slightly, but it is not high in general. It can be concluded that our scheme can guarantee the safety of the traffic in the area,whether the traffic is congested or not.What's more the operation of the program is the best under the circumstance that the flow does not exceed 1500 per hour.

3.2 Effections Of Autonomous Vehicles

With the advancement of science and technology, autonomous technology has become more and more popular. In recent years, autonomous vehicles have come closer to people's life. In order to study the change of the operation mode of the area we designed when the traffic flow contains a certain percentage of autonomous vehicles, we add a certain proportion of autonomous vehicles to the traffic flow, use the procedures we have written to simulate the condition in the toll station. When all of the cars are autonomous vehicles, on account of the fixed route and velocity of autonomous vehicles,they can determine the best choice for export through the precise distance measuring. When the proportion of autonomous vehicles is only a small part of the traffic flow,the acceleration of autonomous vehicle is fixed,if the acceleration of the latter vehicle is too big , rear-end accident may happen.Accordingly, we conducted a simulation to test the rationality of the scheme.

The different between autonomous vehicles and normal vehicles is the react time and the correctness of decision.Autonomous vehicles are controlled by computer mounted with many precision sensors.It's react time should be small enough to ignore it so the react time is only be limited by mechanical braking.What's more,autonomous vehicles are not supposed to make meaningless decision like changing lanes with no reason.

In the model we built,these variable can be represented to change output:

Table 12:Max vehicle flux

Proportion of autonomous vehicles	0	5%	10%	15%	20%	25%
Max vehicle flux	2150	2188	2207	2230	2233	2238

When normal vehicle's chance of changing lanes is 5%

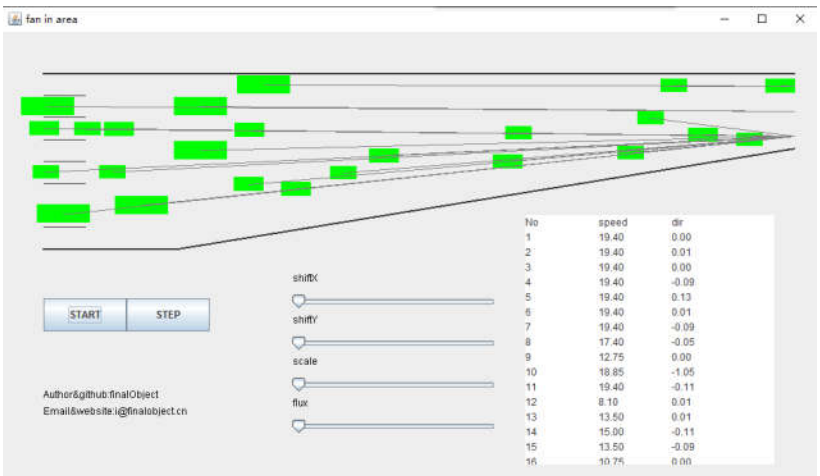

Figure 10:Interface of Program

The simulation results show that ,the maximum traffic flux is 2150vph when there is no autonomous vehicles.What's more,the maximum traffic volume is 2188、2207、2230、2233、2238 when the percentage of autonomous vehicles is 5%、10%、15%、20% or 25%.These datas show an upward trend,which prove that the addition of autonomous vehicles can have an effective improvement on traffic flux.

3.3 Proportions Of Different Tollbooths

From the questions we can know that the existing tollbooth is divided into three types : conventional(human-staffed)tollbooths,exact-change (automated) tollbooths, and electronic toll collection booths (such as electronic toll collection via a transponder in the vehicle).

The service time of ETC is the shortest and there is no need for stopping[9].The other two types have different service time but all need to stop the vehicles.According to the established program, change the number of vehicles passing through different types of tollbooths to simulate the condition:

Vehicles started from ETC tollbooths has a certain initial velocity.

Table 13:Risk of accident

	N1=7,N2 =0,N3=1	N1=6,N2 =1,N3=1	N1=6,N2 =0,N3=2	N1=5,N2 =1,N3=2	N1=5,N2 =0,N3=3	N1=3,N2 =2,N3=3	N1=2,N2 =2,N3=4
Max vehicle flux	2150	2210	2352	2366	2445	2511	2630
Risk of accident	0.000003 %	0.000002 %	0.000012 %	0.000015 %	0.000122 %0	0.000134 %	0.003254 %

When number of tollbooths is 8,chance of changing lanes is 5% ,N1:number of conventional tollbooths,N2:number of exact-change tollbooths,N3:number of electronic toll collection booths

The analysis of the results shows that increasing the number of ETC lanes can increase the traffic volume, improve efficiency of service ,but it will also increase the incidence of traffic accidents. So the configuration of two ETC dedicated lanes is more appropriate which give consideration to both efficiency and safety.What's more,there are not many differences between the effect of conventional tollbooths and exact-change tollbooths.The increment of exact-change tollbooths can increase the traffic volume slightly.

4.Evaluation Model

4.1 Repeatability Test

Input :the number of ETC lanes is 2, the number of normal tollbooths lane is 6, chance of changing lanes is 5%, and the traffic flux is 1500vph.And then the output of Traffic Condition Simulation model is shown as Figure 11 and Table 14.

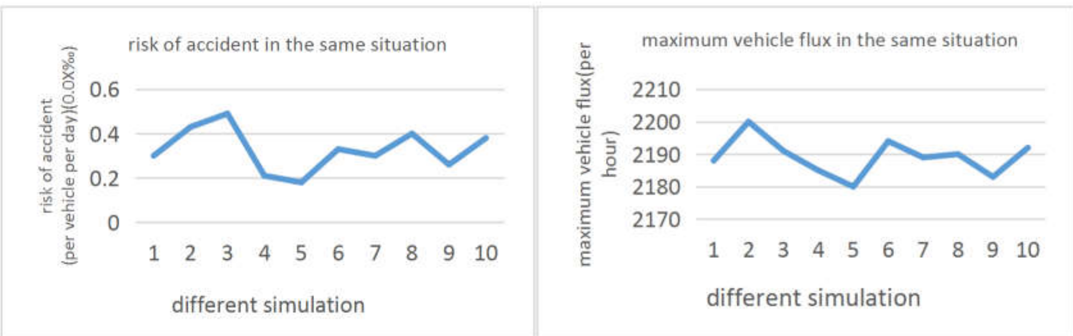

Figure 11:Changes of Output Under The Same Input

The average of risk of accident	The variance of risk of accident	The average of maximum vehicle flux	The variance of maximum vehicle flux
0.00000328%	0.00000000930376	2189.3	5.47813837

Table 14:Average and Variance

The results show that, under the fixed parameters,the output of accident risk is in the same order of magnitude,the fluctuation of it is not obvious.The variance of maximum traffic flux is also small, both of Them have high stability and can adapt to various road conditions.

4.2 Sensitive Analysis

In order to test the Traffic Condition Simulation model's sensitivity of different parameters,We compared the different Changes of accident risk ,when the traffic flux and chance of changing lanes are changing,shown as Table 14 and Figure 11:

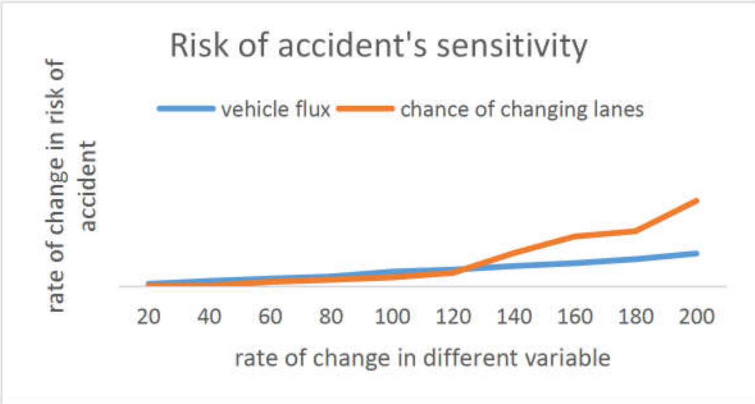

Figure 12:Risk of Accident's Sensitivity

Figure 12 indicates that the change of accident risk is slightly affected by the traffic flux,however the chance of changing lanes has greater impact on it.Which tells us the Traffic Condition Simulation model can sensitively detect the changes of the chance of changing lanes. The sensitivity of this model is high.

5.Strengths and Weaknesses

5.1 Strength

1.The model is effected by many different parameters,and can describe their influence to risk of accident and maximum vehicle flux easily,which is based on quantitative analysis.

2.The simulation of model is a real time dynamic simulation which is based on continuous.Com pared with traditional cell machine,the model is able to describe continuous change of vehicles' loc ation,sensitive expression of different speed and more accurate determination of accident.The step ti me in the simulation can reach 0.01s which simulate the delay time from the happen of an emergenc y to the movement to change vehicle's state, sufficiently.

3.The simulation can be applied in other traffic condition with a slight adjustment.

5.2 Weakness

1.Traditional tollbooths and exact-change tollbooths are different from service time in payment and other parameters,but in the model,the difference can not be distinguish clearly.Maybe we can ad d more variable which can represent service time in next version.

2.The model is not very sensitive to the ratio of number of tollbooths and number of lances.

Letter To The New Jersey Turnpike Authority

January 22,2017

Dear sir or madam,

The number of vehicles has increased a lot with the development of economy in the past few years,followed by stress of traffic. There is no doubt that tollbooth becomes the bottleneck of traffic flow when in the peak period.

We are here to help you solve this problem. Our solution is about the area following tollbooths where vehicles fan in from tollbooths to lanes(‘fan in’ area in short below).

Firstly,due to the huge traffic flow,there are many vehicle are waiting to pay the toll in peak time.We have to set more tollbooths than lanes to order to promote service efficiency and decrease the waiting time of vehicles. The cost(tollbooths and road construction) is another important factor to consider.The number of tollbooths can be determined according to a queuing theory.For example,in common,if there are three lanes of traffic ,eights tollbooth shall performance well.

Then let’s consider about the proportions of traditional tollbooths, exact-change tollbooths, and electronic toll collection booths.Service time of ETC is very short,vehicle just drive slowly through the booths to finish the payment.It is efficient but not every vehicle is equipped with ETC equipment mounted on it.There is an another phenomenon that,in ‘fan in’ area,cars setting up from ETC booths are fast relatively which will become a hidden trouble in traffic problem more or less.As for different type of normal tollbooth,it will be convenient if the booth can support cash or credit card both.Based on the result of simulation,when the number of ETC booths is 2 in 8 booths,it can help to increase the vehicle flux carrying capacity and less influence on the risk of accident.

The shape of ‘fan in’ area is quite significance.Vehicles have to keep a safe distance from each other,they are also have to satisfy the lowest speed requirement in highway from the acceleration in ‘fan in’ area.transitional modulus should not be too acute to stay safe.After satisfying the requirements above,the size of ‘fan in’ area should be as small as possible,since it saves money.The land and road construction is a pay expenses not to be ignored.

After observing toll plazas which are already been implemented,including Dulles Toll(Dulles Toll Rd, McLean, VA 22102),Crossbay Toll(20-57 Cross Bay Blvd, Far Rockaway, NY 11693),Catalina View Toll Booth(CA-73, Newport Coast, CA 92657).We noticed many ‘fan in’ areas’ boundary is convex.After calculating,we found out that maybe it will be better when part of boundary become concave.

The different between these two shapes is transitional modulus,slope,or change rate of road direction.In the convex boundary,at the starting section,transitional modulus is very small and the road is almost in straight line,and it becomes acute with the advance of vehicles.In the end of road,transitional modulus has reached the maximum.However,there is a very important variable,speed.Vehicles set up from static or a low velocity at the starting section,and reached the lowest velocity in highly in the end of ‘fan in’ area.It’s dangerous for a high-speed car to turn into another direction sharply.Things are different in concave boundary.The maximum transitional modulus occurs in the starting section,it is safe for a car which is just setting up to turn into another direction.

Of course,convex boundary will help to increase the carrying capacity of ‘fan in’ area,which is very significance.Our advice is to mix part of concave boundary with convex one and convex part should be still be major.

There is another daring advice for converging pattern.After payment,the booth can give the vehicle tips about which lanes leaving from rather than vehicles choose its target as it like.The tip is based on condition of all lances and can realize the dynamic distribution which should performance better then the situation if the vehicles determined by themselves blindly.

All of our advice and analysis are based on calculation and simulation.You can refer to the paper for more detail,if you are interested.

Looking forwarding to your reply.

Yours sincerely,

A group of youths desiring for a better world

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[9] Junlong Cheng,Study of Capacity for ETC and MTC Hybrid Toll Station[D].Shanghai:Southwest Jiaotong University,2015,30-87.

Appendix

Java Code:

Description

```
/**
 * @author finalObject(Xiaobo Hu)
 *         http://www.finalobject.cn
 *         i@finalobject.cn
 *         https://github.com/finalObject
 * @date 2017.1.21 11:36:22 AM
 * @version 1.0
 * @description
 * All codes are wrote by Xiaobo Hu based on basic tools in Java
 * codes below are necessary field and functions
 * detail process and code about UI are not display
 * compeleted codes are available on github
 * there are three code files:Area.java,Car.java,Scene.java
 */
```

File 1'Area.java':

```
public class Area{
    public double widthT, widthL, lengthT, lengthSpeed;
    double k,b;
    public int checkArea(double x, double y);
}
```

File 2'Car.java':

```
public class Car{
public double maxAccSpeed;
    public double length, width;
    public double x, y;
    // infos of lances
    double[][] lanes;
    public double maxSpeed = 19.4;
    public double maxDir = 60.0 / 180 * Math.PI;
    public double maxAccDir = 30;
    public double speed = 0;
    // rad,normal =0,increase clockwise
    public double direction = 0;
    // target location
    public double tarX, tarY;
    // react time
    public double time = 0.5;
    public double chanceOfChange = 0.0001;
    public double safeDis = 10;
    public double dangDis = 3;
    public double th1 = 20.0 / 180 * Math.PI;
```

```
public double th2 = 30.0 / 180 * Math.PI;
    public double th3 = 5.0 / 180 * Math.PI;



    public int tarLanes = 0;
    public double reactTime = 0;
    public double hopeSpeed = 0;
    public double hopeDir = 0;
    public double accSpeed = 0;
    public double accDir = 0;
    public void changeLanes()
    public void check(Area area, ArrayList<Car> cars)
    public void act(double stepTime)
    public void run(double stepTime)
    public double[] getDistanceWithArea(Area area)
    public double[] getDistanceWithObj
}
```

File 3'Scene.java':

```
public class Scene{
ArrayList<Car> cars;
    Area area;
    double[][] tolls;
    double[][] lanes;
    int numOfToll=8;
    int numOfLanes=3;
    double widthL=3.75;
    double widthT=3.3;
    double lengthSpeed = 93;
    double lengthT = 20;

    double stepTime=0.1;
    double flux = 10000;
    public void checkLeaveCar();
    public void generateCar();
    public void runCar();
    public void checkAccident();
}
```

MATLAB code

Description

```
% @author finalObject(Xiaobo Hu)
%         http://www.finalobject.cn
%         i@finalobject.cn
%         https://github.com/finalObject
% @date 2017年1月20日 15:17:00
% @version 1.0
% @description
% All codes are wrote by Xiaobo Hu based on basic tools in MATLAB
% compeleted codes are available on github
% there are three code files:main.m,getCmd.m,update.m,chooseTollBoothArrive.m,
% chooseTollBoothLeave.m
 */
```

File 1 'main.m':

```
clear;clc;
flux=1.5;
numOfEtcB=1;numOfEtcL=1;
numOfTollbooths=8-numOfEtcB;
numOfLanes=4-numOfEtcL;
tollBooths=zeros(1,numOfTollbooths);
waitTime=zeros(1,numOfTollbooths);
tollBooths=[1,1,0,1,0,0,1];
waitTime=[1,1,0,1,0,0,1];
cmd=zeros(1,numOfTollbooths);
lanes=zeros(1,numOfLanes);
lanes=[0,1,0];
tollBooths
lanes
while 1
    if sum(tollBooths)>0
        [cmd,tollBooths,lanes,waitTime]=getCmd(tollBooths,lanes,waitTime);
    else
        disp('No Cars');
    end
    [cmd,lanes,tollBooths,waitTime]=update(cmd,tollBooths,lanes,waitTime,flux);
    a=input('continue: ');
end
```

File 2 'getCmd.m':

```
function [cmd,tollBooths,lanes,waitTime]=getCmd(tollBooths,lanes,waitTime)
    lengthT=length(tollBooths);
    lengthL=length(lanes);
    cmd=zeros(1,lengthT);
    number=0;
    for i=1:lengthL
        if lanes(i)==0
```

```
            number=number+1;
        end
    end
    for i=1:number
        lanesIndex=0;
        for j=1:lengthL
           if lanes(j)==0
               lanesIndex=j;
               break;
           end
        end
     if sum(tollBooths)==0
        disp('No car in mid');
        return ;
    end
       index=chooseTollBoothLeave(waitTime);
        cmd(index)=lanesIndex;
        lanes(lanesIndex)=1;
        tollBooths(index)=tollBooths(index)-1;
        waitTime(index)=0;
        disp([num2str(index) 'Car toward' num2str(lanesIndex) 'Lanes']);
    end
    tollBooths
    lanes
end
```

File 3 'update.m':

```
function [cmd,lanes,tollBooths,waitTime]=update(cmd,tollBooths,lanes,waitTime,flux)

    lengthC=length(cmd);
    lengthT=length(tollBooths);
    lengthL=length(lanes);
    lanes=zeros(1,lengthL);
    for i=1:lengthC
        if cmd(i)~=0
            lanes(cmd(i))=1;
        end
    end
    number=random('Poisson',flux);
    for i=1:number
        index=chooseTollBoothArrive(tollBooths);
        tollBooths(index)=tollBooths(index)+1;
        disp([num2str(index) 'tooth have a car coming']);
    end
    for i=1:lengthT
        if tollBooths(i)~=0
            waitTime(i)=waitTime(i)+1;
```

```
        end
    end
    tollBooths
    lanes
end
```

File 4 ‘chooseTollBoothArrive.m’:

```
function minx=chooseTollBoothArrive(tollBooths)
    lengthT=length(tollBooths);
    miny=99999;
    minx=0;
    for i=1:lengthT
        if(tollBooths(i)<miny)
            minx=i;
            miny=tollBooths(i);
        end
    end
end
```

File 5 ‘chooseTollBoothLeave.m’:

```
function maxx=chooseTollBoothLeave(waitTime)
    lengthW=length(waitTime);
    maxy=0;
    maxx=0;
    for i=1:lengthW
        if(waitTime(i)>maxy)
            maxx=i;
            maxy=waitTime(i);
        end
    end
end
```