Maneuver Planning for Autonomous Vehicles with MPC Controller

Scientific work within the Forschungspraxis
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Chapter 1

Introduction

Perception, maneuver planning, trajectory generation, and following are the four main components of autonomous vehicle technology. This project is primarily concerned with the maneuvering and path following of autonomous vehicles on highways. The maneuvering and path planning methods for solving the autonomous driving problem are divided into three groups in the article [5]: sampling-based planning methods, path-velocity decomposition methods and numerical optimization methods. The paper provides information about the benefits and drawbacks of these three types of methods. Finding the optimal trajectory is regarded as solving a constrained optimization problem in mathematical optimization problems. The MPC (Model Predictive Control) algorithm is widely used in such algorithmic problems because it can track the desired target state while also dealing with physical restrictions and limitations and traffic rules.It is also the method of planning the path for this project. Using MPC to generate an optimal path necessitates the generation of a desired target state via its upper-level logical maneuver planning. Figure 2.1 in section 2 depicts the relationship between maneuver planning and MPC control. A maneuver planning strategy based on the exact traffic situation will be proposed in this project. This safe maneuver planning strategy is appropriate for the majority of a two-vehicle scenario on highway.

In section 2.1 of this report, the structural relationship between maneuver planning and MPC in this project is introduced, and the logic of maneuver planning is analyzed. The basic information of the public transport system in this project, such as vehicle characteristics and road settings, will be introduced in detail in section 2.2. The analysis is detailed in section 2.3 on how to implement maneuver planning and generate target states. The effects of different maneuver update frequency strategies on vehicle driving behavior and vehicle trajectory will be simulated and compared in the chapter 3, based on the maneuver planning implemented in the chapter 2, and conclusions will be drawn. The chapter 4 will provide a concluding review of the algorithm proposed in this report, as well as points that can be improved and future research directions.

Chapter 2

Maneuver Planning Strategy

2.1 Introduction of Maneuver Planning

In this chapter, we will discuss how the automatic driving system, based on the MCP controller, realizes maneuver planning and trajectory planning for the two vehicles system. The basic flow of the entire automatic driving system is represented in fig 2.1. The vehicle first perceives the present scene, after which it selects a maneuver for the current scene through maneuver planning. The maneuver that is selected determines the ego vehicle's goal lane and goal velocity. The MPC controller will take these as the reference for calculating the cost.The MPC controller solves a non-linearly constrained optimization problem to obtain an optimal control signal (the vehicle's acceleration), which it then sends to the vehicle to control its motion. As a result of the vehicle movement, the scene where the vehicle is positioned will change and update. As a result, new maneuvering and control signals are generated.

M. Sc. Ni Dang first completes the MPC controller component, which is based on the vehicle's point-mass model, which will not be explained in depth here. This project will actually mainly complete the maneuver planning part. The article [1] divides maneuvers into two types: longitudinal and lateral maneuvers. The longitudinal maneuvers include changing to the right lane (LCR), changing to the left lane (LCF), and keeping the lane (LK), while the lateral maneuvers include acceleration (AC), deceleration (DE), and maintaining a constant speed (CS). As shown in fig 2.2, there are a total of 9 maneuver combinations for these maneuvers. Some maneuver combinations are rejected in this article due to risk assessment, while several feasible maneuvers are determined. The method of risk assessment is described in detail in the article [1]. The driver's intention to maneuver is essentially added to the acceptable maneuver planning in the article [1]. The driver's intention is not included as an influencing factor for maneuver planning in this project. In article [3], several feasible maneuvers are chosen and the problem is transformed into a non-linear optimization problem by designing lost. In Automated Driving Toolbox from MATLAB, the program generates various motion trajectories using algorithms such

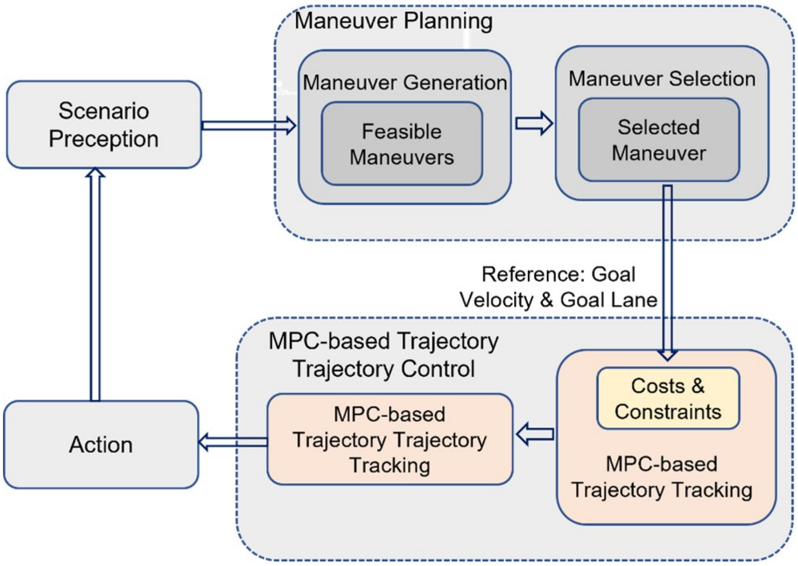

Figure 2.1: A Framework for Autonomous vehicles (from M. Sc. Ni Dang)

as interpolation, and then evaluates the feasibility and efficiency of each trajectory to find the best one. Multiple optimization problems are required, so each planning takes a long time. M. SC. Ni dang proposes obtaining only one maneuver in the grid of maneuvers through multi-level screening. It is expected to build a safe and stable maneuver planner which is suitable for various scenarios.

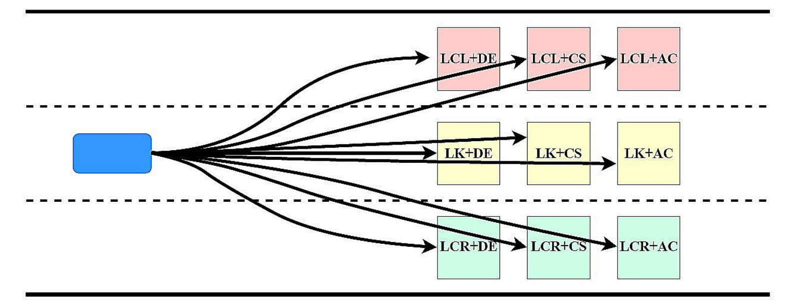

Figure 2.2: Maneuver Combination (from M. Sc. Ni Dang)

In this project, only one maneuver is expected to be selected in each maneuver planning, rather than multiple maneuvers. And the goal lane and velocity are determined based on the selected maneuver in order to achieve the goal of trajectory tracking.The goals of vehicle maneuver planning in general include lateral position, longitudinal position, and judgment of acceleration and deceleration. In this project, the ego vehicle's maneuver planning target will only consider velocity and longitudinal position. First, this reduces the complexity of the maneuvering planning problem by avoiding the need to solve the trajectory multiple times and comparing the results to find the best. Second, because the lateral distance constraints are reduced, this setting reduces the likelihood of not being able to solve during the solution process using the MPC algorithm. Third, after the goal velocity has been defined, we no longer need to worry about whether the vehicle accelerates, decelerates, or maintains a constant speed, because the vehicle's maneuvering to the goal velocity is no longer fixed. For example, if one car wants to overtake another vehicle, it is required to accelerate and change lanes. Instead of monotonically accelerating or decelerating, when the vehicle just has the goal velocity, it can accelerate and then decelerate, or drive at a steady speed and then accelerate. This means the vehicle will be more mobile.Finally, in the future, the system can be extended to multi-vehicle traffic scenarios, and the computation of reducing lateral constraints helps to scale. According to the previous analysis, we can reduce the vehicle's maneuvering options to LCR, LCF, and LK. The goal velocity of the vehicle needs to be set after the maneuver of the vehicle is determined. The challenge now is to determine a maneuver. In article [2], it is proposed to select vehicle maneuvers from the necessity of lane changing. 'Is Lane Shifting Necessary?' asks the author regarding lane-changing planning. He categorizes the responses as "Essential," "Desirable," and "Unnecessary." I've finished the maneuver planning part based on this. Because the necessity judgment is based on the specific scenario, rather than selecting the maneuver directly, the scene classificationÂ will be made first, followed by the maneuver selection. We'll go over how to categorize scenes in the next section.

2.2 Highway Traffic System

Before we get into detail about maneuver planning, it's important to understand what kind of transportation system it's based on. Basic facts regarding vehicles and roads will be introduced in this chapter. This is a two-vehicle system on the highway; one car is the ego vehicle, and the other is the vehicle in the environment; these two vehicles will be referred to as the target vehicle collectively later. The ego vehicle is the primary agent in maneuver planning, in which the target vehicle is supposed to drive at a constant speed in a lane and is unaffected by ego vehicles' actions. The ego vehicle has a length of 4.7 m and a width of 1.83 m. The vehicle has a maximum acceleration and deceleration of 0.5 m/s^2 and -0.5 m/s^2 in the longitudinal direction and 6 m/s^2 and -9 m/s^2 in the lateral direction. The highway has three lanes, each with a width of 5.25 m. The third lane is on the left, and the recommended speed is 36 m/s. The remaining two lanes are the first and second lanes from right to left, with a suggested driving speed of 30 m/s for each lane. On the highway, the maximum speed is 70 m/s, and the minimum is 14 m/s.

2.3 Realization of Maneuver Planning

First, an 'absolute' safe distance between two vehicles will be set. Outside of this range, the ego vehicle's maneuvering selection will ignore the target vehicle's influence. The ego vehicle's maneuvering behavior will be affected only when the target vehicle enters this range.This mechanism divides the entire scene into two halves. If there is a car in front of the subject vehicle, the 'absolute' safe distance for the subject vehicle to change lanes is equal to half the speed recorded on the speedometer, according to highway driving rules. When a vehicle is moving at 90 km/h, the required safety distance to change lanes is 45 meters. Following this rules, I came up with an absolute safe distance of 64.8 m based on the recommended speed for the third lane (36m/s). If the target vehicle is outside the safe distance, the corresponding maneuver can be obtained according to the lane information of the ego vehicle, as shown in table 2.1. In the table, the first column represents the lane where the ego vehicle is located, and the second column represents the maneuver of the ego vehicle. LK and LC are the abbreviations of lane keeping and lane changing respectively. When the ego vehicle is in the first or second lane, it should remain in the current lane at the recommended speed. If the ego vehicle is in the third lane, it should not stay in the third lane for a long time and should change to the second lane and drive at the recommended speed of the goal lane.

Table 2.1: Maneuvering of the ego vehicle when the target vehicle is outside safe distance

Ego Vehicle Location	Maneuver of Ego Vehicle
1	LK
2	LK
3	LC

When the distance between two vehicles is smaller than the absolute safe distance, we need to evaluate elements such as the relative lane position of the two vehicles, the velocity difference between the vehicles, the relative distance between the two vehicles, and who is in front and who is behind. To simplify the complex situation, we can first consider the lane information and lateral position of the two vehicles to determine which maneuvers can be performed by ego vehicles. The first column in table 2.2 corresponds to the lane where the ego vehicle is located. The second column represents the position and lane information of the target vehicle relative to the ego vehicle. If the ego vehicle is in the first lane, then the target vehicle has six situations relative to the ego vehicle: B3, B2, B1, F3, F2, F1. The letter B indicates that the target car is in the lateral position behind the current vehicle, while the letter F indicates that the target vehicle is in front of the vehicle. The lane in which the target vehicle is located is indicated by the number following the letter. We could enumerate the ego vehicle's maneuvering options, which is the third column of the table, based on the relative position information of the target vehicle and the ego vehicle. The maneuver options LC and LK will be assigned to the numbers 0, 0.5 and 1 in the third column, respectively. These numbers represent the certainty that something will happen, won't happen, or can happen: 0 means that it can't happen, 0.5 means that it can happen, and 1 means that it should happen. According to the above introduction, the ego vehicle is in the first lane and the target vehicle position information is B3 and F2 as examples for description. The information represented by the row of B3: the ego vehicle is in the first lane; the target vehicle is in the third lane and is located in the rear of the ego vehicle, then the maneuver of the ego vehicle is lane keeping (1) without lane changing (0). The information represented by the row of F2: the ego vehicle is in the first lane; the target vehicle is in the second lane and is in front of the ego vehicle, then the maneuver of the ego vehicle can be lane-keep (0.5) or lane changing (0.5). In this case, the maneuvering selection of the ego vehicle will require further judgment.

Table 2.2: Maneuvering of ego vehicle when the target vehicle is within a safe range; B: behind, F: Front

Ego Vehicle Location	Target Vehicle Location	Maneuver of Ego Vehicle	
		LC	LK
1	B1	0	1
	F1	0.5	0.5
	B2	0	1
	F2	0.5	0.5
	B3	0	1
	F3	0	1
2	B1	0	1
	F1	0	1
	B2	0	1
	F2	0.5	0.5
	B3	0	1
	F3	0	1
3	B1	1	0
	F1	1	0
	B2	0.5	0.5
	F2	0.5	0.5
	B3	1	0
	F3	1	0

Maneuvering judgments in Table 2.2 are based on the necessity of changing lanes. When the ego vehicle is in the first or second lane, if the target vehicle is behind the ego vehicle or the target vehicle is in the third lane, then the ego vehicle does not need to change lanes. When the ego vehicle is in the second lane and the target vehicle is in the first lane, the maneuver of the ego vehicle will not be affected by the target vehicle, so the ego vehicle does not need to change lanes. If the ego vehicle is in the third lane and the target vehicle is in the first or third lane, then there is no doubt that the ego vehicle should return to the second lane. In the remaining relative position conditions, the ego vehicle can change lanes or not. It can be concluded from the previous description that the scenes of necessary lane change and unnecessary lane changing can be achieved. A maneuver can be identified in these cases, and the goal lane and velocity can be determined based on the determined movement, as shown in table 2.3. Under this condition, the general goal velocity is the recommended speed of the goal lane, but when there is a vehicle in the goal lane behind the ego vehicle, the goal velocity is suggested to be the bigger of the recommended speed and the target vehicle velocity.

Table 2.3: Goal Velocity Set in necessary LC case and unnecessary LC case (V_r: recommended speed in goal lane, V_t: target Vehicle speed)

Ego Vehicle Location	Target Vehicle Location	Maneuver of Ego Vehicle		Goal Velocity
		LC	LK	
1	B1	0	1	max(V_r,V_t)
	B2, B3, F3	0	1	V_r
2	B1, B3, F1,F3	0	1	V_r
	B2	0	1	max(V_r,V_t)
3	B1, B3, F1,F3	1	0	V_r

From the data in Table **??**, we can get five scenarios that require further judgment of maneuver. Before going any further, it should be apparent that lane changing takes priority over keeping the lane; that is, as long as the condition deems that lane changing is permissible, the ego vehicle will execute the lane change. We'll introduce variables TTC and TIV to aid judgment in cases that require more maneuvering judgment. TTC stands for time to collision and represents the following physical meaning: If the two cars maintain their speeds and drive at a constant speed, the time it takes for the rear automobile to catch up to the front car may be calculated using the equation 2.1 below. D is the target vehicle's relative distance in this formula.

$$TTC = \frac{D}{(V_{ego} - V_t)} \tag{2.1}$$

TIV is the abbreviation of time vehicular time. This variable represents the time for the rear vehicle to catch up with the preceding vehicle at a constant speed if the preceding vehicle is stationary. The expression is as follows equation 2.2. V_B represents the speed of the vehicle behind.

$$TTC = \frac{D}{V_B} \tag{2.2}$$

As shown in fig. 2.3 , this is a simple lane changing situation and it shows three time-variables TTC, TIV, t_{LC}. The variable t_{LC} represents the time from the departure point to the lane changing point of the ego vehicle. The lane changing point is defined as the intersection of the center point of the ego vehicle and the lane boundary line. This diagram depicts the essential lane-changing criteria, namely that the lane-changing time t_{LC} must be less than the TTC , that is, the ego vehicle must not crash with the preceding vehicle before completing the lane change.

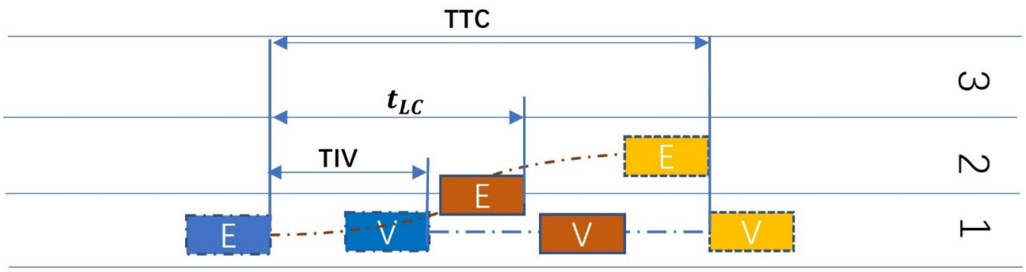

Figure 2.3: Three time variables in lane changing case; E: ego vehicle, V: target vehicle; Blue block: start position, Rot block: lane changing point, Yellow block: catch up point; t_{LC}: time for lane change

If the TTC is smaller, the relative distance between the two vehicles is smaller, and the relative speed is larger. When the ego vehicle is behind the target vehicle and executes lane changing, there is a high possibility that the ego vehicle will collide with the target vehicle during the lane changing. When the TTC is large, the distance between the two vehicles is relatively large, so the possibility of collision between the two vehicles is reduced. However, it is unreasonable to rely only on TTC for maneuvering judgment. For example, when the speed difference between the two cars is very small or even zero, in this case, although the distance between the two cars is small, the TTC will also be large. But the ego vehicle should not change lanes in this instance. If the ego vehicle is in the first lane and the target vehicle is in the second lane, the MPC algorithm may even plan a trajectory for overtaking from the right side during the lane changing process, which is not allowed. The variable TIV is utilized to aid judgment. When the distance between the two vehicles is little and the speed difference is small, the TTC is big but the TIV is small, the ego car will refuse the lane-changing maneuver determined by the TTC. In the first TIV seconds, the ego vehicle is safe because there is no target vehicle on this road segment, and this area is also the main space for MPC to search the trajectory. Therefore, TIV can assist MPC to find the reference trajectory. We can define two thresholds for lane changing based on the above description to evaluate the 'big' or 'small' of the time variable. The determination of this threshold will be based on the description in article [5] and will assess the likelihood of a two-car collision using TTC and TIV, as shown in figure 2.4.

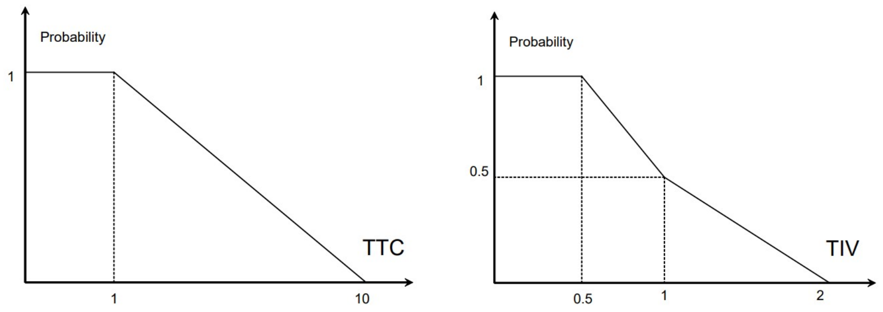

Figure 2.4: TTC (left) and TIV (right) based possibility of collision [5]

In this project, different thresholds will be set according to the traffic information and the lane information of the two vehicles. In the traffic system, the minimum speed is set to 14 m/s, and the recommended speed is generally 30 m/s. Then, according to the maximum safety range of about 65m, the appropriate TTC threshold is about 4 s ($\frac{64}{30-14}$). The speed of the vehicle in the third lane is generally higher than vehicles in the first and second lanes, the vehicle lane changing distance will increase relatively. In the program implementation, the TTC threshold will be appropriately increased. The setting of this value is defined as 6 s in this project after many simulation tests. In actual situations, traffic data can be collected for data analysis. The threshold of TIV is generally 1 s, which represents the minimum reaction time of the vehicle driver (from M. Sc. Ni Dang). When driving in the third lane at a faster speed, the reaction time must be raised accordingly and the TIV threshold is set to 1.2 s. The ego vehicle can change lanes if the calculated TTC and TIV are both greater than the thresholds.

Table 2.4: Goal Velocity Setting if one maneuver is determined; V_t: target velocity, V_r: recommended velocity

<table>
<tr><th>Ego Vehicle Location</th><th>Target Vehicle Location</th><th>Maneuver of Ego Vehicle</th><th colspan="2">Goal velocity</th><th>Goal Lane</th></tr>
<tr><td rowspan="6">1</td><td rowspan="3">F1</td><td rowspan="2">LC</td><td>$V_t \geq 0.95V_r$</td><td>max($1.2V_r$,$1.15V_t$)</td><td rowspan="2">2</td></tr>
<tr><td>$V_t \leq 0.95V_r$</td><td>max(V_r, $1.1V_t$)</td></tr>
<tr><td>LK</td><td colspan="2">min(V_r, $0.95V_t$)</td><td>1</td></tr>
<tr><td rowspan="3">F2</td><td rowspan="2">LC</td><td>$V_t \geq 0.95V_r$</td><td>max($1.2V_r$,$1.15V_t$)</td><td rowspan="2">2</td></tr>
<tr><td>$V_t \leq 0.95V_r$</td><td>max(V_r, $1.1V_t$)</td></tr>
<tr><td>LK</td><td colspan="2">V_r</td><td>1</td></tr>
<tr><td rowspan="2">2</td><td rowspan="2">F2</td><td>LC</td><td colspan="2">max(V_r, $1.2V_t$)</td><td>3</td></tr>
<tr><td>LK</td><td colspan="2">min(V_r, $0.95V_t$)</td><td>2</td></tr>
<tr><td rowspan="4">3</td><td rowspan="2">B2</td><td>LC</td><td colspan="2">max(V_r, V_t)</td><td>2</td></tr>
<tr><td>LK</td><td colspan="2">V_r</td><td>3</td></tr>
<tr><td rowspan="2">F2</td><td>LC</td><td colspan="2">V_r</td><td>2</td></tr>
<tr><td>LK</td><td colspan="2">V_r</td><td>3</td></tr>
</table>

Based on the LC (0.5) and LK (0.5) obtained from the previous analysis, it will be defined as 0 or 1 in this step to determine one maneuver. When the lane keeping or lane changing of the ego vehicle is determined, then the target lane and target speed of the ego vehicle need to be considered. The setting of the target speed will need to take into account the lanes of the two vehicles, the position, the maneuver of the ego vehicle, and the speed of the target vehicle. The goal velocity settings for each situation are listed in table 2.4.

The speed setting logic in table 2.4 are the same as those in table 2.3. In the LC maneuver, under normal circumstances, the ego vehicle needs to be accelerated, so the acceleration degree of the ego vehicle needs to be considered according to the speed of the target vehicle. If the speed of the target vehicle is not lower than 95% of the recommended speed when changing from the first lane to the second lane, then the ego vehicle can take $max(1.2V_r, 1.15V_t)$ as the target speed, and if it is lower, then The target speed of the ego vehicle will be conservatively set to $max(V_r, 1.1V_t)$. This limit (95%) is set as an empirical value. If there is enough traffic data, this limit can be obtained by analysis.

Through the above analysis, the steps of cutting the scene and the process of maneuvering selection can be summarized in the following figure 2.5.

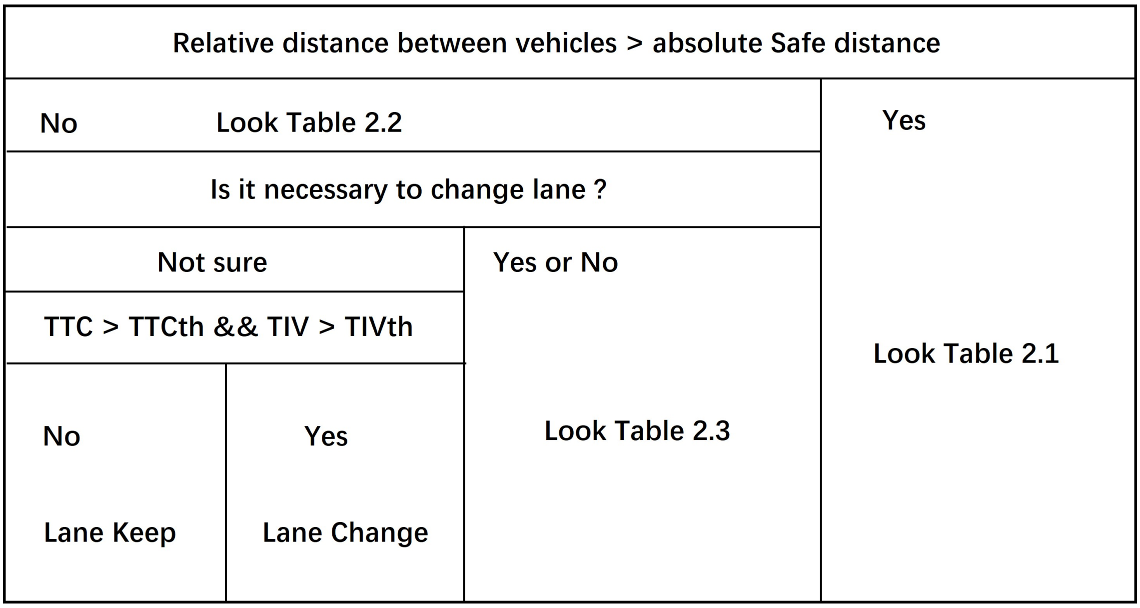

Figure 2.5: Overview for realization of maneuver planning; TTCth: threshold of TTC, TIVth: threshold of TIV

Chapter 3

Comparing Different Maneuver Update Frequency Strategies

3.1 Experimental Setting

In this chapter, simulation tests based on previously determined maneuver logic judgments will be analyzed, and the effect of different maneuver update frequency strategies on the simulation result will be compared. The simulation scene will be split into 3 categories according to the lane where the ego vehicle starts. First, the ego vehicle is in the third lane. The target vehicle is in the second lane; Second, the ego vehicle is in the second lane, and the target vehicle is in the second lane; Third, the ego vehicle is in the first lane and the target vehicle is in the first or second lane. Under each generalized simulation scenario category, different initial lateral initial positions and initial lateral speed of the vehicle will be set for simulation tests.

For each case, the effect of different maneuver update frequencies on vehicle behavior will be tested. The maneuver update frequency strategy can be divided into the following 3 types:

1) Maneuver update only happens at each MPC iteration, like the strategy mentioned in article [4] .

2) In each MPC iteration, the N-steps prediction horizon is generated and used to calculate the optimal control for the current step. In this project, N is set to 25. The maneuver update can occur at each prediction step of the horizon. Of course, within a horizon, maneuver update can also be performed at certain frequencies. In the report, the simulation results are compared when the maneuver is updated every 2 prediction steps, every 5 prediction steps, and every 10 prediction steps at each iteration.

3) Maneuver update can occur with a certain iteration step size, and the simulation

results are compared in this report for every 2 iterations, every 5 iterations, and every 10 iterations. In this case, a comparison will be made with the first maneuver update strategy. These two strategies only consider maneuvering updates according to a certain iterative step size, and do not consider maneuvering updates within the horizon.

According to the above analysis of the maneuver update frequency strategy, the following eight update frequencies are tested for each simulated scenario in the following comparison. The simulation results will be displayed in order of frequency from low to high. The first three frequency settings belong to the third strategy, the fourth setting belongs to the first strategy, and the simulation results based on this setting will be used as a reference for comparison. The rest belong to the second strategy. For each test scenario, there will be the same tests, which will not be repeated hereafter.

1. Maneuver update at every 10 iterations
2. Maneuver update at every 5 iterations
3. Maneuver update at every 5 iterations
4. Maneuver update at each iteration
5. Maneuver update at every 10 prediction steps at each iteration
6. Maneuver update at every 5 prediction steps at each iteration
7. Maneuver update at every 2 prediction steps at each iteration
8. Maneuver update at each prediction step at each iteration

3.2 Experimental Results and Analysis

3.2.1 Ego Vehicle at Third Lane

In this section, we will discuss the scenario where the ego car is in the third lane and the target vehicle is in the second lane. In this scenario, the two vehicles will be simulated under three different sets of initial conditions, such as different starting lateral position and different starting lateral speed.

First specific scenario:

In this scenario, the first specific scenario we observe is set to the ego vehicle in the third lane, the initial lateral distance is 10 m and the initial lateral speed is 35 m/s. The target vehicle is in the second lane, the initial lateral distance is 50 m and the initial lateral speed is 20 m/s. Based on this initial setup, if an intuitive judgment is made, the ego vehicle's maneuver sequence should be to stay in the third lane and overtake the target vehicle, then change to the second lane. The next eight graphs represent the ego vehicle trajectories at different update frequencies.

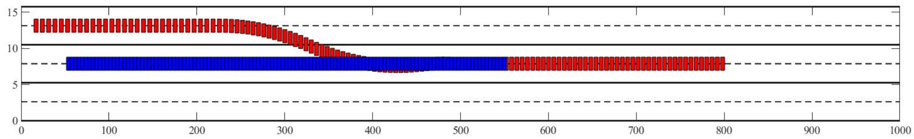

Figure 3.1: simulation result with maneuver update at every 10 iterations, lane change point at about 320 m

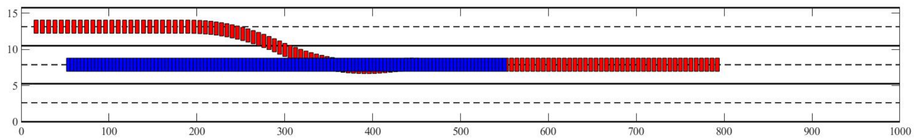

Figure 3.2: simulation result with maneuver update at every 5 iterations, lane change point at about 300 m

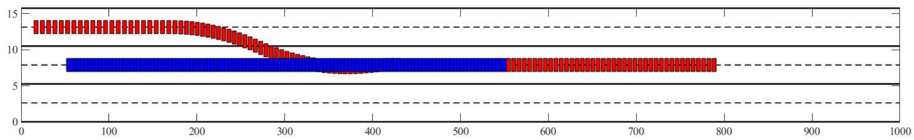

Figure 3.3: simulation result with maneuver update at every 2 iterations, lane change point at about 280 m

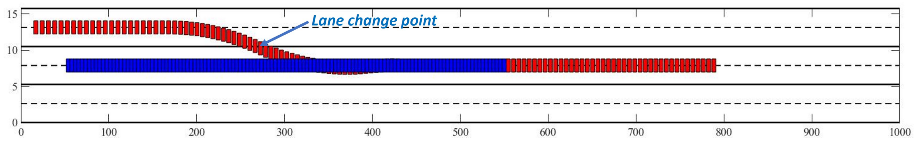

Figure 3.4: simulation result with maneuver update at each iteration, lane change point at about 260 m

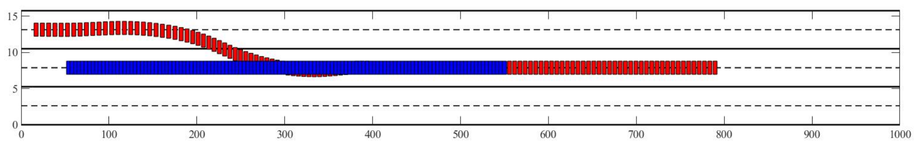

Figure 3.5: simulation result with maneuver update at every 10 prediction steps at each iteration,lane change point at about 230 m

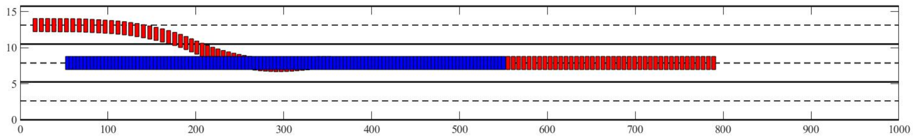

Figure 3.6: simulation result with maneuver update at every 5 prediction steps at each iteration, lane change point at about 200 m

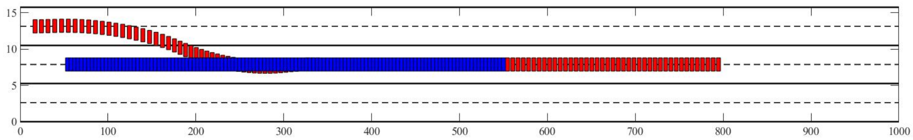

Figure 3.7: simulation result with maneuver update at every 2 prediction steps at each iteration, lane change point at about 190 m

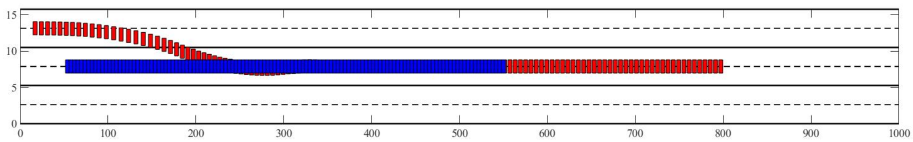

Figure 3.8: simulation result with maneuver update at each prediction step at each iteration, lane change point at about 180 m

At all above-mentioned maneuver update frequency settings, the ego vehicle completes overtaking and switches to the second lane. For the convenience of the following analysis, I define the intersection of the vehicle center point and the lane boundary line as the lane change point, as shown in fig. 3.4. Taking the results of maneuver update at each iteration as a reference, it can be observed that the lane change point is around 260 m. For maneuver update with different frequencies within a horizon, the position of the lane change point in the simulation results is less than 260 m, and its position becomes smaller as the frequency increases. This shows that the algorithm can plan a more efficient path under the second update frequency strategy than the first update frequency strategy. Under the second strategy, the algorithm adds the influence of possible future two-car scenarios on the current path planning. Since the state of the target vehicle cannot be controlled, the algorithm in the second strategy assumes that the target vehicle is traveling at a constant speed. This may be a disadvantage. For the strategy of updating frequency with different iteration steps, the position of the lane change point is larger than 260 m and becomes larger as the frequency decreases. The position of the lane change point in fig. 3.9 gets smaller as the frequency increases. When a maneuver is determined at a certain iteration, the next few iterations will directly target the previously determined maneuver. This approach makes the ego vehicle easy to miss the earliest suitable lane change position and reduces the impact of the target vehicle on the ego vehicle, which is unsafe.

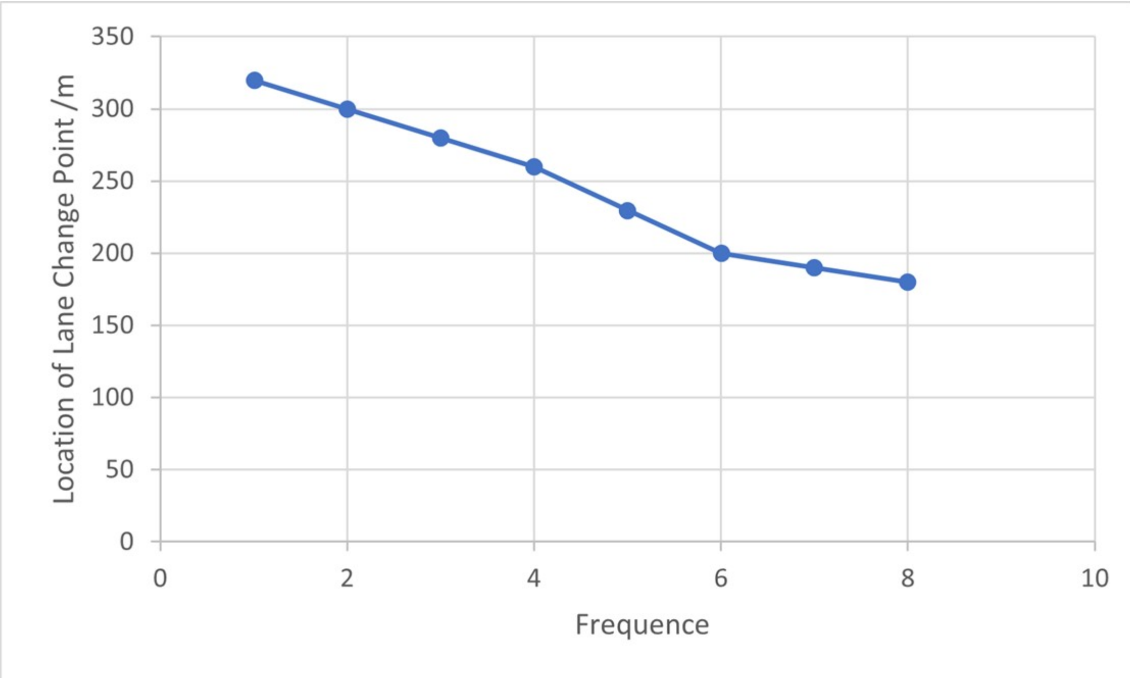

Figure 3.9: Location of lane change point

Second specific scenario:

The second concrete scenario we observe is set with the ego vehicle in the third lane with an initial lateral distance of 10 m and an initial lateral speed of 35 m/s. The target vehicle is in the second lane, the initial lateral distance is 80 m, and the initial lateral speed is 25 m/s. In this setting, there are two possibilities for intuitively judging the maneuvering behavior of ego vehicles. The first is that the ego vehicle stays in the third lane and overtakes, and then changes to the second lane. The second is that the ego vehicle first changes to the second lane, follows the preceding car for a period, and then changes to the third lane before executing overtaking and lane changing. The next eight graphs represent ego vehicle trajectories at different update frequencies.

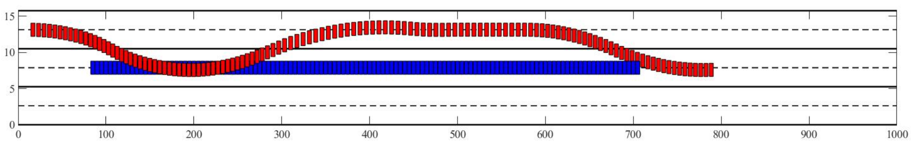

Figure 3.10: simulation result with maneuver update at every 10 iterations, three lane change maneuvers

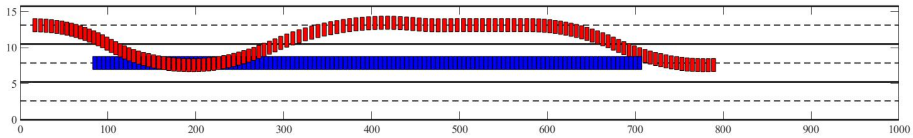

Figure 3.11: simulation result with maneuver update at every 5 iterations, three lane change maneuvers

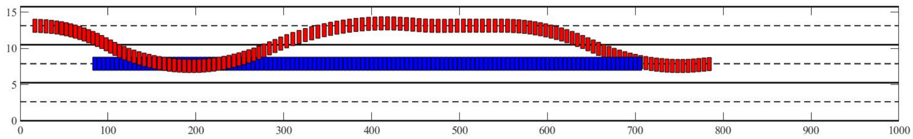

Figure 3.12: simulation result with maneuver update at every 2 iterations, three lane change maneuvers

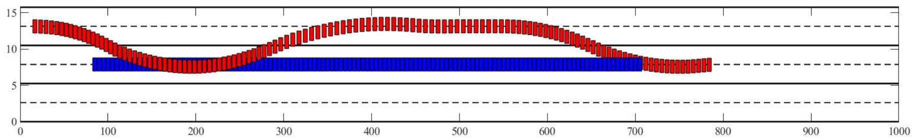

Figure 3.13: simulation result with maneuver update at each iteration, three lane change maneuvers

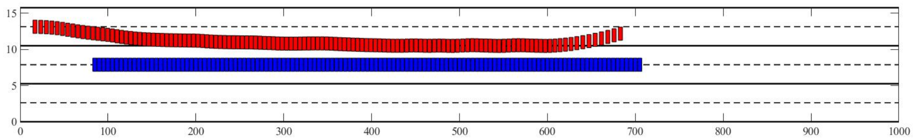

Figure 3.14: simulation result with maneuver update at every 10 prediction steps at each iteration, no lane change maneuver

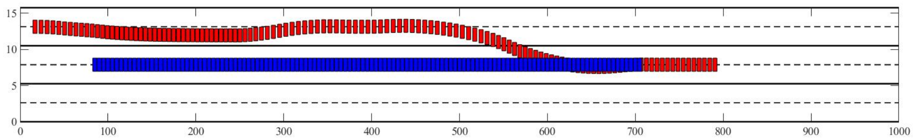

Figure 3.15: simulation result with maneuver update at every 5 prediction steps at each iteration, one lane change maneuver

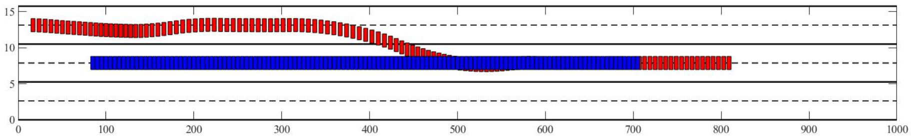

Figure 3.16: simulation result with maneuver update at every 2 prediction steps at each iteration, one lane change maneuver

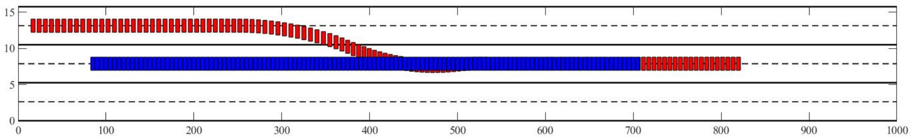

Figure 3.17: simulation result with maneuver update at each prediction step at each iteration,one lane change maneuver

Under the strategy of update once per iteration step, the ego vehicle first changes to the second lane and follows the preceding vehicle, then changes to the third lane and overtakes, and then changes to the second lane. The maneuvering sequence of the ego vehicle is the same as under the first update frequency strategy. Under the strategy with different iteration steps as the maneuver update frequency, the first and second lane change points are the same at these frequency settings, but the location of the third lane change point is further away as the frequency decreases. The reason is the same as in the previous scene. Under the strategy of changing the maneuver update frequency within a horizon, at the update frequency of every 10 prediction steps, every 5 prediction steps, and every 2 prediction steps, the ego vehicle shows a tendency of lane change to the second lane first. With the update frequency increasing, this tendency becomes smaller. Under these three settings, the tendency of lane change is interrupted, and the ego vehicle changes to the second lane after passing the target vehicle. Under maneuver prediction at each prediction step, the ego vehicle shows that it keeps the lane and overtakes the target vehicle, then changes to the second lane. In the early stage of horizon, the maneuvering plan of the ego vehicle is lane change, but in the later stage it is lane keep. As the maneuver update frequency goes from low to high, the likelihood of lane keep for ego vehicle increases. This likelihood is reflected in the before mentioned trends. That's why the ego vehicle makes three lane changes at low frequencies (the first four frequency settings) and one at high frequencies (the last four frequency settings).

Third specific scenario:

The third specific scenario we observe is set on the third lane with an initial lateral distance of 10 m and an initial lateral velocity of 35 m/s. The target vehicle is in the second lane, the initial lateral distance is 150 m, and the initial lateral speed is

15 m/s. In this case, the intuitive judgment of the ego vehicle's maneuver behavior is most likely to first change to the second lane, follow the preceding vehicle for a period, then change to the third lane, later perform overtaking and lane changing. The next eight graphs represent ego vehicle trajectories at different update frequencies.

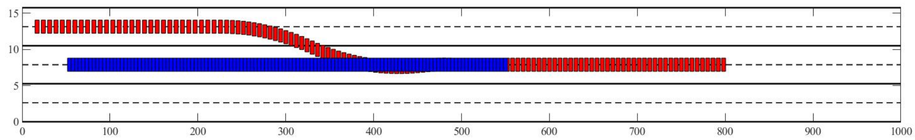

Figure 3.18: simulation result with maneuver update at every 10 iterations,three lane change maneuvers

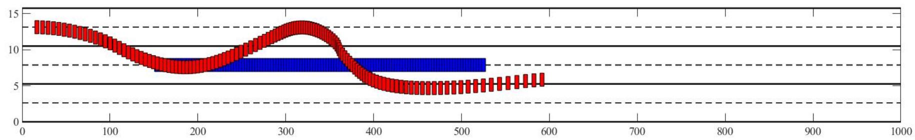

Figure 3.19: simulation result with maneuver update at every 5 iterations, dangerous maneuvering sequence

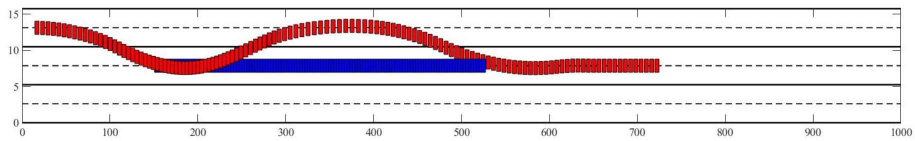

Figure 3.20: simulation result with maneuver update at every 2 iterations, dangerous maneuvering sequence

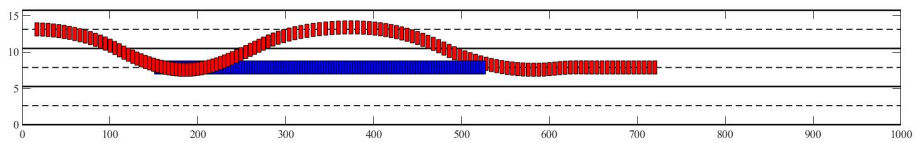

Figure 3.21: simulation result with maneuver update at each iteration, three lane change maneuvers

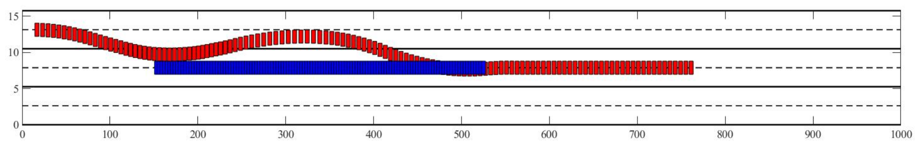

Figure 3.22: simulation result with maneuver update at every 10 prediction steps at each iteration, one lane change maneuver

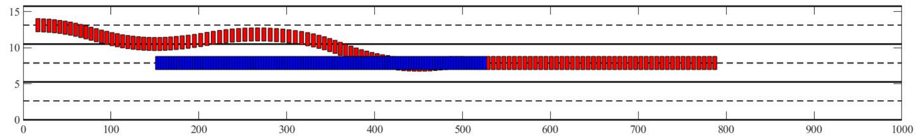

Figure 3.23: simulation result with maneuver update at every 5 prediction steps at each iteration, one lane change maneuver

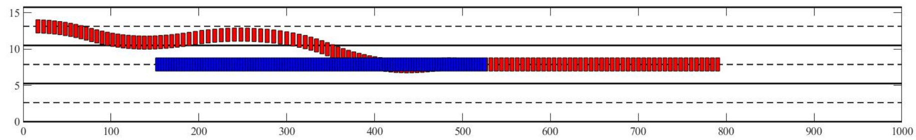

Figure 3.24: simulation result with maneuver update at every 2 prediction steps at each iteration, one lane change maneuver

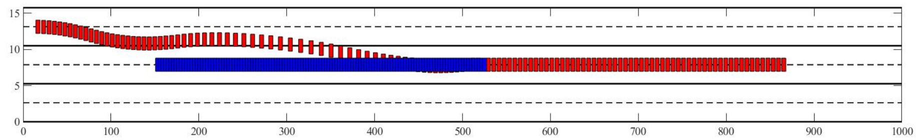

Figure 3.25: simulation result with maneuver update at each prediction step at each iteration, one lane change maneuver

The simulation results for this scenario are similar to the simulation results for the second specific simulation scenario. Based on the second frequency strategy, the simulation results of this scenario under the same frequency setting will be more biased towards the second lane in the 100 m to 200 m road section than the simulation results of the previous scenario. It can be seen from the intuitive judgment that the possibility of the ego vehicle changing from the third lane to the second lane is higher than that in the previous scene. Under the setting of the maneuver update frequency of every 5 iterations, the ego vehicle experienced dangerous driving of multiple lane changes and overtaking from the right side. This is because the interaction between the ego vehicle and the target vehicle becomes less, which makes the overall trajectory planning of the ego vehicle unstable.

3.2.2 Ego Vehicle at Second Lane

In this section, we will discuss the scenario where the ego car is in the second lane and the target vehicle is also in the second lane. In this scenario, the two vehicles will be simulated under two different sets of initial conditions.

First Specific Scenario:

The first specific scenario we observed was set up with the ego vehicle in the second lane with an initial lateral distance of 10 m and an initial lateral velocity of 30 m/s. The target vehicle is in the second lane with an initial lateral distance of 60 m and an initial lateral speed of 30 m/s. In this case, the speed difference, and the initial distance between the two cars are not large. The intuitive judgment of the ego-vehicle's maneuvering behavior is to change to the third lane, and then perform overtaking and lane-changing.

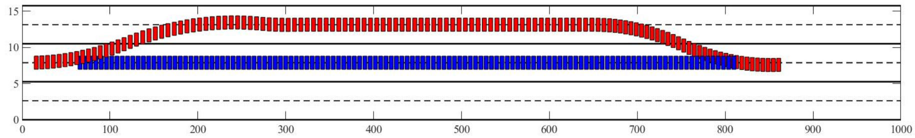

Figure 3.26: simulation result with maneuver update at every 10 iterations, overtake distance is about 740 m

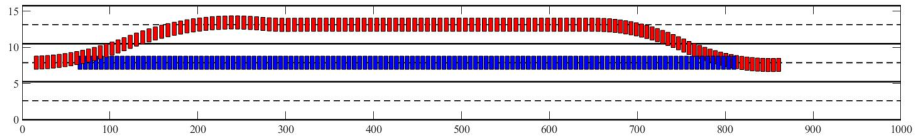

Figure 3.27: simulation result with maneuver update at every 5 iterations, overtake distance is about 730 m

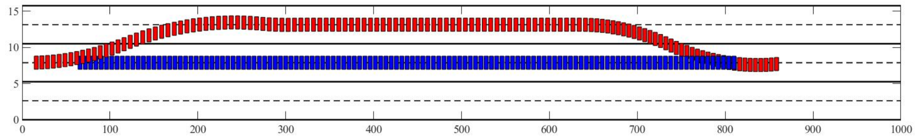

Figure 3.28: simulation result with maneuver update at every 2 iterations, overtake distance is about 610 m

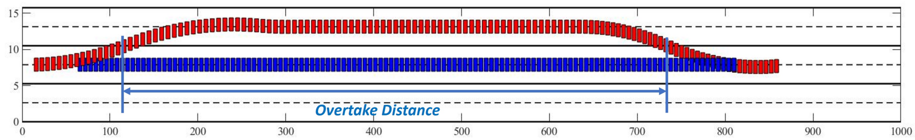

Figure 3.29: simulation result with maneuver update at each iteration, overtake distance is about 610 m

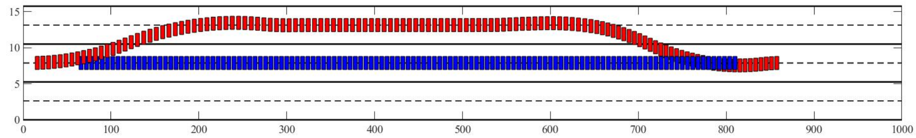

Figure 3.30: simulation result with maneuver update at every 10 prediction steps at each iteration, overtake distance is about 610 m

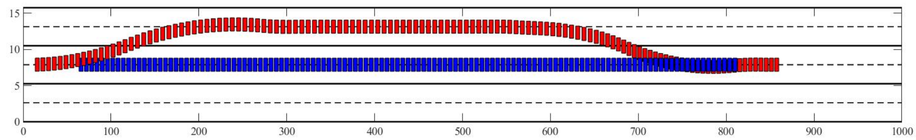

Figure 3.31: simulation result with maneuver update at every 5 prediction steps at each iteration, overtake distance is about 570 m

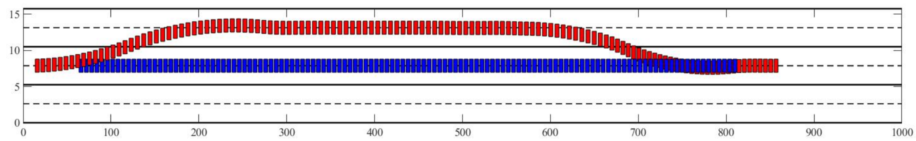

Figure 3.32: simulation result with maneuver update at every 2 prediction steps at each iteration, overtake distance is about 550 m

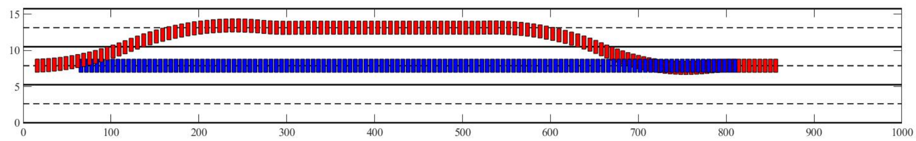

Figure 3.33: simulation result with maneuver update at each prediction step at each iteration, overtake distance is about 520 m

All simulation results for all frequency settings in this scenario are two lane changes for the ego vehicle. The main difference between the simulation results is the distance between the two lane-change points, which I define as the overtaking distance, as shown in fig. 3.29 . By comparing the simulation results, the overtaking distance decreases with the increase of the predicted frequency, as fig. 3.34. The difference in overtaking distance is mainly due to the different locations of the second lane change point. The location of the first lane change point is the same for all frequency settings because the initial conditions are set so that the initial maneuver prediction is a lane change. The scene at the second lane change point is that the ego vehicle is in the third lane and the target vehicle is in the second lane, so the position change of the second lane change point is consistent with the conclusion drawn from the simulation results of the first specific scenario in section 3.2.1.

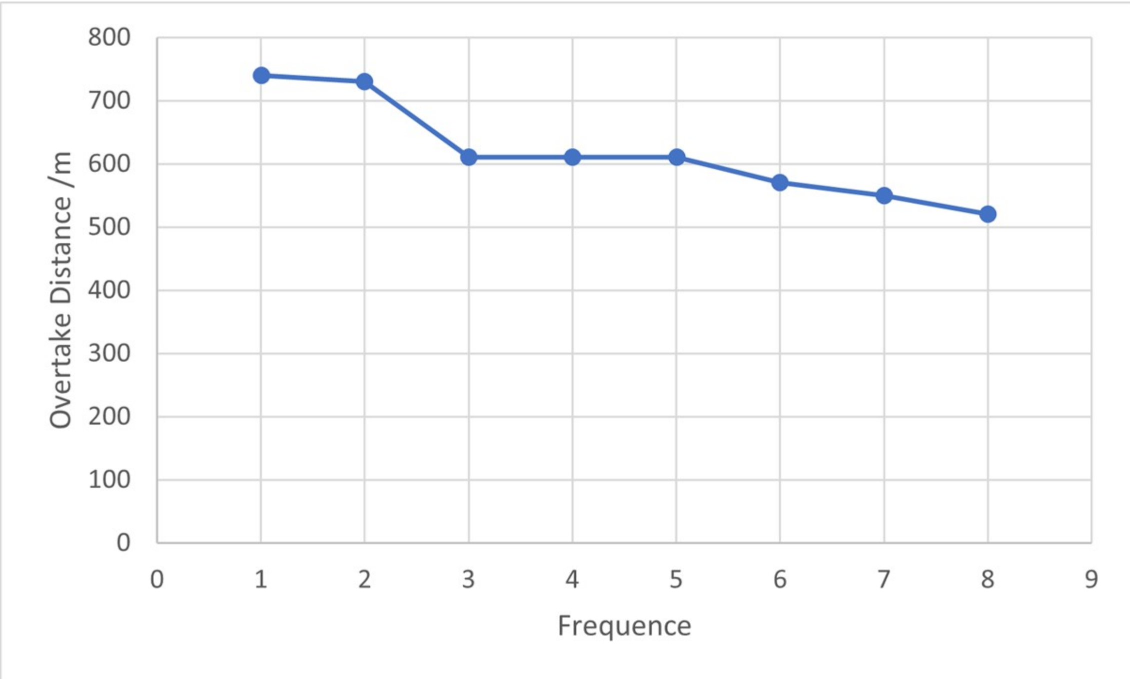

Figure 3.34: Overtake Distance for 8 different frequencies

Second Specific Scenario:

The second specific scenario we observed was set up with the ego vehicle in the second lane with an initial lateral distance of 10 m and an initial lateral velocity of 30 m/s. The target vehicle is in the second lane, the initial lateral distance is 100 m, and the initial lateral speed is 20 m/s. In this case, the velocity of the two vehicles is not much different, but the distance between them is far away. The intuitive judgment of the ego vehicle's maneuvering behavior is to firstly keep the lane closer to the target vehicle in front, then change to the third lane, later perform overtaking and lane changing.

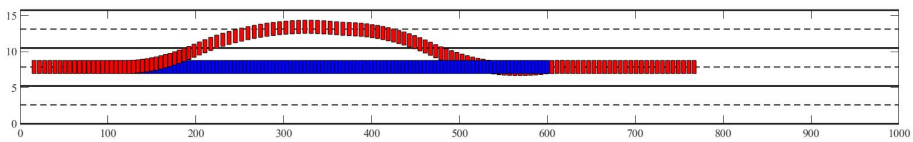

Figure 3.35: simulation result with maneuver update at every 10 iterations, overtake distance is about 280 m

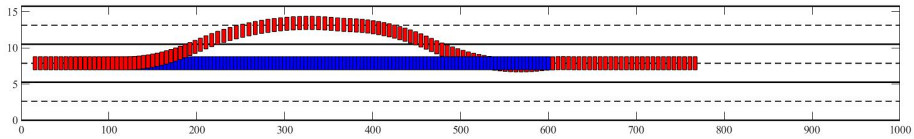

Figure 3.36: simulation result with maneuver update at every 5 iterations, overtake distance is about 270 m

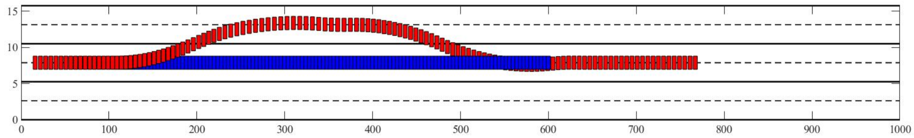

Figure 3.37: simulation result with maneuver update at every 2 iterations, overtake distance is about 260 m

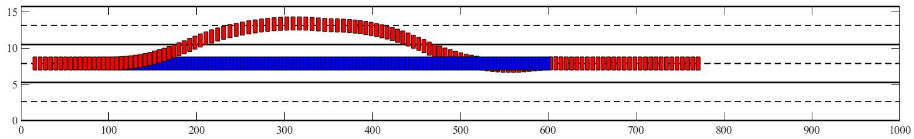

Figure 3.38: simulation result with maneuver update at each iteration, overtake distance is about 260 m, overtake distance is about 230 m

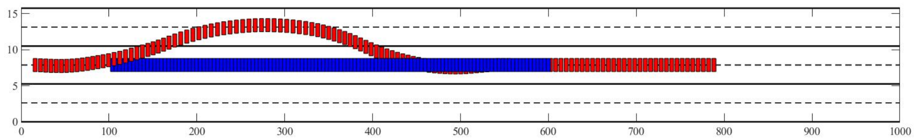

Figure 3.39: simulation result with maneuver update at every 10 prediction steps at each iteration, overtake distance is about 250 m

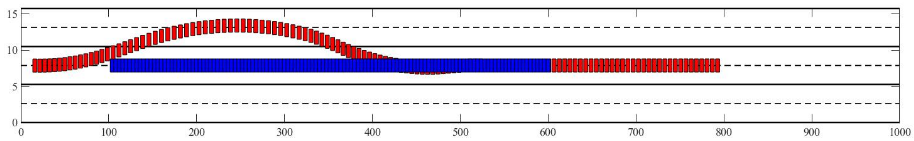

Figure 3.40: simulation result with maneuver update at every 5 prediction steps at each iteration, overtake distance is about 240 m

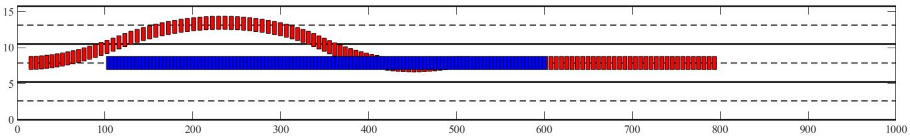

Figure 3.41: simulation result with maneuver update at every 2 prediction steps at each iteration, overtake distance is about 230 m

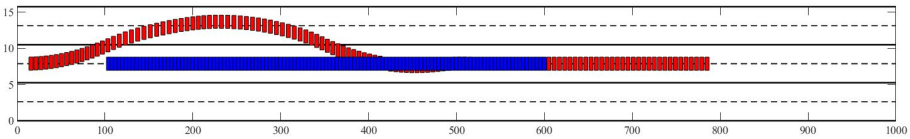

Figure 3.42: simulation result with maneuver update at each prediction step at each iteration, overtake distance is about 230 m

The simulation results for this scenario setup are similar to the simulation results for the previous scenario setup. The ego vehicle changes lanes twice and the overtaking distance increases with decreasing frequency. But the difference from the previous one is the location of the first lane change point. The first lane change point planned by using the first and third maneuver update frequency strategies is farther than that by using the second strategy, that is, the ego vehicle follows the preceding vehicle for a time. If the lane changing conditions are convenient, for example, the distance between the two cars is large and the speed difference between the two cars is not large, the second strategy can be used to obtain a more efficient maneuver sequence .

3.2.3 Ego Vehicle at First Lane

In this section, we will discuss the scenario where the ego car is in the first lane and the target vehicle is in the first lane or in the second lane. The two cars will be tested under a total of three different initial conditions.

First Specific Scenario:

In this case, the first specific scenario we observe is set when both cars are in the first lane and the initial lateral velocity of both cars is 30 m/s. Also, the initial lateral distance of the ego car is 10 m, and the initial lateral distance of the target vehicle is 60 m. In this case, the speed of the two vehicles is the same but the distance between two vehicles is not far. The intuitive judgment of the ego vehicle's maneuvering behavior is to change to the second lane.

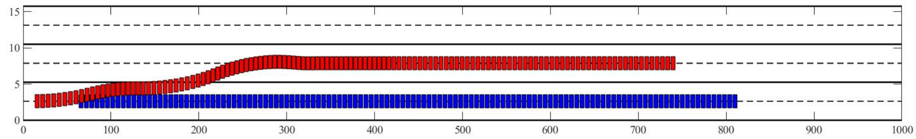

Figure 3.43: simulation result with maneuver update at every 10 iterations

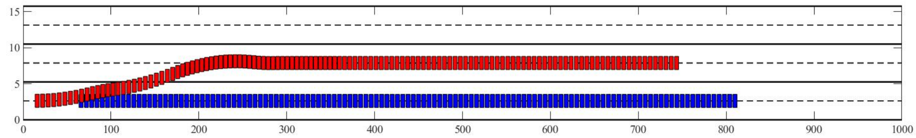

Figure 3.44: simulation result with maneuver update at every 5 iterations

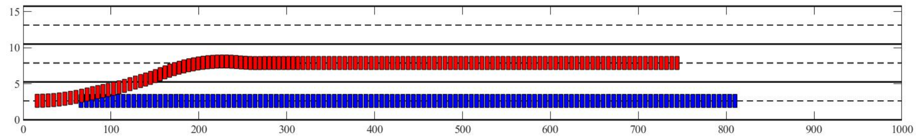

Figure 3.45: simulation result with maneuver update at every 2 iterations

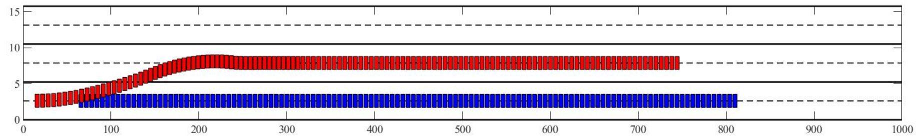

Figure 3.46: simulation result with maneuver update at each iteration

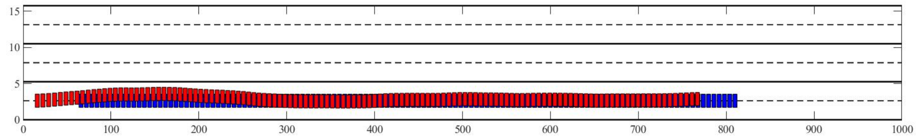

Figure 3.47: simulation result with maneuver update at every 10 prediction steps at each iteration, No lane change maneuver

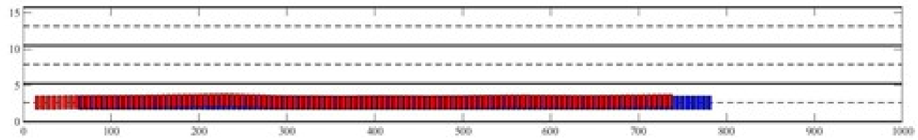

Figure 3.48: simulation result with maneuver update at every 5 prediction steps at each iteration, No lane change maneuver

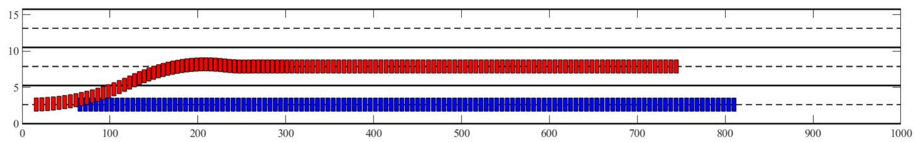

Figure 3.49: simulation result with maneuver update at every 2 prediction steps at each iteration

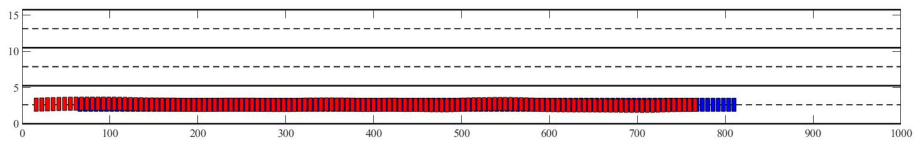

Figure 3.50: simulation result with maneuver update at each prediction step at each iteration, No lane change maneuver

In this simulation scenario, the simulation results at the frequency of maneuver update at each iteration and at different update frequencies with different iteration steps are that the ego vehicle changes lane from the first lane to the second lane. Under these two strategies, the lane change points will be further away as the update frequency decreases. And in the simulation result with maneuver update at every 10 iterations, it can be observed that the ego vehicle does not transition to the second lane quickly and in time. Due to the reduced frequency of maneuver updates, the maneuvering response of the ego vehicle has become sluggish. Under the setting of the second frequency update strategy, at the frequency of every 10 prediction steps, every 5 prediction steps, and each prediction step within a horizon, the ego vehicle does not complete the lane change. But the ego trajectory indicated that there is a tendency of ego vehicles to change lane to the second lane and the tendency becomes less pronounced as the frequency of maneuver updates increases. The ego vehicle only completes the lane change from the first lane to the second lane at the frequency of the maneuver update at every 2 prediction steps. Under the second frequency strategy, the maneuvering choice in the early stage within a horizon is to change lanes, but with the update, the maneuvering choice will be more inclined to keep the lane. So, when the update frequency is high, the algorithm will not plan the path for changing lanes.

Second Specific Scenario:

In this case, the second specific scenario we observe is set up where the ego vehicle is in the first lane and the target vehicle is in the second lane. The initial lateral speed of both vehicles is 30 m/s. The initial lateral distance of the ego vehicle is 10 m, and the initial lateral distance of the target vehicle is 60 m. The two vehicles are in different lanes, and the velocity of them is same but the distance between them is not far away. The intuitive judgment of the ego vehicle's maneuvering behavior is that the ego vehicle firstly changes to the second lane, and then either directly changes to the third lane, then overtakes and changes lane, or follow the preceding vehicle in the second lane for a time and then perform two lane changes to return to the second lane.

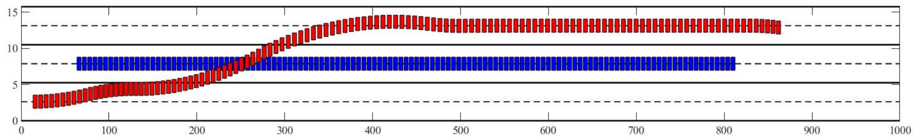

Figure 3.51: simulation result with maneuver update at every 10 iterations

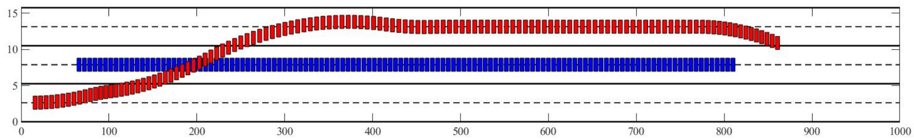

Figure 3.52: simulation result with maneuver update at every 5 iterations

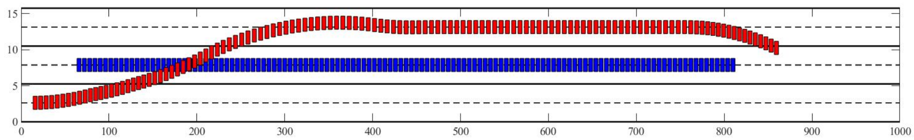

Figure 3.53: simulation result with maneuver update at every 2 iterations

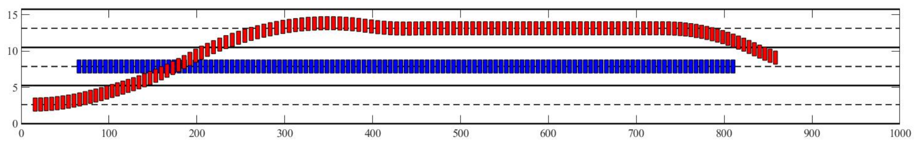

Figure 3.54: simulation result with maneuver update at each iteration

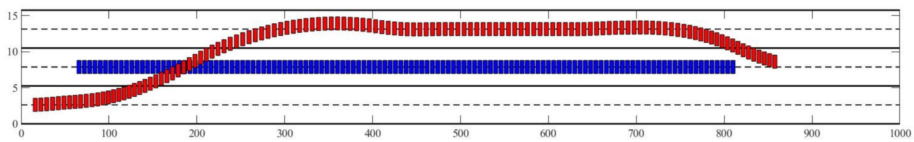

Figure 3.55: simulation result with maneuver update at every 10 prediction steps at each iteration

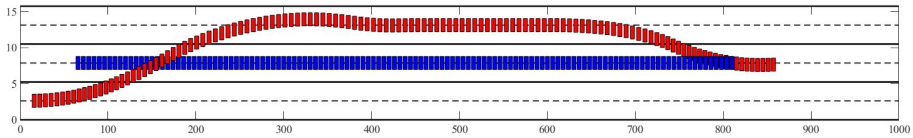

Figure 3.56: simulation result with maneuver update at every 5 prediction steps at each iteration

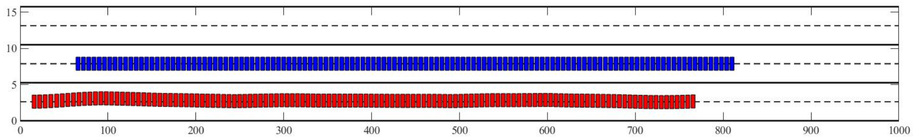

Figure 3.57: simulation result with maneuver update at every 2 prediction steps at each iteration, No lane change maneuver

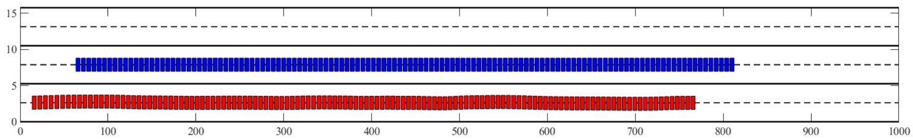

Figure 3.58: simulation result with maneuver update at each prediction step at each iteration, No lane change maneuver

Under the first and third frequency update strategies, the maneuvering behavior of the ego vehicle is consistent with the intuitive inference. But under the third strategy, the occurrence of traveling along the boundary line during the first two lane changes, which is most evident in the simulation result with maneuver update at every 10 iterations. Under the second strategy, only the simulation results at the update frequency settings of every 10 prediction steps and every 5 prediction steps show that the ego vehicle makes 3 lane changes. At other higher update frequencies, the ego vehicle keeps the lane. The reason why the ego vehicle stays in the lane is the same as explained in the previous scenario.

Third Specific Scenario:

In this case, the third specific scenario we observe is set up where the ego vehicle is in the first lane and the target vehicle is in the second lane. The initial lateral speed of the ego vehicle is 30 m/s, and the initial lateral speed of the target vehicle is 20 m/s. The initial lateral distance of the ego vehicle is 10 m, and the initial lateral distance of the target vehicle is 60 m. The two vehicles are in different lanes, and the velocity difference is large, but the distance is not far away. There are two difficulties in intuitively judging the maneuvering behavior of the ego vehicle. One is whether the ego vehicle performs a lane change to the second lane, and the other is whether the ego car will execute the lane change again to the third lane if the first lane change is executed.

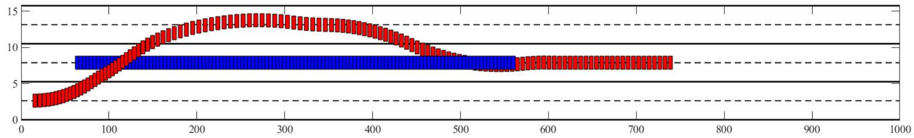

Figure 3.59: simulation result with maneuver update at every 10 iterations

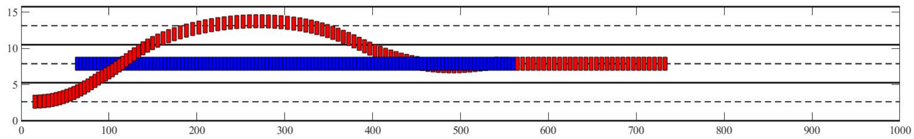

Figure 3.60: simulation result with maneuver update at every 5 iterations

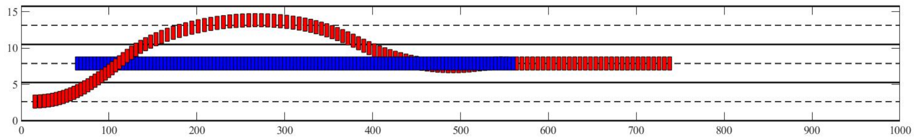

Figure 3.61: simulation result with maneuver update at every 2 iterations

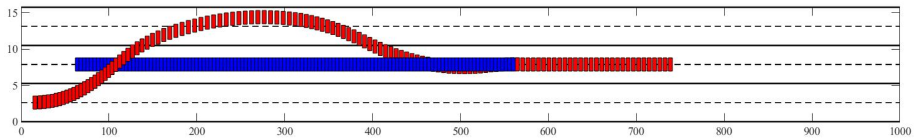

Figure 3.62: simulation result with maneuver update at each iteration

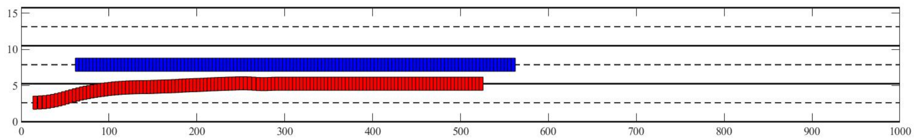

Figure 3.63: simulation result with maneuver update at every 10 prediction steps at each iteration, failed lane change maneuver

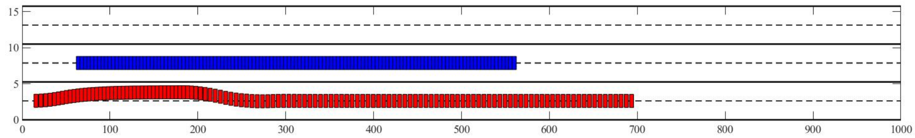

Figure 3.64: simulation result with maneuver update at every 5 prediction steps at each iteration, no lane change maneuver

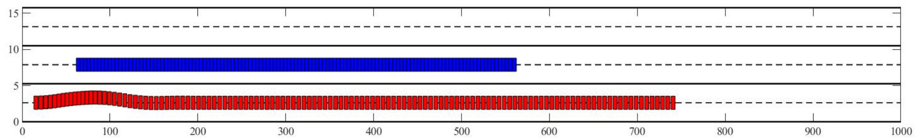

Figure 3.65: simulation result with maneuver update at every 2 prediction steps at each iteration, no lane change maneuver

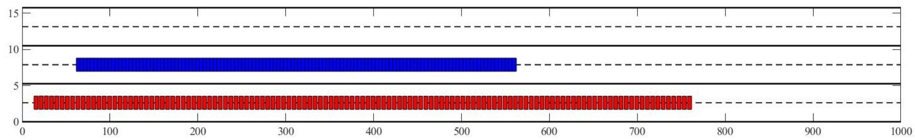

Figure 3.66: simulation result with maneuver update at each prediction step at each iteration, No lane change maneuver

In this simulation scenario, the simulation results with the first and third update frequency strategy are similar to the simulation results in the previous scenario in section 3.2.2. The distance between the first lane change point and the third lane change point decreases with increasing update frequency. Under the second strategy, the simulation results show that the ego vehicle keeps the lane. The reason why the ego vehicle stays in the lane is the same as explained in the previous scenario. The occurrence of traveling along the boundary line, which is most evident in the simulation result with maneuver update at every 10 prediction steps at each iteration.

3.3 Summary

From the appeal test simulations, it can be concluded that the first frequency strategy is the most widely applicable. When the conditions are suitable, the second frequency strategy can plan a more efficient trajectory, but the lane change operation of the ego vehicle will become conservative. The third strategy frequency is not very recommended, because it reduces the interaction with vehicles in the environment and is prone to dangerous driving.

Chapter 4

Conclusion

The maneuver planning method developed in this project essentially fits the project's objectives, and it can be used in a variety of traffic circumstances with a two-vehicle system while remaining safe. The maneuver planner, in conjunction with the MPC controller provided by M. SC. Ni Dang, can efficiently conduct lane change and lane keep movements for the ego vehicle. In the comparative experiment, the maneuver planner with three different update algorithms completed the majority of the lane change and lane keep movements. According to various testing simulations, using the frequency setting for maneuverÂ updateÂ at each MPC iteration is strongly suggested. A lower update frequency is strongly discouraged. The higher update frequency strategy can be tweaked to improve the ego vehicle's maneuverability. With higher update frequency, that is, maneuver update in the horizon of the MPC, the maneuver planner considers both the current vehicle scene and the future scene of the vehicle when selecting maneuver. The impact of the current and future scenarios of the vehicle on maneuver planning is the same. Future scenarios are created by forecasting present vehicle conditions, hence prediction errors should be considered, especially when projecting future scenarios under the assumption of constant velocity and without using Kalman filter or other state prediction and correction algorithms. The most straightforward answer to this problemÂ is to include the conceptÂ of weight, which can decrease the impact of future scenarios on maneuver planning.

The maneuver planning part is designed for specific traffic scenarios (highways) as well as two-vehicle systems. As a result, it's difficult to apply this algorithm to the urban road environment. The system can theoretically be extended to multi-vehicle scenarios on highways. Second, some parameters are derived from empirical values and many simulation tests due to a lack of data required for data analysis. The safety distance, for example, is an experience value setting. Estimation and many simulations are used in the TTC and TIV threshold settings. If there is enough relevant data, more realistic values can be set using regression and classification techniques. The algorithm is highly interpretable because multi-level screening is a two-way logical decision at each level. In theory, such a maneuver planning process is fast. This approach does not create loss function for several reasons. The first reason is that the design of the loss function requires a lot of data. The second is that the data may cause the designed loss function to be serendipitous. The third is that if the loss function is used to turn maneuver planning into a nonlinear optimization problem, it will bring multiple optimal solutions, local optimal solutions, and other problems.When scaling to multi-vehicle scenarios, I recommend building a loss function. Since the two-way judgment is complicated by the number of vehicles in the environment, a uniform variable is required as a criterion in planning.

The algorithm can combine deep learning and reinforcement learning to improve the usability of the algorithm. For example, in this algorithm, the thresholds for TTC and TIV are obtained by testing. We can collect relevant data, such as two-vehicle lane information, relative position and speed information, map high-dimensional data to a low-dimensional space, and find the information of two vehicles and the relationship function of TTC and TIV. This is also a direction that can be tried in the future.

At this point, this project is over, thank M. Sc. Ni Dang for her patient help and guidance.

List of Figures

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