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Problem Chosen

A

2014 Mathematical Contest in Modeling (MCM) Summary Sheet

The Keep-Right-Except-To-Pass rule is employed by many countries where drivers are required to drive in the right-most lane unless they are passing another vehicle. In this context, there is a strong need to evaluate how the KRETP rule determines the overall traffic performance, including both traffic efficiency and security.

To this end, in this paper, we integrate *gipps' car-following model* and *classical lane-changing model* to obtain a unified mathematical model to describe the complete procedure of vehicle behaviors in a microscopic way. In this model, driving behavior is separated into the car following phase and the overtaking phase. In particular, the overtaking phase is treated as two continuous lane-changing procedures. Our model is able to describe various driving patterns with parameters like driving speed, possibility of lane-changing and different real-time parameters. In this way, our model can be used to understand how the KRETP rule affects the traffic performance.

In order to precisely assess our model, we have introduced several indicators as criteria, such as speed, density and flow. The security distance and safe following distance are identified to judge the safety level. We use three main indicators to analyze the overall performance of traffic condition: speed, flow and density, whose relations are carefully studied.

We carry out simulation with VISSIM and data analysis with MATLAB, which enables us to collect real-time data about the employment of our model in practical multi-lane roadway case. With these data, we examine the influence of the model parameters on the overall traffic performance. Furthermore, we analyze how speed limitation, road load, and road take-up percentage affect the performance of the KRETP rule.

After processing and analyzing the raw data collected from the simulation, we obtain several relationships with each two of the criteria parameters. For example, with the speed limitations effect, the speed tends to increase first, and then comes to decline as the flow rises. On the contrary， the security level decreases correspondingly. Most importantly, the experimental results show that the KRETP rule is quite efficient in both generating traffic flow and guarding security compared to No rule condition, though it is not strictly perfect in producing traffic flow. A modification to the rule, including setting different speed limits on different lanes and increasing the number of lanes, is hence suggested, which can promote greater traffic flow and safety. With a simple change of orientation, our model can also efficiently apply to countries where driving on the left is the norm.

Finally, we show how our model can be easily adapted to the intelligent road condition by introducing a brand new incentive-based parameter. This enables us to calculate the feasibility of taking special driving behavior (like overtaking) according to the historical patterns of the driver and the real-time road conditions.

The Keep-Right-Except-To-Pass Rule

Introduction

Traffic problems are becoming more of a threat to modern population. Statistics have shown that problems like traffic congestion or even traffic accidents took place with horrible frequency in recent years, claiming thousands of lives in one short day globally.

Faced with these serious traffic problems, it is essential that efficient traffic rules be applied. This leads us to think over the traffic rules in use and attempt to make an assessment as well as modification if they are found to be not perfect.

Restatement of the problem

In countries where driving on the right is the norm, multi-lane freeways often employ the Keep-Right-Except-To-Pass rule. However, there are always some heated discussions about its effect.

Our goal is to build a model to analyze and evaluate the performance of the rule in both light and heavy traffic, examining tradeoffs between traffic flow and safety. We will pay specific attention to factors such as the role of speed limits and other traffic conditions. In particular, we will suggest and analyze a better alternative and improve it to maintain its effectiveness either in countries where driving on the left is the rule or when vehicle transportation is completely under the control of an intelligent system.

1 Assumptions and parameters

1.1Assumptions

- The vehicle's driver will estimate its speed based on the preceding vehicle to be able to come to a safe and full stop if needed.
- The vehicle's speed will not exceed its driver's desired speed and its free acceleration should first increase and then decrease to zero as the desired speed is reached
- The vehicle's driver will behave under a braking limitation to make sure that there is an additional buffer and a safety margin between itself and the vehicle in front.
- The driver is willing to brake hard and travel as safely and fast as possible.
- The parameters such as τ, the reaction time of the following vehicle, and b, the maximum deceleration of the vehicle, are equal for all drivers.
- In the simulation experiments, we assume there are two vehicle models: the car(98%) and lorry(2%) and the following vehicle is Wiedeman99.
- In the simulation experiments, the widths of lanes are 3.5m and we take samples at the middle of the lane along 500m roadway in 600s.
- Some parameters such as the greatest acceleration are determined by default values in the simulation software.

1.2 Parameters

a_n the n[th] driver's maximum desired acceleration, average as a
b_n the n[th] vehicle's maximum deceleration, $b_n < 0$, average as b
$\hat{b}$ the estimate value of b_{n-1}
V_i the speed at which the driver of vehicle i wishes to travel
$X_i(t)$ the location of the front of vehicle *i* at time t
$v_i(t)$ the speed of vehicle *i* at time t
τ the reaction time
V_{lim} the limit of the speed
L_s static security distance
L_i the length of vehicle *i*
L the distance below which the car following would be unsafe
θ the angle of the vehicle while lane changing
d_s the security distance

2 Background

We have to analyze the vehicles' actions, including mainly two parts: car following and overtaking, with a microscopic method to evaluate the rule more comprehensively and accurately. So far, there are several mathematical models available for analyzing and simulating car following and overtaking.

2.1 Car-Following Models

Car-following models[1] mathematically describe drivers' behaviors when they follow the preceding vehicle in a traffic stream. From these models such as GHR model and CA model, we choose Gipps car-following model[2]. (The justifications and criteria to choose Gipps model will be explained later.) Gipps car-following model describes the car-following formula defined by the reaction time, location, speed and acceleration of the following vehicle. Then Gipps sets several constraints through safety considerations and has developed the model.

2.2 Lane-Changing Models

Lane-changing models[3] mathematically reflect overtaking, when a vehicle's speed is higher than the preceding one and its driver decides to overpass rather than remain in the lane and decelerate. Since 1980s, lane-changing models have received increasing attention and several different models have been established and developed. These models can be primarily classified into two groups: computer simulation and adaptive cruise control. The latter can be further classified into automation models and collision avoidance models.

3 Model

Our model focuses on the completed process of car following and overtaking in a microscopic way, based on Gipps car-following model and Gipps lane-changing model. It consists of countless loops and we describe one loop process in detail as follows.

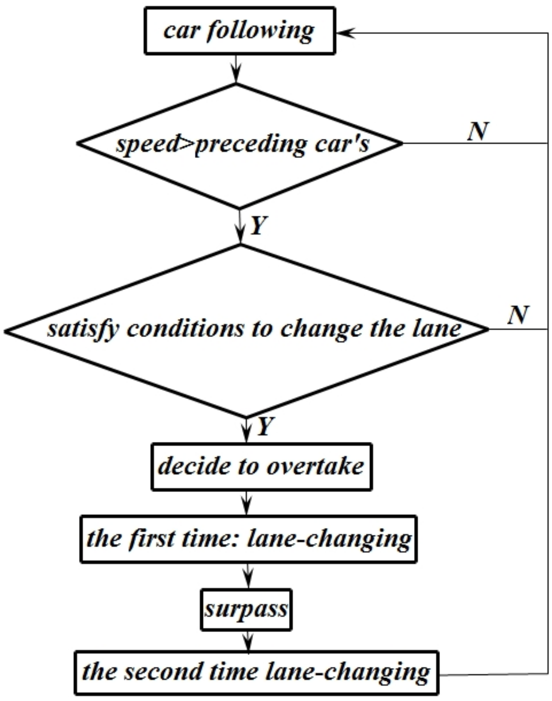

Figure 1: the loop map of our model

As is shown in the diagram, we choose a time when the subject vehicle is following the preceding one as the starting point. If its speed does not exceed the speed of the vehicle in front, the subject vehicle will keep following. If its speed does exceed the preceding vehicle's speed, the vehicle's driver will consider several conditions to decide whether to overtake or not. When the conditions, including objective and subjective conditions, are satisfied, the driver will overtake. If not, the driver will still follow. Once the driver decides to overtake, he or she has to complete a process of three parts: change the lane, surpass and come back to the original lane, according to the keep-right-except-to-pass rule. That is to say, there are two lane-changing processes in one overtaking behavior and we will analyze these two processes separately. Finally, after overtaking, the subject vehicle comes back to the car-following status. This is the end point of this loop and also the starting point of the next loop. All these loops arranged in a time sequence with no time left out between each other describe the vehicle's behavior comprehensively.

We notice that there are two different driving statuses, car following and overtaking, in this whole process. So we apply and develop two models to analyze separately as follows.

3.1 Car-following: Gipps model

As is discussed in the background of car-following models, we choose Gipps model. Here are several justifications:

- Gipps car-following model contains parameters such as the reaction time, location, speed and acceleration, which can describe the car-following behavior more comprehensively. Through adjusting a number of parameters, Gipps model can decide different behavioral features and simulate real situations by program.
- Gipps model reflects a sequence of behaviors, which caters for microscopic analysis. Furthermore, behavioral sequence makes the model as a rule-based model because of the role of rules which limits behaviors. In this way, the model is the best option when we analyze the problem such as the keep-right-except-to-pass rule.
- Gipps presents his model considering security and we can also use his model to analyze how the preceding vehicle's speed affects the subject one's speed, and further its effect on the whole traffic flow. This model is the best when we want to analyze the tradeoffs between traffic flow and safety.

Gipps car-following model is presented below:

$$v_n(t+\tau) = \min\left\{ v_n(t) + 2.5a_n\tau(1-\frac{v_n(t)}{V_n})(0.025+\frac{v_n(t)}{V_n})^{1/2}, \right.$$
$$\left. b_n\tau + \sqrt{b_n^2\tau^2 - b_n(2\left[x_{n-1}(t) - s_{n-1} - x_n(t)\right] - v_n(t)\tau - \frac{{v_{n-1}}^2(t)}{\hat{b}})} \right\} \tag{1}$$

This formula determines the velocity of a vehicle. If the road condition is free-flow, then the first argument is attained. However, if the traffic condition is congested and the headway is small, then the second argument is attained. The speed of each vehicle is limited by the behavior of the preceding one. Actually, we pay more attention to the second argument and apply it for later analysis.

3.2 Overtaking: Gipps lane-changing model and modification

One overtaking process[4] consists of two lane-changing behaviors and we analyze these two separately in microscopic way. We choose Gipps lane-changing model to describe each behavior. The reason why we choose it is the same as that of choosing Gipps car-following model. In this section, we present the model and make some modification.

The whole model can be divided into two steps: gap availability and desirability to change the lane. Furthermore, we introduce another condition and a microscopic analysis to develop this model.

3.2.1 Gap availability

When a driver intends to change the lane, he or she will first check if it is possible, in terms of gap availability. The gap availability will be judged in terms of both the lead and rear gaps (shown in Figure 2), calculated according to the Gipps Car-Following Model criteria for following distance and safe speed.

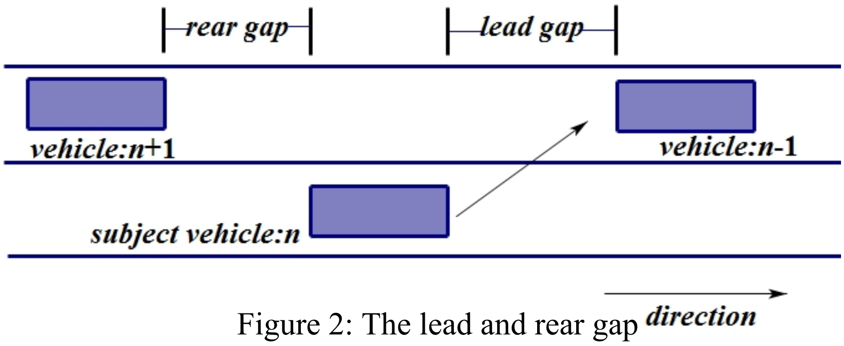

Figure 2: The lead and rear gap

If the vehicle n changes the lane, both the lead and rear gap must satisfy the criteria of being more than the size of the adjusted critical gap, as described below:

$$L = \frac{v_{n-1}^2 - v_{n+1}^2 + 3v_{n+1}b\tau}{2b} \quad (2)$$

The actual car following distance if the vehicle moved in the gap adjustment, unique for each vehicle

$$d = x_{n-1} - L_{n-1} - x_{n+1} \quad (3)$$

Acceptable gap if:

$d \geq FL$ (4)

Where:

$$F = \frac{\text{smallest acceptable gap}}{\text{gap size which allow safe stopping}}$$

3.2.2 Security distance

Gap availability considers whether the gap between vehicle $n-1$ and vehicle $n+1$ satisfies the conditions for the subject vehicle to change the lane. But it neglects the possible collision between the subject vehicle and vehicle $n-1$ and the collision between the subject vehicle and vehicle $n-1'$ [5]. To analyze these details and simulate the real situations, we introduce another condition d_S, defined as security distance, and another parameter, the lane-changing angle θ.

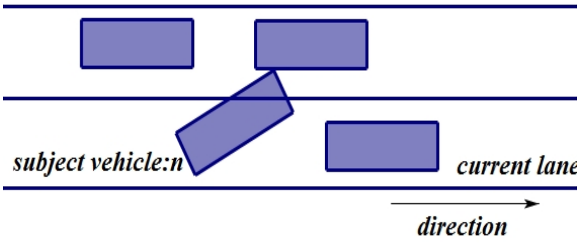

Figure 3: The collision with vehicle n-1

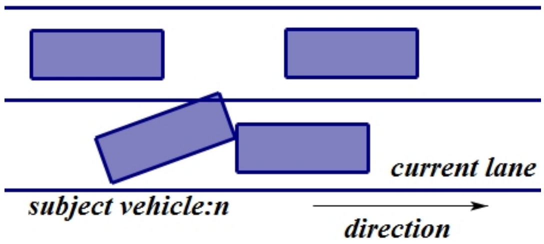

Figure 4: The collision with vehicle n-1

To avoid the collision with vehicle $n-1'$, the security distance should be adjusted because of θ. Considering the worst situation and the fact that θ is a small angle, we have adjusted distance: $\frac{L_n}{2\cos\theta}-\frac{L_n}{2}$. (Because we analyze the distance from the preceding vehicle, we only consider the first half of the vehicle's length.)

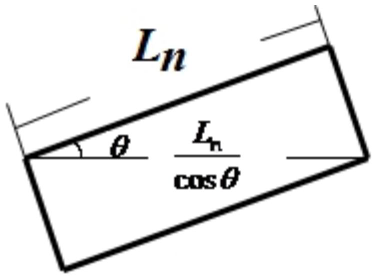

Figure 5: The subject vehicle n

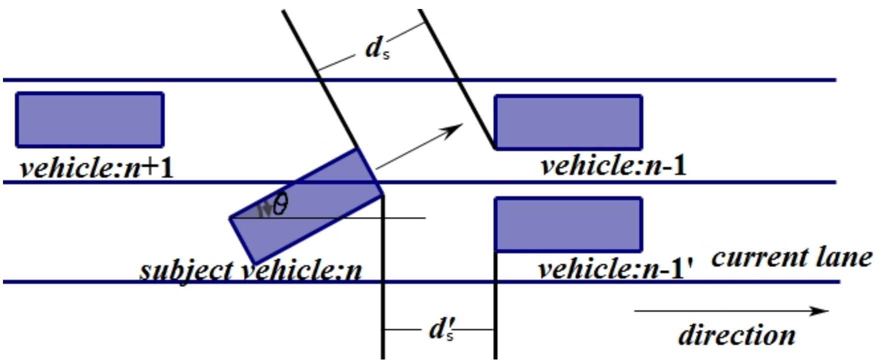

Figure 6: The security distance

Thus, we have:

$$d_s'=L+\frac{L_n}{2\cos\theta}-\frac{L_n}{2} \tag{5}$$

Similarly, to avoid the collision with vehicle $n-1$, we have:

$$d_s=L+2\left(\frac{L_n}{2\cos\theta}-\frac{L_n}{2}\right) \tag{6}$$

That is, when constraints mentioned in Gipps lane changing model are satisfied, the driver will change the lane only if the subject vehicle's distance from vehicle $n-1$ is no less than d_s and its distance from vehicle $n-1$ is no less than d_s. Besides, the security distance is also a criterion to evaluate the traffic system's security.

3.2.3 Desirability to change the lane

Finally, when the two conditions above are satisfied, a driver will change the lane only if the allowable speed on the adjacent lane can be increased up to his or her desired speed, compared to the current lane. And the reaction time lag will also take place during the lane change. The formula for allowable speed is:

$$v_{allow} = \min(\frac{3}{2}b\tau \pm \sqrt{v_{n-1}^2 - 2b(x_{n-1} - L_{n-1} - x_{n+1}) + \frac{9}{4}b^2\tau^2}, v_{des}) \tag{7}$$

Where: v_{des} = the subject vehicle's desired free driving speed

3.2.4 Safe following distance

After the driver decides to change the lane, he or she will accelerate. And during this time, the vehicle's speed increases while it is still following the preceding vehicle. Because its driver is about to change the lane, the vehicle's speed may exceed the speed subject to the conditions according to Gipps car-following model. We introduce another parameter S , the safe following distance, as a criteria, to evaluate the security level of this particular situation.

First, we calculate the distance in which the preceding vehicle (vehicle $n-1$) comes to a stop and have:

$$S_{n-1} = \frac{v_{n-1}^2}{2b_{n-1}} + \frac{v_{n-1}t_\alpha}{2} \tag{8}$$

Where: t_α the time lag because of deceleration

Then, we have the distance in which the subject vehicle (vehicle n) comes to a stop (there is a reaction time):

$$S_n = v_n\tau' + \frac{v_n^2}{2b_n} + \frac{v_n t_\alpha}{2} \tag{9}$$

Thus, we have:

$$\begin{aligned} S &= (S_n - S_{n-1}) + L_s \\ &= v_n\tau' + \frac{v_n^2}{2b_n} + \frac{(v_n - v_{n-1})t_\alpha}{2} - \frac{v_{n-1}^2}{2b_{n-1}} + L_s \end{aligned} \tag{10}$$

The safe following distance is an important criterion to evaluate the safety level. Although the particular situation above is no more than one or two minutes

3.2.5 Overtaking's effect on traffic flow

Gipps lane-changing model actually pays more attention to the safety problem, neglecting several effects on traffic flow. However, overtaking affects traffic flow at least in three aspects：

- Once a driver decides to overtake rather than decelerate to keep following, it's helpful to increase the speed of the whole traffic system.
- When a vehicle starts changing the lane, the following vehicle on the adjacent lane will decelerate, which means the traffic flow on the adjacent lane behind the subject vehicle will slow down. Moreover, the vehicle in front on the adjacent lane may accelerate because of the narrower distance between itself and the vehicle behind.
- The original lane will also be influenced by overtaking. After a vehicle has changed the lane, the vehicle behind it on the original lane will accelerate because of the larger space ahead.

3.3 The criteria to evaluate the rule

We evaluate the keep-right-except-to-pass rule according to two criteria: security and traffic flow.

First, since the speed of the following vehicle is subject to safe considerations in the Gipps car-following model, we only consider security difference when overtaking using two parameters: the safe following distance and security distance to measure the level of security.

Second, we introduce three classic parameters to analyze traffic flow[6]. The first one is speed, defined as the distance covered per unit time. Because of the impossibility to track every vehicle's speed on the roadway, it's estimated by the average speed of all the vehicles in practice. The second one, density, is to describe the number of vehicles per unit area of the roadway, which reflects the road load. And the third parameter is flow, which reflects the number of vehicles passing a given point per unit of time. Applying these three parameters, we analyze how fast and congested the traffic flow is.

Third, there is another influencing factor, the speed limit. We manage to explain the role of the speed limits by examining its effects on traffic flow and security of the whole traffic system.

4 Results and analysis

As is mentioned above, the keep-right-except-to-pass rule is evaluated in three aspects, including security, traffic flow and speed limits in our model. Since these factors dependently affect vehicles' behaviors, we cannot process data with a mutually exclusive method. On the contrary, to analyze the tradeoffs between security and traffic flow and the role of speed limits, we focus on the relations and how they affect each other. To simplify the problem, we perform experiments assuming the roadway load is common and the freeway is 2-lane. (The data is shown in the Appendix 3.1 & 3.2)

4.1Traffic flow: flow-speed-density relationships

First, we perform simulation experiments to analyze traffic flow, applying three parameters (speed, flow and density).

In the experiments, we compare the performances of the keep-right-except-to-pass rule and no rule using simulation software called VISSIM. Here, we set the no-rule situation as the control group and make sure both the experimental group and the control group have the same values of irrelevant variables.

(We consider flow as an independent variable in the experiments below and we first analyze traffic flow on the two-lane roadway.)

This experiment reflects the whole traffic flow performance of the rule, which indicates the relationships between each two of the three parameters. We perform the experiments in three different conditions identified by three levels of the roadway load, also called density, estimated by the road covering efficiency.

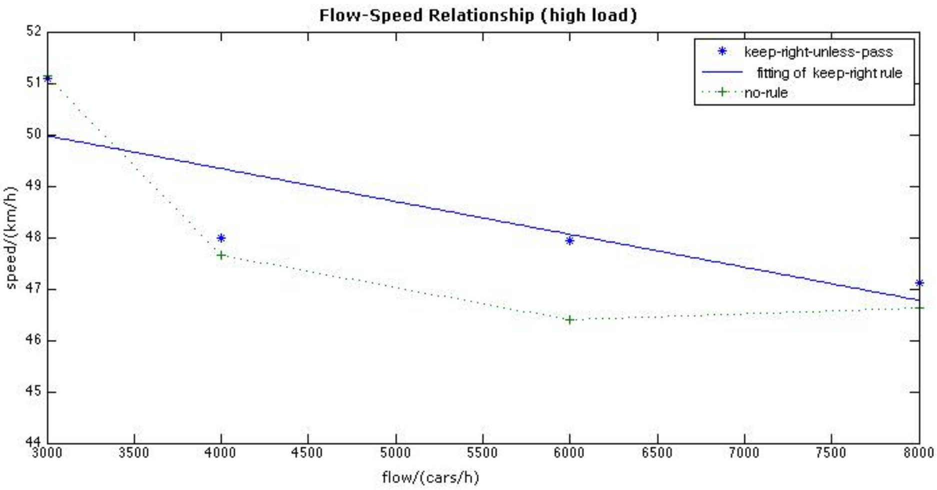

Figure 7: Flow-speed relationship

4.1.1 High load (density> 60%)

When the load of the roadway is high and the density value is more than 60%, the average of speed decreases sharply, both under the keep-right-except-to-pass rule and the no-rule situations. This means the traffic condition is congested and even worse, there may be a traffic jam on the roadway. However, the fitted lines indicate that there is an evident difference of the average of speed between two situations. The overall traffic flow condition, including the average of speed and flow, under the keep-right-except-to-pass rule situation is much better than that under the no-rule situation.

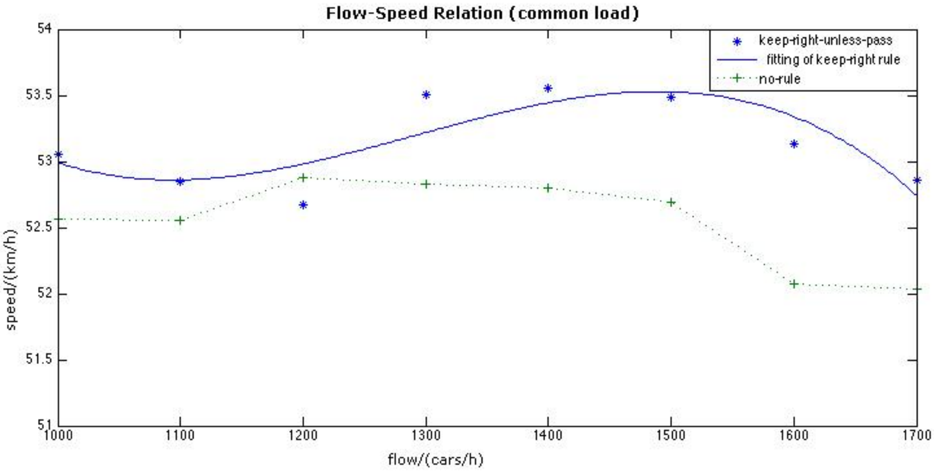

Figure 8: Flow-speed relation

4.1.2 Common load (density is 10% - 60%)

From the diagram above, we can tell that the two fitted lines both first increase and then decrease, which can be clearly explained. With the flow gradually increasing, the space which has been empty with vehicles before are now covered with cars. During this time, the average of speed will rise and the number of vehicles will increase until the speed reaches a peak where there's no possibility that the speed will further rise according to car-following models. In this way, the speed will decline, after it reaches the peak (54km/s in this experiment). Analyzing in detail, we still notice that there is an obvious different between two situations. With the same value of flow, the speed under the keep-right-except-to-pass rule situation is higher, in comparison with the no-rule situation. That is, the keep-right-except-to-pass rule has positive effects and the traffic flow condition is more desirable when the roadway load is common.

4.1.3 Low load (density< 10%)

We analyze the fitted lines and conclude that with the flow change, there is a small difference of the speed, which is less than 1km/h. This indicates a phenomenon that the traffic condition remains in a stable status when the roadway load is low. Furthermore, although there is a very small difference between two situations, we consider the two rules have the same efficiency. (The diagram is shown in the Appendix 5)

4.1.4 Conclusion

The overall traffic flow condition of the keep-right-except-to-pass rule situation is better than that of no-rule situation, which indicates the positive efficiency of the rule. And this positive effect is most obvious to tell when the roadway load is common, while with the high load, the rule still cannot avoid the exacerbation of the congested traffic flow condition. What's worse, when the roadway load is low, its effect is very little.

4.2 Tradeoffs between traffic flow and security

4.2.1 Security-speed relationship

Second, we analyze the safe following distance and security distance to judge different levels of security subject to two conditions: different levels of speed limits and different driving speeds. The result is presented, by MATLAB programming, in the table and diagram below. (The MATLAB programming processes are shown in Appendix 4.1 in detail)

Secutity under different conditions of driving speed and speed limits

speed limit(km/h)	60			80		100		120	
driving speed(km/h)	50	55	60	75	80	95	100	115	120
safe following distance(m)	17.4648	21.5936	25.9866	29.7646	35.2146	37.9355	44.4425	46.1065	53.6705
security distance1(m)	17.5296	21.6584	26.0514	29.8293	35.2794	38.0003	44.5073	46.1713	53.7353
security distance2(m)	17.4972	216260	26.019	29.797	35.2479	37.9679	44.4749	46.1389	53.7029

other parameters
The length of the vehicle： 4.2m
reaction time:0.9s
td: 0.15s
acceleration： 7.3m/ss

Table 1

(The security distance1 and security distance 2 in the table respectively represent the security distance d_s and d_s'.)

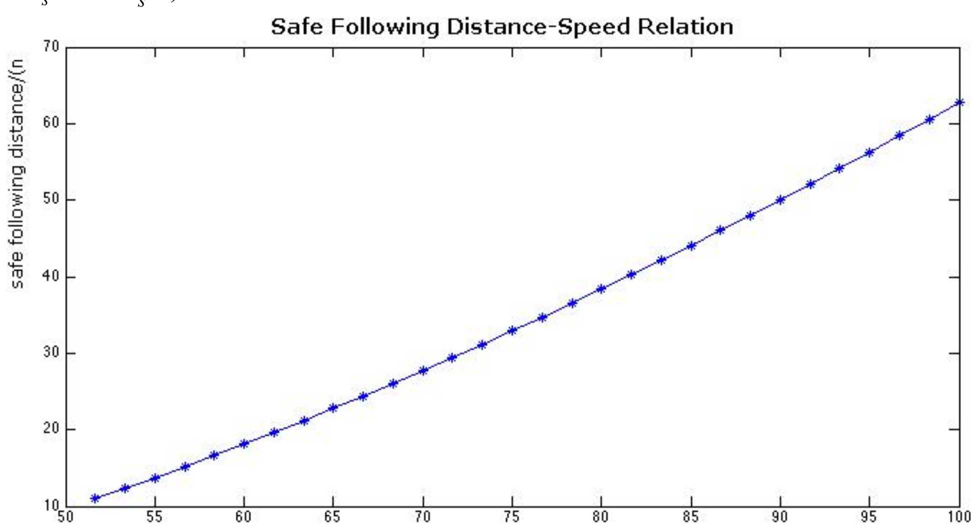

Figure 9: Safe following distance-speed relation

The fitted line shown in the diagram above indicates that the relationship between safe following distance and driving speed is positive, or even linear positive. At the same time, safe following distance also has similar relationships with security distances based on their functional relationship. In conclusion, both the safe following distance and security distances have positive relationships with driving speed. Venturing a guess, we think they are linear relationships with some undetermined coefficients.

4.2.2 Relationships between traffic flow and security

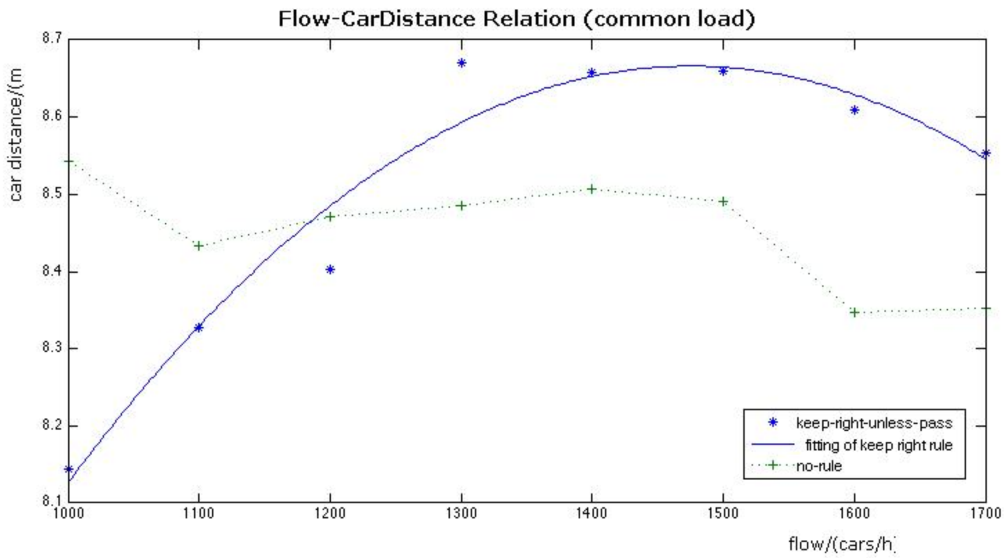

Figure 10: Flow-car distance relation

After analyzing the security's relationship with speed, we now do the simulation experiments to analyzing tradeoffs between security and the whole traffic flow, assuming the roadway load is common. We still apply speed, flow and density to describe traffic flow and safe following distance and security distance to describe security.

As is shown in the diagram above, the average car distance has a trend to increase and then comes back to decline as the flow increases. Considering the trend to decrease is smaller, we focus on the speed increasing before its peak. The car distance represents the smallest distance to avoid collision, and it's easy to understand that it will rise as the flow increases, which means with larger traffic flow, traffic accidents will be more likely to happen. However, the traffic condition is safer if the keep-right rule is adopted.

4.3 The role of speed limits

In this experiment, we analyze the traffic flow condition to evaluate the effect of the rule under different levels of speed limits (54km/h and 90km/h), assuming that the roadway load is common. (Because speeds are calculated subject to the conditions guaranteeing security in our model, so we consider the traffic is under the same level of security. Here we focus on the role of speed limits in affecting traffic flow.)

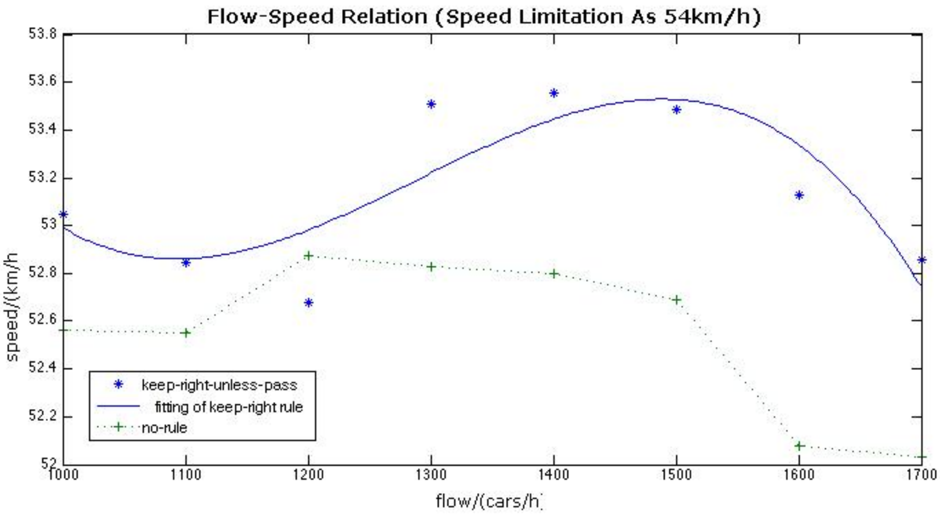

Figure 11: Flow-speed relation(speed limit 54km/h)

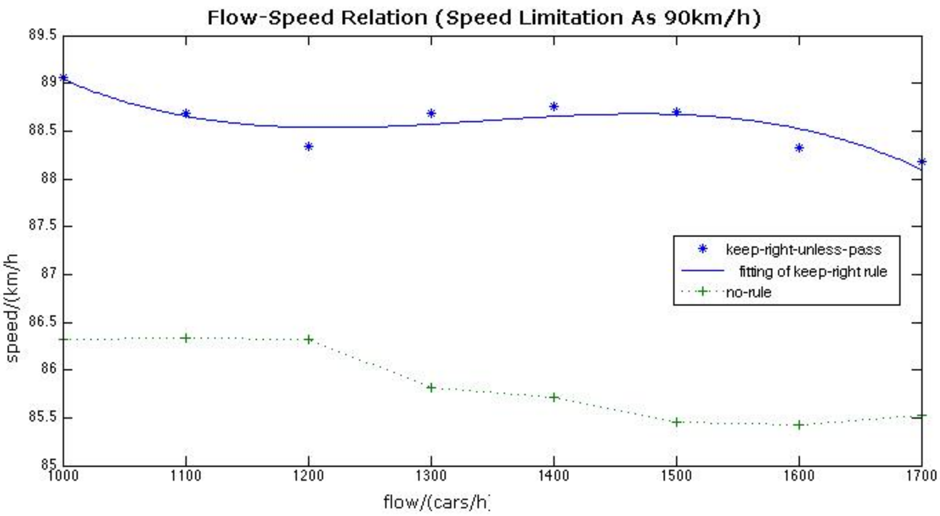

Figure 12: Flow-speed relation (speed limit 90km/h)

Comparing the fitted lines in two diagrams, we conclude that the fitted lines are similar in general with different speed limits. That is, once the roadway load and the rule are given, the general fluctuation trend is almost unchangeable in spite of the change of speed limits. But the traffic flow condition is affected deeply, reflected by obviously different speeds, by two levels of speed limits.

Furthermore, we also notice that as the speed limit rises, the speed difference between the keep-right rule situation and the no-rule situation increases. We consider a reasonable higher lever speed limit will make the keep-right rule more efficient to improve the traffic flow condition.

5 Optimization

5.1 3-lane roadway

In our simulation experiments, we assume the roadway is 2-lane, which makes the experiments lack the ability to solve the problem in practice. Here, we improve our model and increase the number of the lanes to 3.

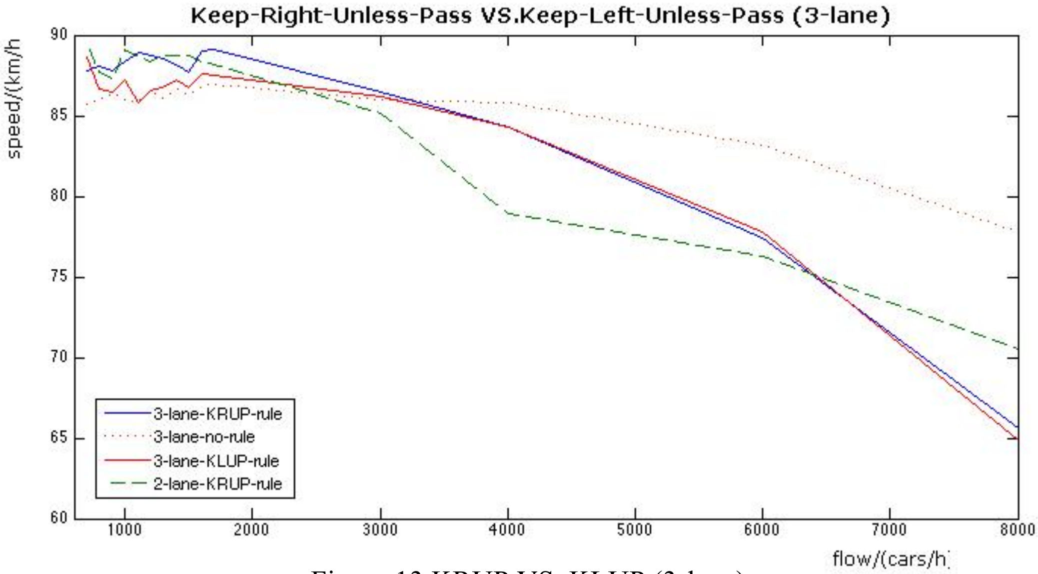

Figure 13 KRUP VS. KLUP (3-lane)

We perform the simulation experiments on the 3-lane road, assuming the speed limit is 90km/h. (The diagram above will be applied again later in Part 5.2)

In the diagram, the fitted lines of the keep-right rule on the 2-lane and 3-lane roadway are similar, while the traffic flow condition is better on the 3-lane roadway. However, when the flow is large enough, it's more likely to be congested on the 3-lane road.

5.2 In driving-on-the-left counties

To better employing the rule in counties where driving on the left is the norm, we compare the keep-right-unless-to-pass rule, the keep-left- unless-to-pass rule and no-rule situations.

From the Figure 13, it's evident to tell that although the fitted lines are similar in general, there is a significant difference of speeds when the flow is between 3000 and 6000. That is, the efficiency of the keep-left-unless-to-pass rule is worse than the keep-right rule when flow is not too high, especially when it's common.

This result indicates that additional traffic requirements or rules are needed when the rule changes its orientation. Maybe, the requirements are some more severe traffic rules about speed, speed limits and security distance.

5.3 New rules

Given the result that the traffic flow condition will improve with more lanes under common flow and density situation and the fact that a higher speed limit is helpful to increase the traffic flow, we set rules as follows:

We still keep the original rules, which is maintaining the keep-right rule in countries where driving on the right and the keep-left rule in driving-on-the-left countries.

In multi-lane roads, every lane can be covered by car-following and overtaking, which means there are no special passing lane.

We set different speed limits on different lanes. For example, in driving-on-the-right counties, the speed limit on the most left lane highest and it becomes lower to the next right lane one by one. This distinguished method will greatly help to increase the efficiency of the whole traffic system.

5.4 Under the intelligent system

- A few parameters change under the intelligent system including the decrease of reaction time τ and some other behaviors of drivers.
- We choose the incentive model from lane-changing models and introduce the incentive parameter. The formula is:

$$\rho = \gamma_1 \rho_{self} + \gamma_2 \rho_{overall}$$

Where: γ_1, γ_2 weight coefficient

ρ_{self} the driver's feature's effect on the decision of overtaking, which can be measured by the facts, such as the overtaking record of the driver

$\rho_{overall}$ the subjective parameter's effect on the decision, such as the number of vehicles

This parameter will be a criterion for a driver to decide whether to overtake or not.

- The intelligent system provides dynamic accommodations when we analyze parameters, such as acceleration, deceleration and speed. We will examine the tradeoffs between security and traffic flow at every moment, which makes our analysis more accurate.

6 Strengths and weaknesses

A both comprehensive and microscopic analyzing method must be the greatest strength of our model. We apply two classic models and make some improvements to describe every driving status, considering parameters as many as possible to simulate the real situations. Furthermore, through analyzing these parameters in a microscopic way, we obtain a more accurate result. Although some specific situations or parameters' change may happen and last only in a few seconds or even less, we consider these effects as influencing factors. Because one effect will be exaggerated, due to the dependent behaviors of each vehicle, and vehicles' speed on the freeway is high, which indicates that the vehicle's distance in a few minutes is long enough to affect the whole traffic system. At the same time, plenty of parameters can be classified to consider various features, such as the attribute of the vehicle and the driver's behavior. And we also repeat the same experiment 5 times or more and calculate the average value of the results to avoid accidental errors in simulation experiments. In this way, our microscopic method dramatically increases the accuracy of the result.

However, the problem to evaluate security should not be overlooked. In both the models we apply, the following vehicle's speed and the decision whether to change the lane or not are subject to conditions which guarantees security of the whole traffic system. As a result, it's not easy for us to judge and evaluate the level of security. Although we set some criteria, such as the distance between two vehicles in diverse situations, to analyze it, we consider them imperfect. Other weaknesses include that some assumptions for simplicity are unlikely to hold. For example, the vehicle's acceleration and deceleration is determined by its driver and the road condition, which is unpredictable to some extent. And another assumption that some parameters are equal for all the drivers is also vulnerable. To better describe real situations, we have set different levels for each parameter to reflect the unique behavior of each driver. But there are still a number of problems to solve because of its complexity.

Reference

[1] R. Eddie Wilson. An Analysis of Gipps' Car-following Model of Highway Traffic. Oxford: *IMA Journal of Applied Mathematics,Vol 66,Issue 5,* Oct 16 2000.

[2] Rahman, Md. Application of Parameter Estimation and Calibration Method for Car-Following Models (2013).*All Thesis Paper* 1763.

[3] Nathan Alexander Webster. Driver Model for Traffic Simulation, with Tactical Lane Changing Behavior. Tokyo: *Dissertation Presented by the Department of Civil Engineering of the University of Tokyo*, February 2007.

[4] Wei, Bai; Cunjun Li. Overtaking Model Based on Different Limiting Speed. Chengdu: *Journal of Transportation System Engineering and Information Technology, Vol.13, No.2,* April 2013, U491.6.'

[5] Lisheng Jin, Bart van Arem, Shuangbin Yang, Mascha van der Voort, Martin Tideman. Safety Lane Change Model of Vehicle Assistant Driving on Highway. Changchun: *Journal of Jilin University(Engineering and Technology Edition), 2009, 39(3), U461.91*

[6] Wikipedia: Traffic flow
http://en.wikipedia.org/wiki/Traffic_flow, accessed Feb8 2014.

Appendix

1. Introduction of VISSIM

VISSIM is a microscopic, time interval and driving behavior based simulation modeling tools. It is used in traffic modeling and analyzing the urban transport and public transport under various traffic conditions. The scientific foundation of the software is the traffic model developed by Rainer Wiedemann in 1974 at Karlsruhe University. This traffic model ruling the movement of vehicles is a car-following model that considers physical and psychological aspects of the drivers.

2. VISSIM simulation

The colored rectangles are cars running on the road.

2.1 2-lane road

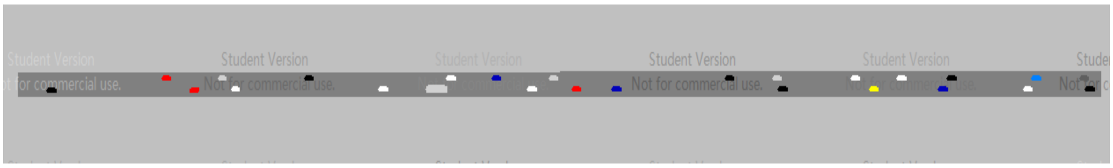

Figure 14: 2-lane road simulation

2.2 3-lane road

Figure 15: 3-lane road simulation

3. Datasets collected from VISSIM simulation

3.1 2-lane road with speed around 50km/h, speed limitation as 55km/h

Keep-right-except-to-pass rule

flow(cars/h)	mean speed(m/s)	average car distance(m)
500	14.9	8.806
550	14.957	7.256
600	14.95	7.5
650	14.804	7.373
700	14.6	7.338
800	14.687	7.965
900	14.646	7.968
1000	14.736	8.144
1100	14.679	8.327
1200	14.632	8.403
1300	14.863	8.671
1400	14.877	8.658
1500	14.857	8.659
1600	14.758	8.61
1700	14.682	8.553
3000	14.195	8.172
4000	13.328	7.419
6000	13.319	7.389
8000	13.087	7.171

Table 2

No-rule

flow(cars/h)	mean speed(m/s)	average car distance(m)
500	14.564	8.435
550	14.664	8.219
600	14.678	8.292
650	14.74	8.253
700	14.736	8.298
800	14.677	8.421
900	14.756	8.533
1000	14.601	8.543
1100	14.598	8.434
1200	14.688	8.471
1300	14.675	8.486
1400	14.666	8.507
1500	14.636	8.491
1600	14.466	8.347
1700	14.454	8.352
3000	14.205	8.18
4000	13.235	7.336
6000	12.888	6.994
8000	12.955	7.036

Table 3

3.2 2-lane road with speed around 80km/h, speed limitation as 90km/h

Keep-right-except-to-pass rule

flow(cars/h)	mean speed(m/s)	average car distance(m)
500	25.283	18.223
550	25.214	17.35
600	24.157	16.363
650	24.369	16.681
700	24.373	16.609
800	24.456	17.108
900	24.381	16.793
1000	24.551	17.348
1100	24.704	17.321
1200	24.635	17.489
1300	24.594	17.072
1400	24.502	17.32
1500	24.365	17.211
1600	24.718	17.678
1700	24.738	17.628
3000	24.014	16.95
4000	23.424	16.453
6000	21.496	14.838
8000	18.227	11.831

Table 4

No-rule

flow(cars/h)	mean speed(m/s)	average car distance(m)
500	23.95	17.092
550	23.827	16.734
600	23.808	16.495
650	23.754	16.653
700	23.795	16.716
800	23.889	16.855
900	23.999	16.951
1000	23.891	16.863
1100	23.849	16.854
1200	24.014	16.904
1300	23.909	16.921
1400	24.063	16.996
1500	23.97	16.857
1600	24.126	17.095
1700	24.157	17.194
3000	23.889	16.943
4000	23.836	16.859
6000	23.099	16.217
8000	21.619	14.889

Table 5

Keep-left-except-to-pass rule

flow(cars/h)	mean speed(m/s)	average car distance(m)
500	23.898	16.91
550	23.87	16.83
600	23.815	16.697
650	23.888	16.78
700	23.89	16.858
800	23.884	16.885
900	23.873	16.83
1000	23.849	16.866
1100	23.771	16.817
1200	23.874	16.876
1300	23.81	16.821
1400	23.774	16.799
1500	23.681	16.713
1600	23.629	16.672
1700	23.551	16.635
3000	22.944	16.085
4000	21.677	14.957
6000	18.196	11.832
8000	18.547	12.16

Table 6

3.3 3-lane road with speed around 80km/h, speed limitation as 90km/h

Keep-right-except-to-pass rule

flow(cars/h)	mean speed(m/s)	average car distance(m)
500	25.283	18.223
550	25.214	17.35
600	24.157	16.363
650	24.369	16.681
700	24.373	16.609
800	24.456	17.108
900	24.381	16.793
1000	24.551	17.348
1100	24.704	17.321
1200	24.635	17.489
1300	24.594	17.072
1400	24.502	17.32
1500	24.365	17.211
1600	24.718	17.678
1700	24.738	17.628
3000	24.014	16.95
4000	23.424	16.453
6000	21.496	14.838
8000	18.227	11.831

Table 7

No-rule

flow(cars/h)	mean speed(m/s)	average car distance(m)
500	23.95	17.092
550	23.827	16.734
600	23.808	16.495
650	23.754	16.653
700	23.795	16.716
800	23.889	16.855
900	23.999	16.951
1000	23.891	16.863
1100	23.849	16.854
1200	24.014	16.904
1300	23.909	16.921
1400	24.063	16.996
1500	23.97	16.857
1600	24.126	17.095
1700	24.157	17.194
3000	23.889	16.943
4000	23.836	16.859
6000	23.099	16.217
8000	21.619	14.889

Table 8

Keep-left-except-to-pass rule

flow(cars/h)	mean speed(m/s)	average car distance(m)
500	24.275	17.245
550	24.286	17.247
600	24.16	17.182
650	25.073	17.994
700	24.615	16.719
800	24.07	16.555
900	24.016	16.652
1000	24.232	16.346
1100	23.838	16.131
1200	24.053	16.514
1300	24.108	16.506
1400	24.215	16.867
1500	24.09	16.899
1600	24.323	17.298
1700	24.307	17.211
3000	23.939	16.837
4000	23.413	16.354
6000	21.618	14.905
8000	18.029	11.732

Table 9

4. Safe Following Distance-Speed Relation Calculated from matlab

4.1 program piece

```
function [VF,L,dd,ds] = speedRsecuritydis(V_lim,times)
    V_base = V_lim*3/4;
    step = V_lim/(4*times);
    Lf = 4.2;
    tr = 0.9;
    td = 0.15;
    Ls = 0;
    af = 7.3;
    al = 7.3;

    vl = V_base;
    vf = V_base+step:step:V_lim;
    vf = vf/3.6;
    vl = vl/3.6;
    theta = 10*pi/180;
    L = vf.*tr + (vf.^2)./(2*af) + (vf-vl).*td./2 - (vl.^2)./(2.*al) + Ls;
    dd = L + 2*(Lf/(2*cos(theta)) - Lf/2);
    ds = L + Lf/(2*cos(theta)) - Lf/2;
    VF = vf.*3.6;
    plot(vf*3.6,L,'b*',vf*3.6,L,'b-');
```

4.2 discrete data

```
>> [vf,L,dd,ds] = speedRsecuritydis(60,4)

vf =

   45.0000   50.0000   55.0000   60.0000


L =

   13.6003   17.4648   21.5936   25.9866


dd =

   13.6651   17.5296   21.6584   26.0514


ds =

   13.6327   17.4972   21.6260   26.0190
```

```
>> [vf,L,dd,ds] = speedRsecuritydis(80,4)

vf =

    65    70    75    80


L =

   19.6573   24.5788   29.7646   35.2146


dd =

   19.7221   24.6436   29.8293   35.2794


ds =

   19.6897   24.6112   29.7970   35.2470



>> [vf,L,dd,ds] = speedRsecuritydis(100,4)

vf =

    85    90    95   100


L =

   25.7143   31.6928   37.9355   44.4425


dd =

   25.7791   31.7576   38.0003   44.5073


ds =

   25.7467   31.7252   37.9679   44.4749
```

```
>> [vf,L,dd,ds] = speedRsecuritydis(120,4)

vf =

  105.0000   110.0000   115.0000   120.0000


L =

   31.7713    38.8068    46.1065    53.6705


dd =

   31.8360    38.8716    46.1713    53.7353


ds =

   31.8037    38.8392    46.1389    53.7029
```

5. Low load

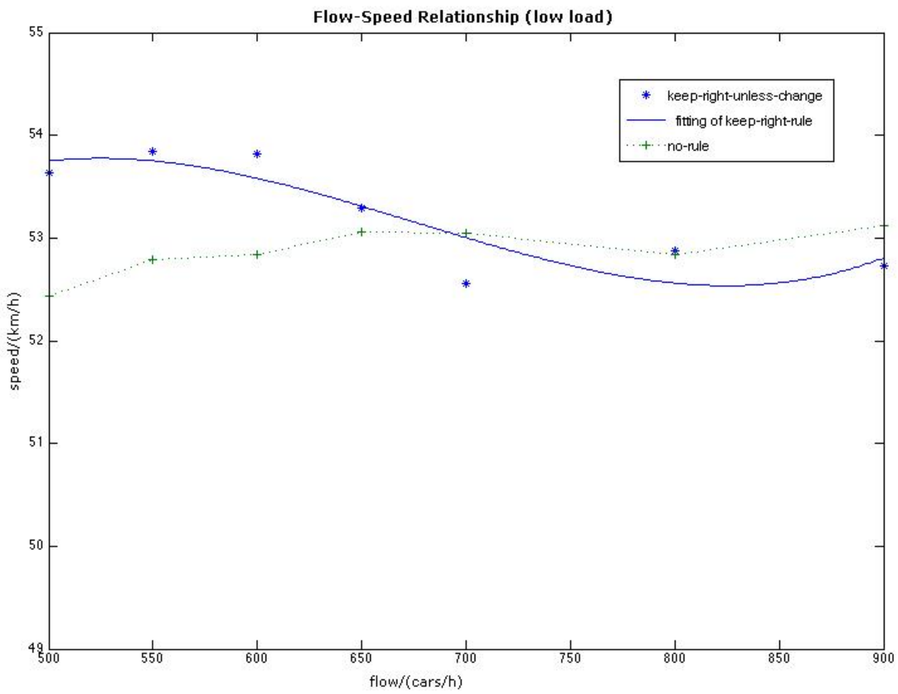

Figure 16