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# SPIM

## Thèse de Doctorat



école doctorale sciences pour l'ingénieur et microtechniques

UNIVERSITÉ DE TECHNOLOGIE BELFORT-MONTBÉLIARD

# Contribution à l'intersection coopérative: commandes longitudinale et latérale

■ XUGUANG HAO





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## Thèse de Doctorat



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UNIVERSITÉ DE TECHNOLOGIE BELFORT-MONTBÉLIARD

N° X | X | X |

THÈSE présentée par

**XUGUANG HAO**

pour obtenir le

Grade de Docteur de

l'Université de Technologie de Belfort-Montbéliard

Spécialité : **Automatique**

## Contribution à l'intersection coopérative: commandes longitudinale et latérale

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# ABSTRACT

The intersection management has received a particular attention during more than a half of century for improving the urban traffic throughput. The perspective of autonomous vehicles able to communicate with the surrounding environment allows reconsidering the traffic management at intersections. This thesis focuses on cooperative intersection management by synchronizing the velocities of conflicting vehicles, in order to avoid unnecessary braking and acceleration. More precisely, the vehicles adapt their speed according to the vehicle ahead detected by sensors as well as to the priority vehicles coming from the other routes. The position and the velocity of the vehicles that are out of the field of vision are received by an onboard unit through a centralized dedicated short range communication network. In order to fully benefit from the cooperative intersection management, the longitudinal control and lateral control of vehicles are considered.

In this thesis, two issues of cooperative longitudinal are treated. The first one is raised by the communication problems and kinetic constraints. The adopted longitudinal control is a non-linear function in which a maximum communication time that should be respected at the worse case and a deceleration constraint are considered. If the constraints are not respected, the function triggers the stop of vehicle. The results of simulation in dangerous cases show that the control approach allows a safer and more comfortable braking. The thesis addresses also the problem of traffic efficiency. There are two approaches for the speed synchronization but because the synchronization point is determined, each of both raises either the problem of empty lanes or the problem of slow clearing of the potential zones of collision. The thesis proposes an approach that spreads out the synchronization during all the travel of vehicle. The simulation results in eight-shaped circuit show that the proposed longitudinal control significantly reduces the use of braking in contrary to the other two existing approaches.

For the lateral control of vehicle at intersection, there are two problems. The first is the limit of the field of vision due to sharp curves. The second is the delay of the processing by cameras. Thus the thesis proposes a control based on the calculation of Frenet curvature coupled with correction of deviation from tracking path. Both the curve tracking and the correction are deduced from the circular motion induced by the steering wheel angle. The advantages of this approach compared to traditional approaches (the Linear Quadratic Regulator with Feed Forward and the Stanley) are to be not greedy in terms of the necessary field of view and to have more flexible real-time constraints. The comparison with current approaches shows that the proposed approach under urban traffic conditions is able to resist against a longer sampling time in contrary to the other two traditional approaches.



# RÉSUMÉ

L'amélioration de la fluidité du trafic aux intersections a reçu une attention particulière depuis près d'un siècle. Avec la perspective de véhicules contrôlés et communicants, la régulation aux intersections connaît un nouvel essor. Dans la thèse nous nous intéressons à la régulation coopérative des intersections par la synchronisation des vitesses. Afin d'éviter des arrêts inutiles aux intersections, les véhicules régulent leur vitesse en fonction non seulement des véhicules qui les devancent sur la même voie mais aussi des véhicules prioritaires provenant des autres voies en conflit. La synchronisation des vitesses grâce à la communication sans-fil a plusieurs avantages mais pour les exploiter pleinement, il est nécessaire d'aborder les problématiques des commandes longitudinale et latérale des véhicules.

En ce qui concerne la commande longitudinale, la thèse s'intéresse à deux problématiques. Pour des raisons évidentes de sécurité, les délais de communication sans-fil avec les véhicules des autres voies, à savoir hors de la portée des capteurs, doivent être pris en compte. Pour ce faire, la commande longitudinale adoptée est une fonction non linéaire qui considère un temps maximal de communication et une borne de décélération. Si les contraintes de ne sont pas respectées, la fonction déclenche l'arrêt du véhicule. Les résultats de simulations étant concluants dans des cas extrêmes, la thèse aborde la problématique de fluidité du trafic. En effet, le comportement du trafic dépend du choix du lieu où commence la synchronisation des vitesses. La thèse discute les deux approches classiques et propose une solution de lissage. Sur un circuit sous la forme d'un huit, l'effet du lissage permet de réduire considérablement le recours au freinage contrairement aux deux autres approches actuelles.

En ce qui concerne la commande latérale, l'intersection pose deux problèmes. Le premier est la limite du champ de vision à cause des courbures serrées des mouvements tournant et la deuxième est le délai du traitement par les caméras. Ainsi, la thèse propose une commande basée sur le calcul de la courbure de Frenet couplé à la correction des écarts. Le suivi des courbures et la correction sont tous les deux déduit à partir du mouvement circulaire induit par l'angle du volant. Les avantages de cette approche par rapport aux approches classiques (Linear Quadratic Regulator with Feed Forward et Stanley) est d'une part, de ne pas être gourmande en termes de champs de vision nécessaire et d'avoir des contraintes temps-réels plus souples. La comparaison avec les techniques actuelles démontrent que notre approche, dans des conditions de circulation urbaine est capable de résister à des temps d'échantillonnage plus longs contrairement aux deux autres.





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# INTRODUCTION

The growth of transportation demand in modern cities increases pressure on the traffic network. The congestion, the most obvious result of the pressure, generally occurs at intersection. The traditional intersection management is based on traffic lights, if the traffic is heavy. With the development of technologies, many researches on signal system are carried out to dynamically program the traffic light cycle. For the control of isolated intersection, some methods could consider vehicle's motions measured by sensors so as to estimate the incoming traffic flow. The estimation helps to optimize the traffic light cycle, stages and offset. Different from the traditional traffic light system, the cooperative intersection management introduces the driver assistance system into the intersection management. The driver assistance system gathers the information of surrounding vehicles by wireless communication system and positioning system. However, both systems aren't able to respect the real-time conditions. Many authors propose a linear control coupled with a computation overhead to fulfill the real-time conditions. However, for safety reasons, it is interesting to have the appropriate control function able to face latency. One can later add computation overhead to obtain better performances.

The first precondition of implementing cooperative intersection management is to avoid collision. There are at least two reasons making autonomous vehicles collide. First, the data about the obstacle arrives lately. Second, the required actions to avoid collision are physically unfeasible. In our opinion, different from most of adaptive cruise control of vehicle, the longitudinal safety mainly depends on the ego-vehicle reaction to face unexpected brake of the vehicle ahead. Hence, for safety reasons, in addition to velocities and to acceleration capabilities of heading vehicle and ego-vehicle, ego-vehicle's reaction time should also be considered into the longitudinal control approach. Basing on this view, a longitudinal control method named as Reaction-Time based Cooperative Velocity Control (RT-CVC) will be proposed to improve vehicle's longitudinal safety at intersection environment. From the point of view of traffic safety, the centralized cooperative intersection management is the most proper architecture because it allows the default deny. It manages the intersection by sequencing the approaching vehicles and then by authorizing vehicles to cross the intersection. Combining the RT-CVC method with the sequence formation, vehicles are considered as different types of obstacles. The vehicles detected by sensors are called real obstacles whereas vehicles that are out of the field of view are called virtual. The latter are vehicles that are coming from other lanes. A method named Reaction-Time based Cooperative Adaptive Cruise Control (RT-CACC) will be proposed to implement to consider both kinds of obstacles. This approach is very interesting for improving the traffic at intersection. However, even if the cooperative intersection management based in RT-CACC is efficient, there many problems that deserve a particular



attention.

For the longitudinal control of cooperative intersection management, there are two proposed position for launching the cruise synchronization. In order to synchronize the speed, there are already some strategies, in the literature. The first strategy suggests that vehicles begin the speed synchronization immediately, i.e. at the beginning of the lane. In this case the lane is underused since vehicles stop at the upstream. The second one, the vehicles slow down to be able to stop near the potential collision zone. While slowing down, if the vehicles are able to safely traverse the intersection, they accelerate after getting the right of way. In this case, vehicles need more time to clear the intersection. Hence, the intersection space is ineffectually occupied which leads to decrease the throughput. Deciding the synchronization point raises the dilemma between enhancing the use of either the incoming lanes or the intersection space depending on the speed is synchronized upstream or downstream the lane. In this thesis, we propose to spread out the synchronization during all the travel of vehicle.

In urban intersections, curves are sharp. Hence, it is hard to have a good visibility of the path by only sensors. However, the existing lateral control approaches work under hard real-time constraints (about 15 ms) and hence need to build a long path to cover the time required to detect the path from images (about 150 ms). More precisely using on-board sensors, especially the vision-based sensors, raises the problem that the perception step of tracking path costs too much time which is normally bigger than the reaction time of existing approaches. For the lateral control, the raised problem is to control the movement of vehicle by considering the time constraints as well as the short field of view. We address this problem by proposing a non-linear control based on Frenet curvature corrected by the circular movement of the vehicle.

The rest of this thesis is organized as following.

The first part reviews the traditional tricolor traffic signal system of isolated intersection management, the cooperative intersection management architecture and the autonomous vehicle. The autonomous vehicle is one foundation of the cooperative intersection management. The proposed longitudinal control and lateral control are built basing on the cooperative intersection management reviewed in this part.

In the second part, the reaction time based longitudinal control method and corresponding control strategy are proposed to increase usage of upstream lane of intersection, to decrease the occupancy of intersection area and to increase the density of traffic flow after intersection. In the end of this part, some experiments are conducted on the circuit course.

In the third part, a lateral control method is proposed to increase the accuracy of vehicle's lateral movement at intersection environment. In the end of this part, some comparisons between the proposed method and other existing methods are conducted under different assumptions. They show the performance of the proposed lateral control approach, in different conditions.

# ISOLATED INTERSECTION CONTROL

## 2.1/ OVERVIEW

The transportation has always been a core element that influences urban live and economic development. We have witnessed the phenomenon of traffic congestion for long time. It has attracted a great attention because of the fast increasing number of vehicles and demand in all transport modes. The congestion occurs when a large number of vehicles try to pass the same infrastructure at same time. When the infrastructure capacity is fully utilized, a slowdown in traffic flow happens. When the traffic demand exceeds the capacity of infrastructure, congestion causes a significant deterioration in the quality of driving, a significant increase in environmental pollution, reduced safety and queues with excessive delays. In urban areas, congestion amplifies when multiple streams of vehicles try to access the same place. According to the definition given by the Traffic Engineering Handbook [136], an intersection is situated at the joint of some roads. The intersections are shared by several conflicting vehicle flows. They are thus at the center of urban concerns.

Some intersections are unsignalized, where conflict vehicles spontaneously pass the crossing areas according to their priorities of movement. However, such unsignalized intersections have very low capacities (measured by rate of flow that passes the intersection) [88]. They are only adequate for low traffic demands and basing on the assumption that all drivers spontaneously obey the priorities of passing the conflict zone. When the traffic flows are heavy at an intersection, the control of traffic flows is necessary. Hence, most of urban intersections are controlled by traffic signals. The traffic signals, also known as traffic lights, are signaling devices deployed at intersections and other crossing locations to regulate conflict traffic flows. At the very beginning, the traffic signals were in the form of manually operated semaphores, which can be traced back to the year 1868 in London [4]. Later, James Hoge developed the first electric traffic signal, which was installed in Cleveland, United States, in 1914 [1]. Since then, the traffic signals have been continuously developed and became important components of modern transportation systems.

The traffic signals are controller for the traffic flows. Their parameters such as effective green times, the cycle, the offsets and etc should be the control variables in transportation models. At the beginning, these parameters were usually fixed. But as number of vehicles continuously increase, the fixed-time control strategies can not face the serious transportation problem. This situation has motivated researchers to develop traffic-responsive strategies which dynamically regulate the parameters of traffic signals according to the

real-time traffic data [78].

At present, more complex transportation situations and demands require further more precise control of intersection. The short increase of traffic flow, normal one of these situations, could not be absorbed by the traffic lights. Many external factors, for example the energy crises, the environmental emergencies, leads to the demand of increasing capacity of road infrastructure. But the limits of economic resources and environment slowdown the expansion of transportation network. Some improvement has been implemented for dealing with the limitations, for example redesigning the road network to give higher priority of road to public transport, like bus and bicycle. But this influences the private cars. On the other hand, Special transport becomes an active business domain in Europe. It transports heavy or oversized load that could not be dismantled into units that can be transported without exceeding the limitations in terms of the dimensions and/or mass. Except the escort cars for safety, it also needs blocking traffic flows at passing intersection. A significant example is the transport of a giant gas turbine of 400 tons at Ville de Belfort, France. The Figure 2.1 shows the block of an intersection during the transport. As this type of transport happens more and more frequently, the transportation system



Figure 2.1: Special transport: Transporting a giant gas turbine of 400 tons at Belfort, the June 29, 2015

should change to deal with it. One way is to assign different priority of passing intersection to different type transport, for example the bus, the special transport, the ambulance

and the private cars. Thus, the current traffic situation in our cities shows a renewal requirement of transportation management approaches. This has led many researchers to consider a series of strategies deployed across multiple scales ranging development of information systems around new systems mobility based on the intelligent vehicles and infrastructures.

These research works are encouraged by the rapid development of information technology and wireless communication.

In future developments of urban mobility systems, the intersections will remain in the central concern of the future. Indeed, it should not only be noted that the intersections are the sharing places of urban infrastructure, but also that system mobility will be considered and a high-level operating of intersections basing on the technology that will be embedded in vehicles. This translation of the central role of intersection has convinced many researchers to explore opportunities for improving control in these strategic nodes.

## 2.2/ TRAFFIC LIGHTS CONTROL AT ISOLATED INTERSECTION

An intersection is a sharing place that at least two roads cross. The characters of a road includes the length, the number of lanes, the direction of traffic circulation and so on. The **movement** of vehicles at an intersection is defined by its origin and its destination. A traffic **flow** is normally a group of some movements that have no movement conflict. Certain lanes of a road could be grouped into a movement, for example the movements of turning left. Basing on the geometry of infrastructure and different crossing rules, an intersection could be assigned different schemes. However, we could identify three different functional zones in every intersection:

- **conflict zone**: it's composed of all the trajectory of vehicles of passing this joint area. In other words, this is the critical area that the collision of vehicles may occurs. Traditional traffic signal system mainly concern the control of this area.
- **storage zone**: the enter lanes of an intersection. All vehicles that come from upstream and will cross the conflict zone exit this area and enter the conflict zone. Before get the right of occupying the conflict area, they are blocked in this area.
- **exit zone**: the exit of conflict zone. It's also the upstream of an storage zone of the downstream intersection.

It's supposed that the trajectory of a vehicle of passing an intersection must be a precise order: the storage zone, the conflict zone and the exit zone. A conflict point is an area that at least two movements meet at same place. The conflict zone consists of all the conflict points of movements of an intersection.

A typical intersection with four branches and without the crossing for pedestrians or bicycles is shown in Figure 2.2a. Each branch is a two direction road. Basing on this simple intersection, more complex intersections could be rebuilt, for example, an intersection with more than four branches or with more than one incoming lanes.

Most of intersections are controlled under a signal system of tricolor traffic lights. This signal is located on the border of each storage zone and the conflict zone. Its principle

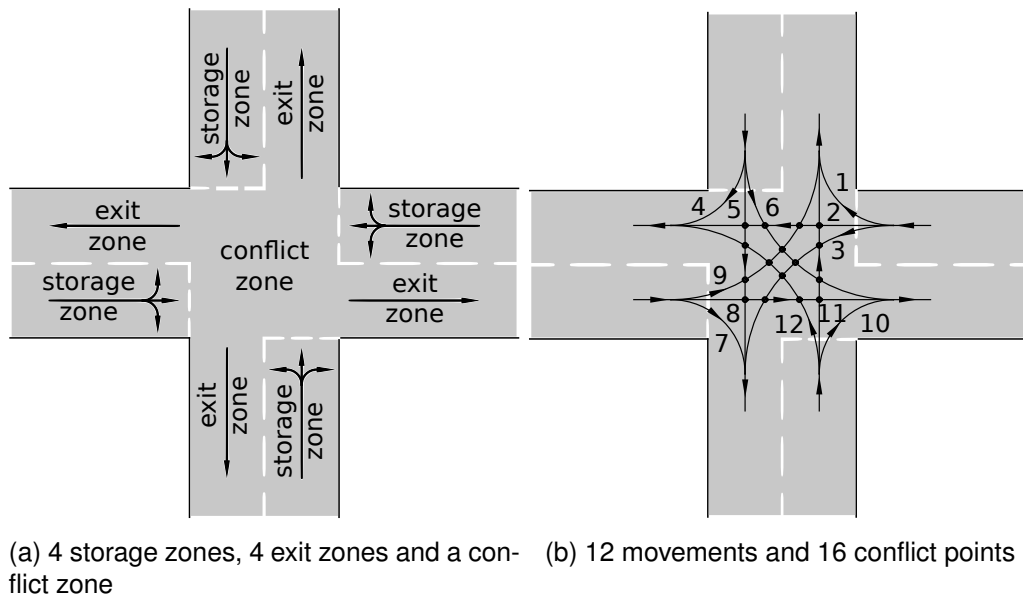


Figure 2.2: An intersection of four branches without crossing for bicycles or pedestrians

is to cut the use time of the conflict zone for different groups of traffic flows or antagonistic movements. Accordingly, it blocks some traffic flows or movements and meanwhile assigns right of road to the rest of movements that have no conflicts for the **security** of crossing the conflict zone.

The choice of the duration of each state of the traffic lights and the timing between them are involved in the managing of traffic flows. This normally have multiple orientations depending on the city policy choices and relevant involved agencies. For example, the control policy can promote the soft modes, the public transport or special corridors. However, these choices must reflect the local characteristics of travel and infrastructure of intersection. In other words, it is not desirable that the control policy implemented generates disturbances (congestions), and the policy places the criterion of efficiency of traffic flow in second level.

The traffic flow management is carried out through **the control loop of the intersection** (see Figure 2.3). This loop consists of two parts which are the intersection and the associated **traffic signal system**. The intersection is characterized by its geometry, the traffic flows through it, all the possible movements and so on. The associated traffic signal system is selected according to the city control policy, while ensuring the safety and efficiency of traffic flow.

### 2.2.1/ CONTROL LOOP

At the very beginning, the traffic signals were in the form of manually operated semaphores, which can be traced back to the year 1868 in London [4]. The current electric traffic light was invented by Mr. Lester Farnsworth Wire, a detective for the Salt Lake City police force, in 1912 in Salt Lake City, United States, [102]. At that time, the lights were bicolored, green and red, like the signals made for the control of railway traffic. Since then, the traffic lights have evolved to adapt to the growing demand of traffic and the development of flows crossing the intersection. Indeed, the bicolored signals encoun-

tered quickly the security problems and was replaced by tricolored traffic lights (see Figure 2.4) invented by James Hoge and was installed in Cleveland, United States, in 1914 [1]. Since then, traffic signals have been continuously developed and become important components of modern transportation systems. Their parameters such as effective green times, the cycle, the offsets, etc should be the control variables. Before 1938, the researchers have contributed to the rapid improvement of the traffic light system which has a similar configuration to that we have today [91]. Indeed, Tyack's article [2] reflects the implementation of a control loop which is similar to that we have now (see Figure 2.3). At initial stage, these parameters were usually set fixed. But as vehicles continuously increase, the fixed-time control strategies can not face the serious transportation problem. This situation has motivated researchers to develop traffic-responsive strategies which dynamically regular the parameters of traffic signals according to the real-time traffic data [78].

The traffic light system associated to an urban intersection is generally a complex system. It's not only a visible signs that could be seen by the drivers but also requires many assistants for assuring its function of control, for example the instruments of positioning, of measuring and an control center. For studying an isolated intersection, three elements composed the traffic signal system are needed to be identified at least. These three elements consist the control loop of an intersection. They are:

- **infrastructures of measurement:** These instruments reflect the state of traffic flow approaching the intersection through its various parameters. These quantities are measured normally by sensors installed at the infrastructure level.
- **regulator:** It's the core of the control loop. Basing on the measurements given by the infrastructure of measurement, it realize the real-time control strategies in order to achieve special objectives such as minimizing the waiting time of vehicles

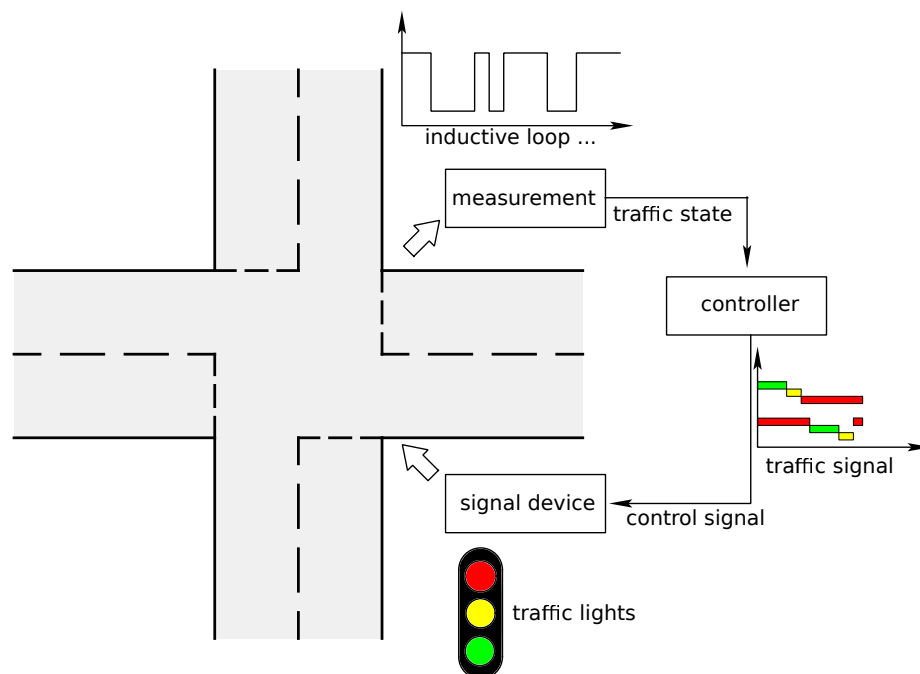


Figure 2.3: Control loop of an isolated intersection



Figure 2.4: The first electric traffic signal in Cleveland

at storage zone, the length of sequence of vehicles at storage zone and so on.

- **signal system:** This is all the signals transmitted to the drivers for providing safe passage of the vehicles through the intersection. They aim at avoiding the conflict of movements. In the context of an isolated intersection, the traffic signal system is characterized by the presence of traffic light.

From above descriptions, there are three separate systems. At the most visible part of the control loop, the signal system is constructed basing on the volumes of traffic flows and the geometry of intersection. The traffic safety is one of its major targets. It consists of all the signaling devices and could call the measuring instruments for the detection of incidents [72]. The infrastructures of measurement is the first part of the control loop and also the most basic element in the loop. Its data reflects the traffic situation. The actions of the other two elements are basing on the data gathering from this part. Normally, its components reflect the requirement of regulator. The function of control system depends on the data from measure infrastructures and aims at regulating the traffic flows with the action of signal system. Normally, each system or each elements in the control loop of an intersection (see Figure 2.3) is treated separately. Most of researches about the control of traffic flow focus on the regulator.

### 2.2.2/ SIGNAL SYSTEM

As the most visible component of control system of an intersection, it's generally the tricolor traffic lights that authorize the right of passing the conflict zone. It is located at be

beginning of conflict zone in order to make sure that it could be seen clearly by the drivers of vehicles waiting in the storage zone. Each traffic light is consist of three light colors: green, yellow and red. Their functions are:

- **green**: It authorizes the vehicles waiting in respective storage zone to pass the conflict zone.
- **yellow**: It lights immediately after the green light. It means that the authorization is canceled and the red signal comes immediately. So the drivers must stop before the conflict zone when they notice this signal for avoiding conflict at conflict zone.
- **red**: It forbids any enter of the conflict zone of the vehicles in respective storage zone.

There are some basic concept about the signal lights. The time duration of one or more traffic flows admitted simultaneously to cross the conflict zone constructs a **phase**. The phases are divided basing on the conflict of movement or the constraints. It aims at removing or minimizing the conflicts with taking into account the safety and fluidity. So the chosen of a phase mainly depends on the potential conflicts between certain movements. All phases of an intersection construct an traffic light **cycle**. The cycle is defined as the time between two successive passage of all signal lights of one phase, where the phase could not be retracted.

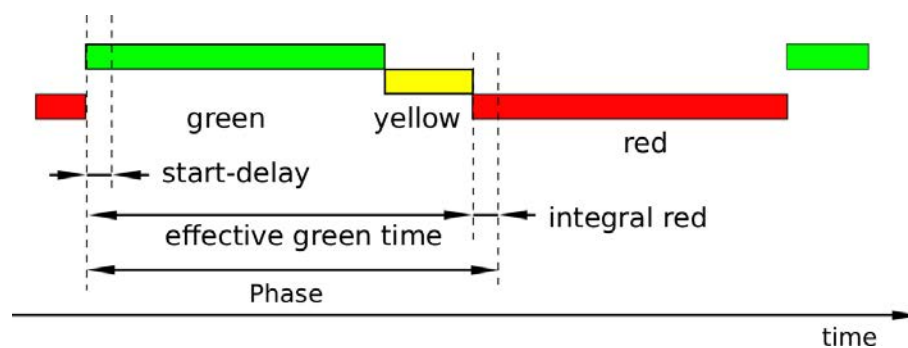


Figure 2.5: Allocation of a phase time

Every phase consists of an **effective green time** (see Figure 2.5) and an integral red time. The effective green time is the sum of **usable green time** and yellow time which follows the usable green time. It's the actual available time for the movements of vehicles. Generally, because of the reaction time of driver, there is also a delay of the movement which is called start-delay time located at the beginning of every effective green time. The **integral red time** is a short time at the end of every phase after the light changes from yellow to red. During any integral red time, all the traffic lights of an intersection are red for safety reason. It is able to clear the conflict zone before assign the right-of-way to the traffic flows of an phase. The end of integral red is the start of green time of another phase. This duration of integral red must be weighed case by case, depending on the characteristics of each intersection. The difference between the cycle time and effective green time of respective cycle is the **usable red time**. The way of generating the sequence and the duration of phases is the control strategy of an intersection. The control strategy generally depends on the traffic situation estimated through real-time



measurement. So the traffic fluidity is mainly the target of control system which decides the sequence and the duration of phases.

The traffic fluidity depends directly on the time duration of cycle, the phases themselves and how they are composed to the cycle as following:

- *Duration of cycle:* Because of the existence of integral red (see Figure 2.5), the sum of effective green time, the actually operated time in an intersection, is less than the cycle time. The integral red time is considered as lost time. Actually, there are also some other types of lost time, for example, the start-delay driver at the beginning of every phase. All the lost times are incompressible. The ability of an intersection is proportional to the cycle. So, if the cycle is long, the lost time is long and finally influence the sequence of waiting vehicles and the capacity of the intersection.
- *Number of phases:* Every phase contains the lost times, so the lost time in a cycle is proportional to the number of phases. If some movements contained in a phase has potential conflict, there is also a braking time of vehicle. The potential conflict slows down the movement of vehicle and consequently traffic fluidity in the phase. It's necessary to find the compromise between the lost times at the beginning and end of a phase and the lost time during a phase caused by potential conflict.
- *Duration of phase:* It decides the time assigned to the movements of a phase. The duration time should evacuate the vehicles accumulated during the other phases, at least decrease the number of waiting vehicles to a certain number for balancing the stress of every storage zone of the intersection. If a driver observes more than one red light during his respective phase before passing the conflict zone, it means there is a saturation at the intersection.

Now regarding the intersection as shown above in Figure 2.2, for safety the vehicles from four entry lanes can not pass the conflict zone at the same time. Assuming the dominant movements are direct movements (go straight) and the movement of turning left and turning right has a lower priority of passing the conflict zone, the movements could be divided into two phases. In detail, Figure 2.6 shows that, in phase 1 (see Figure 2.6a), the flows 1-3 are approved while the flows 2-4 are denied; in phase 2 (see Figure 2.6b), the authorization is exchanged between flow 1-3 and flows 2-4.

Suppose that the duration of phase 1 and phase 2 are same and that the phase sequence is fixed. And suppose that the traffic lights located before traffic flows 1-3 are initially the usable green and then followed by yellow light. After the phase respect to traffic flows 1-3, the phase of flows 2-4 starts. The two phases consist a traffic cycle (see Figure 2.7).

### 2.2.3/ MEASUREMENT INFRASTRUCTURE

There are many types of sensors that allows to measure directly or indirectly the variables of traffic circulation. They could be distinguished into several categories, intrusive sensors that are implanted directly into the floor of road, non-intrusive sensors that are placed at the border of road and embedded sensors. A basic utilization of sensor is to detect the presence of a vehicle at a point given on the infrastructure. Among the categories of sensors, we can identify many technologies: inductive loop sensors, piezoelectric sensor,

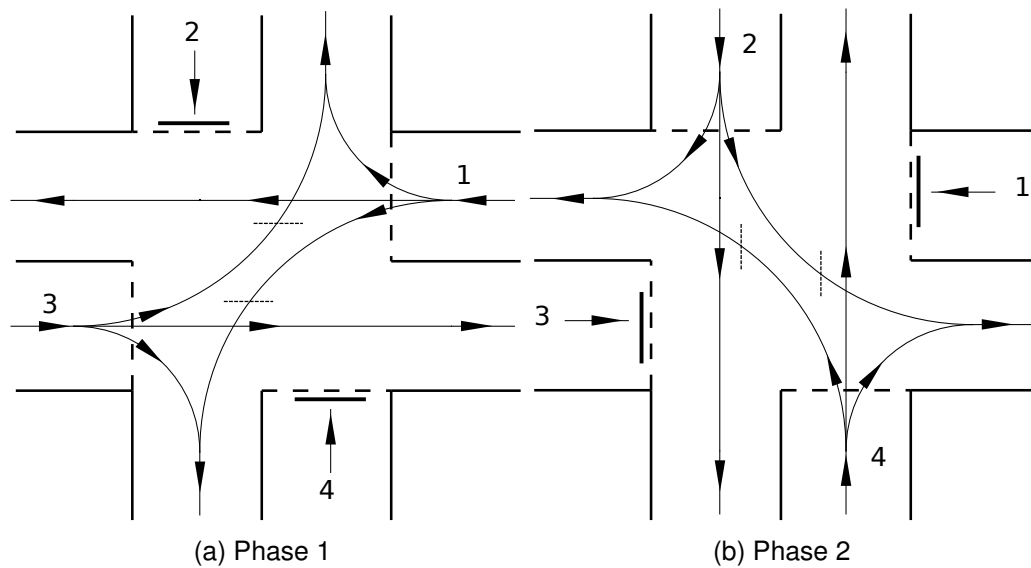


Figure 2.6: Two-phases-separation of movements of the intersection (Figure 2.2)

pneumatic tube, optic fiber, ultrasonic, laser, infrared, video camera and so on [102]. There are mainly three types of sensors used in observing and controlling traffic flows:

- Inductive loop sensor:** The inductive loop sensor is the most applied system in the world to detect mobile entities. It could measure many global variables in a space defined by a road. The sensor is placed directly under the surface of road so as to detect the passage of vehicle. The passage of vehicle will generate disturbances in the magnetic field generated by the inductor. The disturbances are converted to voltage. The signal is full or none and is directly related to the presence of a vehicle. A inductor could only indicate the presence of vehicle. Two or more neighboring inductors on the direction of road could give more detailed information about the vehicle, for example the length of vehicle or its speed. The collected data during a period could be used to analyze the vehicle flow. The application of inductive loop sensor is motivated by the development of a system of collecting and processing data. Indeed, the SIREDO program (Système Informatisé de REcueil de DONnées) provides a way to centralize traffic data throughout France in real time and deferred time, through numerous stations based on the use of inductive loop sensors [49]. It is thanks to the adjustment of flow curves/speed curves or flow/occupancy from inductive loop sensors.
- Ultrasonic sensor and Doppler radar:** This type of sensor comprises an antenna which is positioned in the direction of circulation of traffic flow. The antenna constantly emits waves that propagate at a known rate. When passing of a vehicle occurs, the transmitted wave encounters an obstacle and is reflected. From the difference between the frequencies of the wave emitted and received, the vehicle's speed can be estimated.
- Video sensor:** Video sensors are normally used on highway to observe the level of congestion and incident. At beginning, an observer is necessary to watch the video continuously. Thanks to the development of qualities of video, many analysis and monitoring methods are developed [158, 75]. And the video from cameras

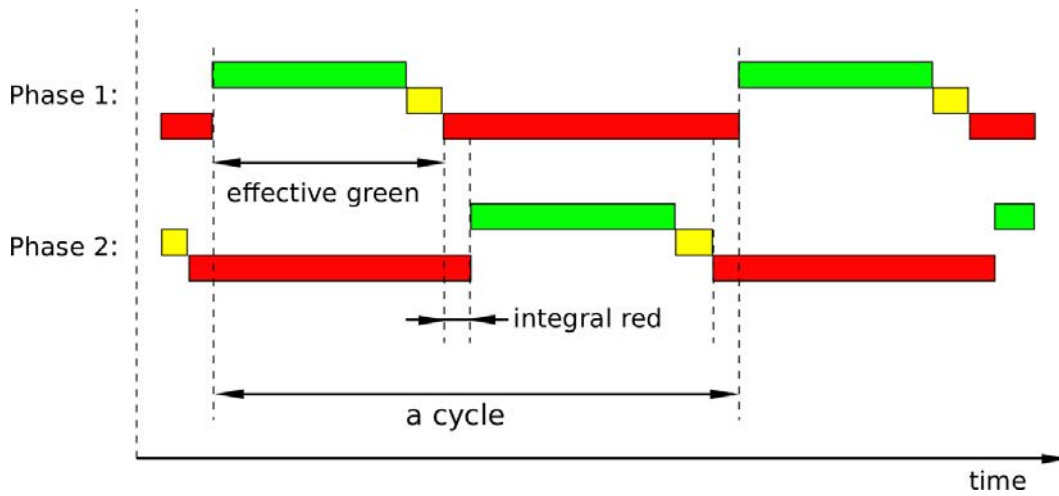


Figure 2.7: A traffic light cycle

could be processed automatically to drive the traffic parameters, for example the automatic detection of congestion and the incident detection [74, 47]. An important application deserved to be mentioned is that, except the function of observation, the video sensor could also be used to detect the space occupation of a vehicle. This is very useful. When we need to measure the occupation of an exit zone beside a storage zone, it's easy to add a function into the processing of image than to deploy a new inductive loop sensor under the ground of exit zone.

As shown in Figure 2.3, the regulator needs some data/values from the infrastructure of measurement. These values reflect the situation of circulation of vehicles at an intersection in two levels. The sensors mentioned above and some other unmentioned detectors could give the traffic variables on macroscopic scale and microscopic level. The normally values [55, 127, 76] used in control of intersection are :

- **Mean speed:** The speed of a vehicle is defined as the distance it travels per unit of time. There are two type of mean speed: time mean speed  $\bar{u}_t$  and space mean speed  $\bar{u}_s$ . Time mean speed is the arithmetic mean of the speeds of vehicles passing a point during an interval time. It's found by:

$$\bar{u}_t = \frac{1}{n} \sum_{i=1}^n u_i \quad (2.1)$$

where,  $n$  is the number of vehicles passing a point,  $u_i$  is the speed of  $i$ th vehicle. Space mean speed  $\bar{u}_s$  is the harmonic mean speed of vehicles passing a point during an interval time. It's found by

$$\bar{u}_s = \frac{nL}{\sum_{i=1}^n t_i} \quad (2.2)$$

where,  $n$  number of vehicles,  $L$  the length of section of lane,  $t_i$  the time that the  $i$ th vehicle takes to travel cross the given section

- **Density:** It is the number of vehicles present on a given length of roadway or lane. Sometimes, it is referred as concentration. Normally, density is reported in terms

of vehicles per mile or per kilometer. High densities indicate that individual vehicles are very close to each other, while low densities imply greater distances between vehicles. Density is a difficult parameter to measure directly in the field. Direct measurements of density can be obtained through aerial photography or video camera. It's defined as the average consistency  $k(x_1, x_2, t)$  at time instant  $t$  on the lane section given by coordinate  $x_1$  and  $x_2$ :

$$k(x_1, x_2, t) = \frac{n(x_1, x_2, t)}{x_2 - x_1}$$

where  $n(x_1, x_2, t)$  is the number of vehicles on the given section at instant  $t$ .

Basing on the equation above, the density  $k(x, t)$  [76] at coordinate  $x$  and time instant  $t$  is defined as:

$$k(x, t) = \lim_{\Delta x \rightarrow 0} k\left(x - \frac{\Delta x}{2}, x + \frac{\Delta x}{2}, t\right)$$

suppose that  $\Delta x$  is of the order from 50 to 100 meters.

- **Volume:** It is simply the number of vehicles that pass a given point on given lane in a specified period of observation time. The average volume  $q(t_1, t_2, x)$  at given point during the time instants  $t_1, t_2$  is found by:

$$q(t_1, t_2, x) = \frac{n(t_1, t_2, x)}{t_2 - t_1} \quad (2.3)$$

where,  $n(t_1, t_2, x)$  is the number of observed vehicles pass the coordinate  $x$  between the two time instants  $t_1$  and  $t_2$ . Like the density  $k(x, t)$  mentioned above, the volume  $q(t, x)$  at point  $x$  and time instant  $t$  could be defined as:

$$q(t, x) = \lim_{\Delta t \rightarrow 0} q\left(t - \frac{\Delta t}{2}, t + \frac{\Delta t}{2}, x\right) \quad (2.4)$$

where  $\Delta t$  is of the order from 10 to 20 seconds.

- **Length of waiting:** It's the number of vehicles waiting before the stop line during one loop of circulation. It's one of the properties of evaluation of the control strategy.
- **Time headway:** It is the difference between the time the front of a vehicle arrives at a point and the time the front of the next vehicle arrives at that same point. Time headway is usually expressed in seconds. This microscopic level variable is very useful in the control of traffic.
- **Classification:** Inductive-loop detector electronics units and loop configurations are capable of vehicle classification. The classification information could be used to provide different priority treatment at regulator.
- **Occupancy:** Occupancy is conventionally defined as the percentage of time that vehicles spend atop a loop detector. In particular, occupancy is a proxy for density. The occupancy is computed as:

$$\tau = (L + l)k \quad (2.5)$$

where  $L$  and  $l$  are respectively the average length of vehicles and the length of inductive loop.

Table 2.1 [102, 91] shows short summary of strengths and weaknesses of commercial sensors mentioned above.

The Table 2.2 shows parts of the useful functions of sensors mentioned above and relative to the control loop of intersection.

Table 2.1: Strengths and weaknesses of sensors technologies

| Sensor                | Strengths  | Weaknesses   |
|-----------------------|--|--|
| Inductive loop sensor | <ul style="list-style-type: none"> <li>• Mature, well understood technology</li> <li>• Provides basic traffic parameters (e.g. volume, presence, occupancy, speed, headway and gap)</li> <li>• Provides best accuracy for count data as compared with other commonly used techniques</li> <li>• Common standard for obtaining accurate occupancy measurements</li> <li>• High frequency excitation models provide classification data</li> </ul> | <ul style="list-style-type: none"> <li>• Installation requires pavement cut</li> <li>• Improper installation decreases pavement life</li> <li>• Installation and maintenance require lane closure</li> <li>• Wire loops subject to stresses of traffic and temperature</li> <li>• Multiple loops usually required to monitor a location</li> <li>• Detection accuracy may decrease when design requires detection of a large variety of vehicle classes</li> </ul> |
| Doppler radar         | <ul style="list-style-type: none"> <li>• Direct measurement of speed</li> <li>• Multiple lane operation available</li> </ul>   | <ul style="list-style-type: none"> <li>• Cannot detect stopped vehicles</li> </ul>   |
| Ultrasonic sensor     | <ul style="list-style-type: none"> <li>• Multiple lane operation available</li> <li>• Capable of overheight vehicle detection</li> </ul>   | <ul style="list-style-type: none"> <li>• Environmental conditions such as temperature change and extreme air turbulence can affect performance</li> <li>• Large pulse repetition periods may degrade occupancy measurement on freeways with vehicles traveling at moderate to high speeds</li> </ul>   |
| Video sensor          | <ul style="list-style-type: none"> <li>• Monitors multiple lanes and multiple detection zones/lane</li> <li>• Easy to add and modify detection zones</li> <li>• Rich array of data available</li> </ul>  | <ul style="list-style-type: none"> <li>• Installation and maintenance, including periodic lens cleaning, require lane closure when camera is mounted over roadway</li> <li>• Performance affected by inclement weather; vehicle shadows; vehicle projection into adjacent lanes; occlusion; day-to-night transition; vehicle/road contrast and so on</li> <li>• Reliable nighttime signal actuation requires street lighting</li> </ul>                            |

Table 2.2: Traffic output data (typical) of commercially available sensors

| Sensor            | Speed          | Density        | Volume | Length of waiting | Presence | Time headway | Classification | Multiple lane | Occupancy      |
|-------------------|----------------|----------------|--------|-------------------|----------|--------------|----------------|---------------|----------------|
| Inductive loop    | √ <sup>1</sup> | √ <sup>2</sup> | √      | √ <sup>3</sup>    | √        | √            | √ <sup>4</sup> |               | √              |
| Doppler radar     | √              |                | √      |                   | √        |              | √              | √             | √ <sup>5</sup> |
| Ultrasonic sensor | √              |                | √      |                   | √        |              |                |               | √              |
| Video sensor      | √              | √              | √      | √                 | √        | √            | √              | √             | √              |

1. <sup>1</sup>: The estimation of speed requires a special installation such as an inductive loop or Piezoelectricity cable.
2. <sup>2</sup>: The calculation of density requires proper installation of several inductive loops between the enter and exit of given section of lane. It's also could be estimated in an approximate way as shown in relation 2.5.
3. <sup>3</sup>: It requires several inductive loops.
4. <sup>4</sup>: Needs special electronic unit containing embedded firmware that classifies vehicles.
5. <sup>5</sup>: It works only when all vehicles are not stop

### 2.2.4/ CONTROLLER

As outlined in Figure 2.3, the controller plays a core role in the control loop. It could be a special automatic device or involve human intervention [78]. Basing on a group of computing methods and/or well defined regulations of intersection, the controller deals with the measurement of traffic flow from measure infrastructures, for example the traffic flows of each lane, and represents its reaction through the signal system which are normally the duration of phase and the sequence of phases of a control cycle. The controls of an intersection could be classified into four families as following.

#### 2.2.4.1/ SEMI-ADAPTIVE CONTROL

The measurement of traffic flow in real time or in past time could help to compute different plan of traffic light which includes the duration of cycle and every phase of the cycle. Considering the fluctuation of traffic flow, there are some different approaches [5, 6, 73]:

- **Timely-programming control:** With the observation of daily traffic flows of an intersection at different point of time, there could be some certain estimations respect to different time, for example different cycles respect to different point of time of one day (the morning, the noon and the night) or the point of time if it's rush-hours and so on [78, 13]. Basing on these estimations, this control method applies different control strategy to different traffic flow.
- **Micro-control:** The micro-control is used for unique and random variation and for low and medium volumes of traffic [9, 15, 17, 23, 27, 30]. With the real-time observation of the inputs of an intersection, the controller makes changes on the phases of the traffic lights plan, for example the insertion of phases of bus or phases of lanes with low traffic volumes. The micro-regulation is also applicable to a small group of intersections. There are two technologies implemented largely in the micro-control methods:
  - **Vehicle actuated:** This technology appears before 1938 [2]. It could be used in two cases, either particularly some special lanes of an intersection or completely all the lanes of an intersection [9]. The first case is about the application on the lanes with low volumes. At the upstream point of every lane, there is an inductive loop for detecting the arrive of vehicles. If there is no vehicle arrives on the lane, controller ignores it and give more concern on the lanes with heavy volume. Until a vehicle's arrive is detected on the low-volume lane, the controller gives a minimum green time for the passage of the vehicle. If other vehicles arrive during the green time, the time duration is automatically expended until a prespecified maximum green time. Normally, the differences between different vehicle actuated control are the choice of the minimum time, the maximum time and the unit extension time respected to the arrive of a vehicle. The maximum time is generally decided by the maximum volume of lane at rush-hour.
  - **Correction of cycle time:** This method changes the length of cycle time basing on the observation of increase or decrease of traffic volumes of intersection, lower traffic flow leads to a shorter duration of cycle and longer cycle time respects to rush-hour. In order to adjust the duration of cycle to the increase



of demand, the cycle time is raised until the occupancy of inductive loop is beyond the critical rate. However, because the observation of lower volume reduces the cycle time, it's important to notice that if this low volume is not observed during a long period, for example an hour [10], or if the volume does not raise during the rush-hour, the controller needs to re-validate cycle level.

- **Macro-control:** Different from the micro-control, this method is suitable to all type of variations of traffic system. It's used for a group of intersections in longer time period and for coordinating or synchronizing the intersections. As far as we know, TRANSYT [7, 8] is the first method. It determines a fixed cycle duration for an intersection network basing on known traffic volume at different time of a day. The improvement of TRANSYT for real-time operation leads to the SCAT [11] and the SCOOT [12]. SCAT is able to react on the durations of phase and also the total time of cycle. Derived from TRANSYT, SCOOT uses a fixed cycle duration whose phases could accept little variation depending on the application. Later, the CLAIRE [21] was developed to take into account the micro-control technology to detect congestions, to provide analyze of traffic situation and to recommend the reactions.

#### 2.2.4.2/ DISCRETE ADAPTIVE CONTROL

Instead of considering the traffic system through chain of cycles, the discrete adaptive control methods use a time discretization of a time horizon. This generally constant time horizon consists of steps that correspond to a few seconds of time intervals. At each step, the controller is able to decide whether prolong current phase or move to the next phase. The optimization process is carried out progressively from the sequence of steps. However, decisions are not applied at all steps that are grouped in the form of stages. The regulator therefore implements its choices step by step to consider the vehicles present in the intersection at same time and the estimation of future traffic.

Each controller is characterized by optimization method, which is based on a particular criterion (usually the delay). This criterion could be assessed in different ways. There are also several possible approaches to measure the current traffic and to estimate future traffic. Because most of optimization methods are expensive in terms of calculation time, some approaches attempt to approximate the optimal solution quickly. Some famous discrete adaptive control are as following:

- OPAC (Optimization Policies for Adaptive Control) [14]
- PRODYN [16]
- CRONOS (ContROl of Networks by Optimization of Switchovers) [24]
- RHODES [26, 38, 59, 58]
- UTOPIA (Urban Traffic OPTimization by Integrated Automation) [18]
- ALLONS-D (Adaptive Limited Look ahead Optimization of Network Signals - Decentralized)

Except ALLONS-D, the horizon of above controls is usually fixed and is the average cycle time between 60 and 150 seconds. The horizon of ALLONS-D is extended until it finds a solution in which all previewed arrivals are processed.

### 2.2.4.3/ STORE-AND-FORWARD CONTROL

Store-and-forward control considers same cycle duration for all the intersections. This simplification enables it to control the intersection network at the level of a city [66]. This method is derived from classical cycle concept but also takes into account adaptive control theory. Each cycle is considered as a step. Current control step is decided basing on the result of previous step temporally discretely. By evaluating the occupancy of storage zone, the objective calculate sufficient green time to make sure the phase is saturated. Normally, it's expressed through an objective function of quadratic form to define the duration of green time of every phase and needs a synchronization algorithm [45, 65, 204]. In addition, the simplification means:

- The temporal discretization can not be less than the duration of a cycle which limits the observation of local phenomena.
- The duration of the calculated green time generally corresponds to the duration of a phase which not possible to consider the oscillations of the waiting.
- As for cyclical approaches, the result of the optimization only gives the duration of phase without specifying the appropriate moment of application.

### 2.2.5/ CONCLUSION

The different technologies mentioned above has contributed much to the traffic fluidity. They works well in most of traffic situations. With the increasing demands of traffic, we noticed that more flexibility and precision are necessary in the control loop, see Figure 2.3, not only the measurement infrastructure but also the signal system [175].

- Division of phases and sequence of phases:
  - Because of the architectural differences of intersections, it's necessary to study carefully each traffic situation to define precisely the phases and the sequence of phases. The more there are enter lanes and possible movements, the more there are points of conflict, see Figure 2.2b. And the increasing number of type of vehicles, for example the bus, the tramway, the ambulance and so on, raise significantly the complexity of dividing phases. And with the increasing of special transport, the traffic lights could do nothing to response this temporal demand.
  - From point of view of security, the traffic lights could not to control all the conflict points. And for efficiency, there normally are some conflict movements in one phase, for example the turning-left movement in two-phases control of an intersection with four enter lanes, see Figure 2.6.
- Measurement of traffic volumes:
 

Table 2.1 and Table 2.2 introduces the characteristics and functions of common measure devices used in traffic detection. They could supply many useful information of traffic situation. But development of traffic system requires more detailed information.

- The measurement could not precisely represents traffic flows. On one hand, traffic fluid or light congestion may be detected similarly as same traffic volume. On the other hand, the volume given by measurement could only show the information of previous measure duration which has just ended.
  - Inductive loop and video camera could classify type of vehicles, see Table 2.1. But they are normally basing on estimation and known informations stored in the detectors. And many external conditions may influence the detecting result, for example the weather.
  - The capacity of lane depends particularly the time duration for measure the volumes. But it's difficult to infer the precise capacity and the rush-hour demands. The time discretization also affects the real calculation of capacity.
- Traffic signal system:

The authorization, normally green light, of passing conflict zone is given to the whole respective lanes of current phase. In other words, all vehicles waiting on the lane get the right of way during the green light. When the transitional yellow light appears, different reactions of driver whose vehicle is the first one of the sequence of vehicles leads to different result. Figure 2.8 shows a sequence of vehicles. The color of floor shows the color of light when the respective vehicle becomes the first one of the sequence. For the third vehicle, some drivers will stop before the stop line while others may accelerate to try to pass the conflict zone before the red light. The unknown action of the third vehicle may cause vehicle's block in the conflict zone, see Figure 2.2a.

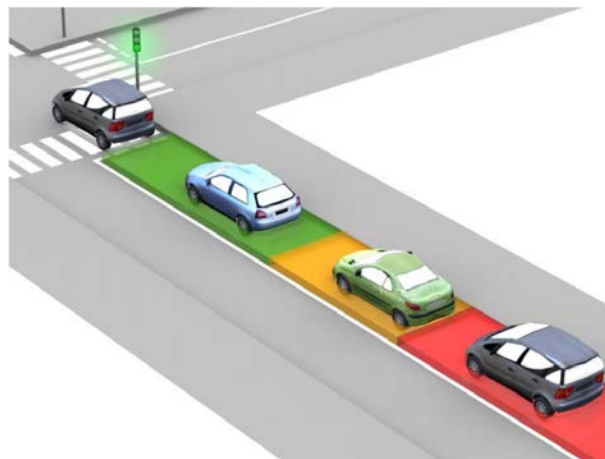


Figure 2.8: Example of passage of a sequence of vehicles during a phase

The occupancy of conflict zone may consequently leads to the block of other movements, see Figure 2.9a, or more seriously the grid-block of a network of intersections, see Figure 2.9b. One of major reasons of grid-block is the missing detection of occupancy of the exit zone. There are already many researches carried out on this issue. In [206], the author has proposed a strategy of anti-interblock control, which is named as SVACRI (le Système du Véhicule Actionneur Coopératif pour les Réseaux d'Intersections), to dealing with the grid-block. The strategy was built basing on autonomous vehicle and cooperative intersection management system.

Different from the traditional tricolor traffic light signal system, the autonomous vehicle and the cooperative intersection management system provide a new point of view of

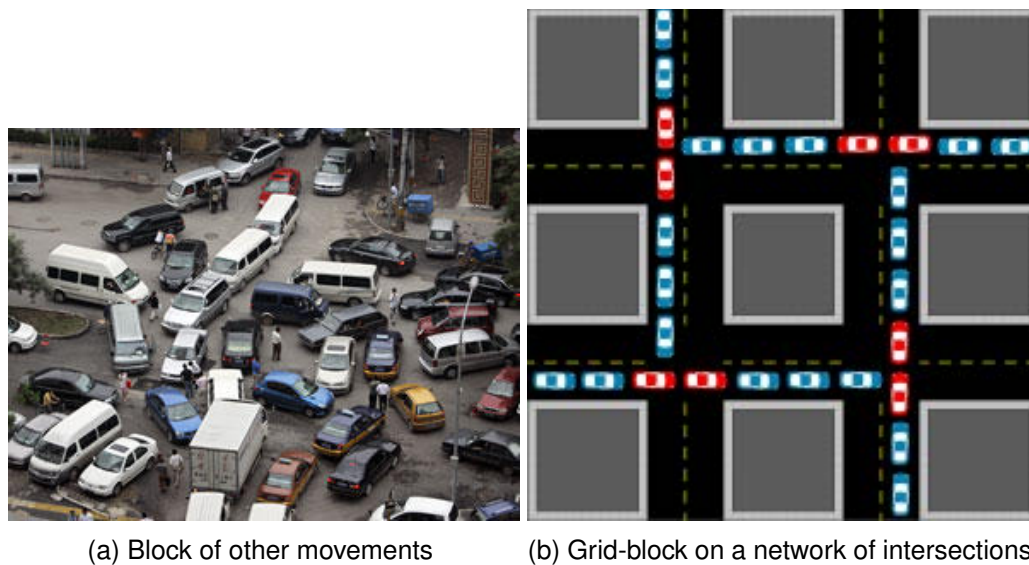


Figure 2.9: Examples of traffic block

dealing with the problems of transportation system. The contributions of this dissertation are founded basing on these new technologies. At the beginning, the autonomous vehicle appeared to improve the driving experience and safety. Later with the development of the positioning system and the wireless communication, it was introduced into the management of transportation system, especially the cooperative intersection management.

### 2.3/ ADVANCED INDIVIDUAL VEHICLE CONTROL

Since early twentieth century, with the continued developing of information and communication technologies, the domination **Intelligent Transportation Systems** (ITS) attracts more and more studies on improving traffic systems with new technologies. The ITS are advanced application which aim to provide innovative services to enable various users to be better informed and make safer, more coordinated, and 'smarter' use of transport networks. The EU Directive has defined ITS as systems in which information and communication technologies are applied in the field of road transport, including infrastructure, vehicles and users, and in traffic management and mobility management, as well as for interfaces with other modes of transport [149].

Indeed, in recent years, partially or completely controlling of the vehicle becomes a reality, and provides new traffic control perspectives. Basing on these developments, recently, some interesting works have proposed new approaches of cooperative control. These methods seem very promising, however many constraints arise and require further investigation, including through full-scale tests.

From above definition of ITS, different from traditional traffic control, the advanced individual vehicle control is the foundation of the control of isolated intersection. At present, the Advance Driver Assistance Systems (ADAS) are the main direction of advanced individual vehicle controls. They are systems developed to reduce or even eliminate driver's error for traffic safety, further more to enhance the efficiency of traffic and transport [54, 94].

The support for car drivers is a growing field of interest for both engineers and researchers

– with the latter reaction to understand the interactions occurring between drivers and the assistance devices introduced to help them. Based on function and position, the driver assistances are divided into different categories.

In [123], the authors have divided levels of automation within the car-driving domain into two categories: *vehicle automation* and *driving automation*. The vehicle automation level mainly covers the devices that carry out the low level control of vehicle and a small part of human–machine interactions. The most part of human–machine interactions and cooperation between driver and machine are classified into the driving automation level.

In [57], based on a functional approach, the authors consider the cooperation as the management of interference between individual activities to facilitate the team members' sub-tasks and the team's common task when there is one. In the car-driving domain, with a three-level of functional cooperations (*action level*, *plan level* and *meta level*), the article [135] classified the driver-vehicle cooperation mode into three levels: *perception mode*, *mutual control mode* and *function delegation mode*.

In the mutual control mode, the vehicle is defined that it could interpret the information in terms of limits to be respected in relation to risk assessment and so as to be able to provide drivers with feedback on their actions. This mode is categorized into three sub modes basing on different level effects on driver's action: warning mode such as Lane departure warning systems (LDWS), action suggestion mode and limit mode such as Lane keeping assistance systems (LKAS).

In the perception mode level, the assistance device acts as an extension of the sensorial organs. It could also be considered as two level-mode: symbolic mode and sub-symbolic mode. As opposed to processing of symbolic mode level where there is an interpretation of perceptual information, the sub-symbolic processing only deals with the perceptions. The article [60] shows that the travel speed is controlled in order to maintain lateral acceleration at an acceptable costing level. The sub-symbolic mode could be parallel and much less costly in terms of attentional resources and response time. The *response time* is a considerable factor in the driving assistance systems.

The function delegation mode corresponds to a lasting function delegation from the driver to the vehicle. In the mediatized mode, a control is considered as an order and is implemented using a procedure that covers a certain period of time. The control mode substitutes the driver or managers to achieve numbers of loaded tasks. The control mode could mainly be separated into two parts. The automatic steering controller carries out the lateral control of vehicle mainly basing on the road information around vehicle. Meanwhile the cruise control controller carries out the longitudinal control of vehicle with movements of neighbor vehicles that running on same path.

In another point of view, individual driving vehicle control requires the vehicle's self-acting and self-regulating capability, therefore it is able to operate in and react to its environment without outside control. Normally, the driver assistance system of self-controlled vehicle could be separated into different functions: (1) perceiving and modeling the outside environment, (2) localizing the vehicle within the environment, (3) deciding and designing its desired motion and (4) executing the vehicle's desired motion [86].

In accordance with functionality and level, the control process could be separated into three stages (see Figure 2.10): (1) evaluating outside and inside situations of ego-vehicle with various sensors, (2) making appropriate driving decision at high-level, (3) vehicle's motion controller react to the decision with longitudinal action and lateral action.

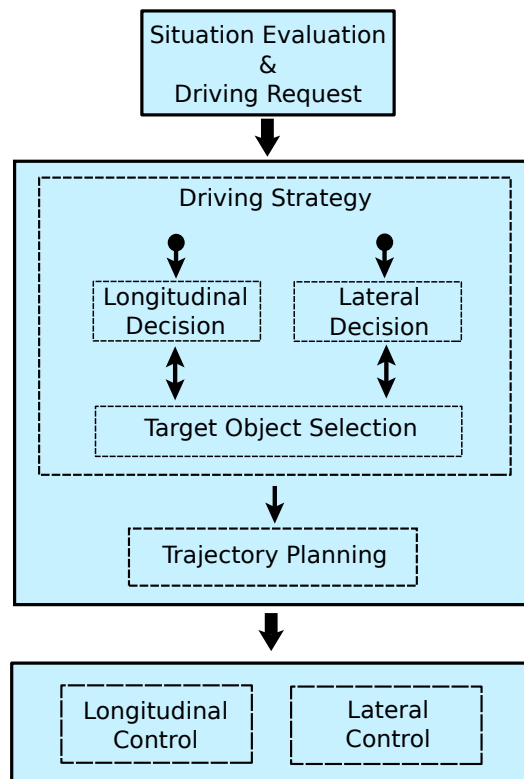


Figure 2.10: System structure for advance driver assistance system

The first stage in Figure 2.10 is the foundation of the whole control process. It includes two types of environment information: the positioning of vehicle [117] for accurate location of ego-vehicle, the wireless communication systems [94] for the communicating between vehicles and between vehicle and infrastructures. Actually, it's unimagined in the domain of ITSs without positioning the vehicles and sharing the information between vehicles and/or infrastructures. So, in this section, we firstly recall the development of position system of vehicle and the wireless communication system.

### 2.3.1/ POSITIONING SYSTEM

Like the infrastructure of measurement in control loop, see Figure 2.3, the positioning systems are also one of information resources of the control loop of vehicle. They provide the estimation of the position of object in real-time [46]. The positioning systems that have emerged and are being implemented for civilian applications could be possibly separated into two categories: the *absolute positioning systems* and the *relative positioning system*.

#### 2.3.1.1/ ABSOLUTE POSITIONING SYSTEMS

The absolute positioning systems allow to locate an object in relation to a global coordinate system of environment. The systems positioning through satellites are known as **Global Navigation Satellite System** (GNSS) and mainly consists of many satellites [128]. The most widely used absolute positioning system are **Global Positioning System** (GPS) [105] initiated by the United States in the 1970s. Today, there are also other

positioning systems named **GLObal NAVigation Satellite System** (GLONASS, [36]), **GALILEO** ([48]), **BeiDou Navigation Satellite System** (BDS, also known as COMPASS [173]), **Indian Regional Navigation Satellite System** (IRNSS, [212]) and **Quasi-Zenith Satellite System** (QZSS, [79]) are developed by or are under developing respectively by the Russia, Europe, China, India and Japan. All the satellites of GNSS forms a blanket around the earth which allow to obtain the position of an object on the surface of earth on in the heaven. A major advantage of these systems is its availability to the general public. Indeed, military, aviation and maritime transport have priority over the use of such systems, benefiting from access to improved accuracy.

Beside the convenient of accessing the GNSS, the major disadvantage of GNSS is its lower precision of positioning for generic public. Normally, an user must capture at least 3 satellites to calculate its position. The calculating error may be from a few meters to some dozens of meters, especially in urban areas, because of the reflection effects of waves on grand buildings. The signal from satellites may also be degraded during the its transportation. The lengths of the major parts of vehicles are private and are generally less than 6 meters. So it's unacceptable that the positioning error is beyond one meter for the mobile entities because of the risk of collision, especially when the vehicle is passing an intersection.

In order to improve the position information gathered from satellites positioning system, some other systems are imported to achieve the error of centimeter-level accuracy.

- **Real Time Kinematic (RTK):**

The RTK is a technique used to enhance the precision of position data derived from satellite-based positioning systems. It allows a reference station to send corrections based on the use of phase measurements of the carrier waves of satellite signals [63, 199, 68, 126].

- **Differential Global Positioning System (DGPS):**

The DGPS is another enhancement to global positioning system that provides improved location accuracy, from the 15-meter nominal GPS accuracy to about 10 cm in case of the best implementations. It is based on the principle of the installation of a network of fixed stations, which serve as references for detecting the differences between the measured position of a satellite and its known actual position [29]. The known errors could be communicated to correct the calculation. Two examples of using DGPS are **European Geostationary Navigation Overlay Service (EGNOS)** [56] and **Wide Area Augmentation System (WAAS)** [160].

The widely utilization of digital map is generally considered as another way to correct the errors of satellite positioning [67].

### 2.3.1.2/ RELATIVE POSITIONING SYSTEMS

The absolute positioning systems and their assistant systems could provide a quite precise position of an object in global coordinate system. Normally, it's sufficient for locating a vehicle in transportation system. But because of some disadvantages of GNSS, absolute positioning systems are not enough for the transportation systems. For example, the lost of signals from satellite may causes security issue, the positioning errors affect accuracy of inter-distance between two vehicles and consequently bring risk of collision.

So relative positioning systems are also imported into traffic control systems, especially in the control at intersections. They could be installed on vehicles or at the floor.

Among the relative positioning systems, we would like to recall the **Odometry**, the **Radar** and **Light Detection And Ranging** (LIDAR), the **video capture**, the **Radio-Frequency Identification** (RFID) systems, the Gyroscope and the Accelerometer. The odometry uses the data from motion sensors or video camera to estimate the change in position over time [95, 211]. This method is sensitive to errors due to the integration of velocity measurements over time to give position estimates. The Radar or LIDAR systems are enable to detect objects or even analyze their form through scanning [96]. The video capture motivates a growing interest in recent years because of the increasing quality and speed of capturing image and corresponding real-time analyzing methods. It could be placed on a fixed position to detect and to track moving vehicles [138, 139], or be installed directly on vehicle for detect and identify dynamical objects or static objects [89, 110]. The RFID system is comprised of readers and tags that can be used in transport and is originally developed for the identification of tagged objects [162]. It is possible to place labels (position markers) on the infrastructure (for example, the intersection), the vehicle equipped with the reader could know its relative position by detecting the tags [192]. Contrarily, the exchange of reader and tags between infrastructure and vehicle allows the infrastructure to obtain informations of vehicles [120]. A gyroscope could measure the rotation of vehicle, while an accelerometer can detect movement in all directions.

All the detectors mentioned above could be assembled together on a vehicle for refining the position of vehicle [118].

### 2.3.2/ WIRELESS COMMUNICATION

Recently, the development and deployment of many wireless communication technologies occurs in many domains. The **General Packet Radio Service** (GPRS), **Global System for Mobile Communications** (GSM), **Wi-Fi**, **Worldwide Interoperability for Microwave Access** (WiMax) **3G**, **4G**, **Zigbee**, **Bluetooth**, **G5** (IEEE 802.11p), **RFID** etc. protocols are tested and/or applied in the field of traffic control systems. All these communication methods are already exist in the field of transportation to deliver a quantity of information, especially for control the compliance of schedules in bus networks, trams, airplanes, trains, etc.

Basing on these technologies, a special effort was made on the development of communications in short and medium range exclusively dedicated to ITS. These communications can be one-way or two-way, are gathered in the name **Dedicated Short-Range Communications** (DSRC) [40, 80, 93, 145]. The term "Short Range" in DSRC is meant to convey that the communication takes place over hundreds of meters, a shorter distance than cellular and WiMax services typically support.

In the beginning, the DSRC was mainly used to make sure the security of road and its users through transporting the information of road conditions and situations of other type of users [98]. Later, it was applied into traffic management for reducing congestions and avoiding accident. There are also other applications of DSRC concerning vehicle, for example, accessing internet on vehicle, gathering information of parking space, automatic road tolling, road-use pricing [44] and so on.

In order to enable different users to apply the DSRC into the improving of traffic ser-



vice, it's necessary to establish a DSRC communication standard [129]. Although the applications of DSRC in Europe, United States of America and Japan are all basing on the IEEE 802.11 standard, because of the differences on technology, politics and economic, the actual implementation strategies are different. In Europe, the standardization organisation Comité Européen de Normalisation (CEN), sometimes in co-operation with the International Organization for Standardization (ISO), have defined the standards by choosing the 5.9GHz frequency band, with a bandwidth of 20MHz. In Japan, the 5.8GHz frequency band has been chosen by the **Association of Radio Industries and Businesses** (ARIB) with a bandwidth of 80MHz. In the USA, the Federal Communications Commission (FCC) has allocated 75 MHz of licensed spectrum in the 5.9 GHz band for DSRC communication [167].

With the DSRC technologies, the **Vehicular Ad hoc NETWORKS** (VANETs [112, 161, 157]), a subclass of **Mobile Ad hoc NETWORKINGS** (MANETs, [39, 64]), attract more and more researchers. Because of its tremendous potential to improve vehicle and road safety, traffic efficiency, and convenience as well as comfort to both drivers and passengers, it has become an active area of research, standardization and development. In the VANETs there are two type of entities: the mobile entities (the vehicles) and fixed entities (communication equipments located along road and at intersections). The VANETs are used to manage the transmission of information between the entities which is considered as a router that could communicate with other ones. The communications could be categorized into two types: **communication between Vehicle and Vehicle** (V2V) and **communication between Vehicle and Infrastructure** (V2I).

As the DSRC is about communication in short range, the protocols of MANETs could not be used directly in the VANETs and the vehicle's movement cause a number of constraints in the development of VANETs. The constraints are rare in classical wireless communication network and depend on the type of applications. On the level of communication between entities, the degradation of signals must be taken into account, because of not only the vehicle's speed but also the buildings in urban environment [22]. On macro level, the communication through the whole network, rapid changes of connection between them may occurs because of the vehicle's movement. Further, the a small group of vehicles with high speed might could not establish a solid connection between them, for example in case of highway. In addition, the existence of redundancy of information also needs to be taken into account to create a solid strategy for distribution of messages. At last, the security of communication must be considered seriously [119]. If the message could be accessed by unauthorized entity, the risk of leak of private information may occurs. In addition to risk, the juggled information may lead to receiver's wrong reaction or even more critical accident of recipient vehicle.

Based on the perceptions, the second stage as a high-level control layer shown in Figure 2.10 could make proper control strategies, for example accelerating, changing lane. Considering these orders as input, the third stage carries out the longitudinal and lateral control of vehicle with environment information.

### 2.3.3/ LONGITUDINAL VEHICLE CONTROL

At the beginning, driver assistance systems are normally about the longitudinal movement of vehicles. They are founded on the technologies mentioned above: the wireless communication (V2V and V2I) and the vehicle positioning. At the beginning, they were

just designed to help to control the cruise speed. Then, with the development of technology and deep research of driver assistance system, researchers become focus on the safety of driving and improvement of controlling traffic system. The future target is to equip step by step the ADAS on all vehicles in order to not only increase the global safety of driving but also decrease the congestions especially in urban environment.

#### 2.3.3.1/ CRUISE CONTROL

The speed control in automobiles appeared as early as 1900. Later, in 1948 the engineer Ralph R. Teetor [3] invented the **Cruise Control** (CC) system for keeping the vehicle runs at a specified constant speed basing on a controller of acceleration and implemented it on vehicle in 1958. The most suitable application environment of the CC system is on freeway. When running in a complex traffic environment, the vehicle with CC system will be in risk of collision with previous vehicle.

#### 2.3.3.2/ ADAPTIVE CRUISE CONTROL

For avoiding the collision with previous vehicle, the **Adaptive Cruise Control** (ACC) system was invented [31, 101]. The ACC system maintains a non-constant speed of vehicle, basing on the measurement of detector installed in front of ego-vehicle. Many ACC models were invented and more are in developing.

#### 2.3.3.3/ COOPERATIVE ADAPTIVE CRUISE CONTROL

Actually, the simple information of previous vehicle given by detectors are not enough for the safety controlling of ego-vehicle. More information of previous vehicle's movement are needed. Applying wireless communication on vehicles leads to the latest improvement of the ACC system which is called **Cooperative Adaptive Cruise Control** (CACC) [111, 153, 200]. Combining the movement information from front detector and message from previous vehicle, the CACC system could determines a more safe control than the ACC system. An important application of CACC system is the platooning of vehicles. The ego-vehicle could receive the movement informations of previous vehicles running in the downstream of the platoon. Taking into account these informations, the CACC system could make a more safe and efficient control strategy for ego-vehicle [184, 195].

#### 2.3.4/ LATERAL VEHICLE CONTROL

Lane departures are number one cause of fatal accidents. So in addition to longitudinal control of vehicle, lateral vehicle control also attracts more attentions. Three types of lateral control systems have been developed in the automotive industry that address lane departure accidents: lane departure warning systems (LDWS), lane keeping systems (LKS) and yaw stability control systems.

A LDWS is a system that monitors the vehicle's position with respect to the lane and provides warning if the vehicle is about to leave the lane. A LKS, which is also named as path tracking systems, automatically controls the steering to keep the vehicle in its lane

and also follow the lane as it curves around. Yaw stability control systems that prevent vehicles from spinning and drifting out have been developed and recently commercialized by several automotive manufacturers [42, 33]. Such stability control systems are also often referred to as yaw control systems or electronic stability control systems.

The lateral position measurement is one of foundations of lateral control. The magnetic field from the embedded permanent magnets was used for lateral position measurement of the vehicle [32]. Vision cameras are also be used for lateral position measurement [41]. Recently, vision cameras are used in recognizing and following a road [84] or in detecting an previous vehicle to apply the same path [166]. In addition, the stereovision with a dual cameras is particularly able to detect the depth of field of view [146]. In the case of an open space without reference, the use of GPS coupled with gyroscope is a practical method for positioning. If there is no vehicle could be tracked and the road has no visible markings, the fusion of GPS, gyroscope, speedometer and visual data could be a practical method to provide real time and accurate localization information [121].

### 2.3.5/ AUTONOMOUS VEHICLE

The mentioned technologies show the potential completely control of vehicle or called autonomous driving [201]. In recent years, the Defense Advanced Research Projects Agency (DARPA) has organized two notable competition named "DARPA Challenge ". It helped to motivate the autonomous researches in autonomous driving field. In 2005, the race showed the feasibility of using mobile robots operating autonomously in real world scenarios where the vehicles were designed to move on a desert environment [113]. In 2007, the challenge demonstrated how cutting-edge perception, control, and motion planning techniques can allow intelligent autonomous vehicles not only to travel significant distances in off-road terrain, but also to operate in urban scenarios [132]. Many groups have already offered prototypes of autonomous vehicles, for example the "Google car" [152].

In order to standardize the control of circulation of vehicles, in the United States, the National Highway Traffic Safety Administration (NHTSA) has defined vehicle automation as having five levels [191]:

- **Level 0 - No-Automation:** The driver is in complete and sole control of the primary vehicle controls at all times.
- **Level 1 - Function-specific Automation:** Automation at this level involves one or more specific control functions, for examples the electronic stability control or pre-charged brakes. The vehicle could automatically assist with braking to enable the driver to regain control of the vehicle or stop faster than possible by acting alone.
- **Level 2 - Combined Function Automation:** This level involves automation of at least two primary control functions designed to work in unison to relieve the driver of control of those functions. An example of combined functions enabling a Level 2 system is adaptive cruise control in combination with lane centering.
- **Level 3 - Limited Self-Driving Automation:** Vehicles at this level of automation enable the driver to cede full control of all safety-critical functions under certain traffic or environmental conditions. The vehicle monitors the changes and could

transit back to driver control if necessary for occasional situations. The Google car is an example of limited self-driving automation.

- **Level 4 - Full Self-Driving Automation:** The vehicle is designed to perform all safety-critical driving functions and monitor roadway conditions for an entire trip. The driver only need to provide destination or navigation input. And during the trip, the driver is not expected to control at any time.

Several projects are interested in marketing of fully autonomous vehicles for passenger transport [209]. Generally these vehicles are limited by a low speed and are able to move easily in an urban environment through an observation system. There remains much works to do in the development of fully controlled vehicle, both from the standpoint of the law and the technical point of view [197]. In addition to the control of an individual vehicle, the wireless communication technology could also be used to connect individual vehicles and the transportation system.

Figure 2.3 shows the control architecture of the tricolor traffic light signal system. The *measurement* and *signal* could be considered as the communication between the traffic flow and the controller at intersection. Similarly, the intersection management could also be implemented through the wireless communication between vehicles and intersection controller. It is named as Cooperative Intersection Management (CIM). Different from the tricolor traffic control, which mainly controls the traffic flow, the introducing of autonomous vehicle and the wireless communication technology is able to control the motion of individual vehicle. Basing on controlling individual vehicle, it is able to control traffic more precisely so as to improve the traffic flow, such as avoiding the grid-block in [206].

## 2.4/ COOPERATIVE INTERSECTION MANAGEMENT

Basing on the positioning system, wireless-communication technology and the advanced driver assistance system, it's possible to control autonomous vehicle equipped these systems to pass an intersection. Dealing with the information translated by V2I communication and the movement conflicts, an intersection manager, similar the controller mentioned in Section 2.2, could maintain a sequence of vehicles for driving vehicles to pass the intersection safely and efficiently. This type of intersection manager is called in terms of the **Cooperative Intersection Management** (CIM). This is not an advanced traffic light system [115, 137, 178, 190, 196] or a cooperative collision avoidance system [87, 108, 98]. The basic principle of the CIM is negotiating the right-of-way of passing the conflict zone, see Figure 2.2b, in many different ways.

Normally, a complete CIM system consists of three components: **communication architecture**, **control protocol** and **control policy** which must adapt to a number of constraints. The communication architecture is designed to define the material used and possible interactions between the various entities (mobile or fixed). The control protocol is based on the communication architecture and sets the basic rules that ensure the proper functioning of the control especially in the point of view of security. The control policy uses the advantages of the protocol to try to improve the fluidity of the intersection.

### 2.4.1/ CONSTRAINTS

Before developing a CIM system, it's necessary to consider several constraints. First of all, it's essential to consider the sequencing vehicles to pass the intersection as a discrete phenomenon and the vehicle's movement as a continuous behavior. Then, from the point of view of principle of discrete system, it must to treat the 'real-time' constraints as well as the physical constraints. It's important to notice that no work on CIM system could solve the problem in one time. Indeed, in literature the most part of these constraints are often ignored in the first stage before treating them gradually. Moreover, managing these constraints always leads to a compromise between the efficiency and the safety.

#### 2.4.1.1/ REAL-TIME CONSTRAINTS

The real-time constraints concern taking into account the delays of all systems for being applied on continuous problem especially in the point of view of security. Indeed, at least four example systems with these constraints should be considered:

- **the communication system:** The exchange of information between entities will spend some time.
- **the detectors:** Reading the data from detectors, for example obstacle detectors, is not instantaneous, so there is a delay of current data in relation to the reality.
- **the computing system:** Computing a decision needs a certain time, especially in case of an optimization process or treating many data.
- **the control system:** After a decision was made, the vehicle's controller also needs a certain time to realize the reaction, for example braking or accelerating.

#### 2.4.1.2/ PHYSICAL CONSTRAINTS

There are always errors between theoretical targets and final results achieved by the physical systems. The two principle systems affected by physical constraints are:

- **the detectors:** There are always detecting errors lie in the detected information, for example the positioning systems.
- **the control systems:** The vehicle controller must implement the demands of control as possible as it could, especially for safety, for example keeping safe distance headway from previous vehicle at high speed.

Except the constraints mentioned above, it's also essential to take into account the possible technical problems, for example system failures. Some studies are also made to consider outside factors, such as the weather conditions, the joint of vehicles to existing network and so on.

### 2.4.2/ COMMUNICATION ARCHITECTURE

As described previously, there are two type of communication modes between entities of an transportation control system as shown in Figure 2.11: V2I and V2V. The communication architecture defines the transferring route of messages between entities basing on one or two of them. It's also necessary to adapt an appropriate communication protocol especially in the point of view of security. For example, in order to prevent identity theft, it's essential to import a system of encoding/decoding messages. From the point of view of adopting the V2I and/or V2V communication, there are three types of communication architecture: decentralized architecture, centralized architecture and semi-centralized architecture.

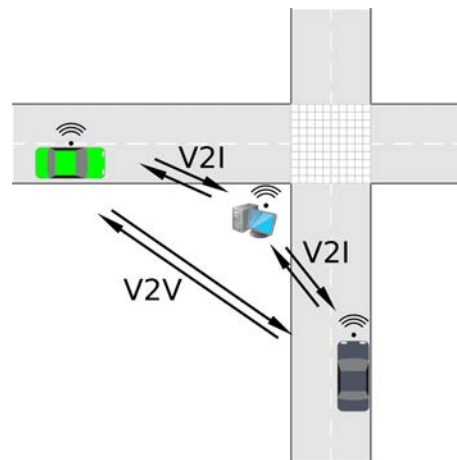


Figure 2.11: Communication architecture

#### 2.4.2.1/ DECENTRALIZED ARCHITECTURE

In 1997, a decentralized intersection management was proposed to increase safety and to avoid congestion without requiring much additional infrastructure, for example the intersection server [37]. In this architecture, the communication only occurs between vehicles (V2V), see Figure 2.11. There are also other researchers are focusing on this type of communication architecture [71, 83, 130, 168]. When approaching the conflict zone, one vehicle must negotiate with other vehicles for the right-of-way through V2V communication. Each vehicle transmits its own situation while collecting directly information from others. One main advantage of this architecture is that a vehicle could easily join in a network of vehicles if it has been equipped with an appropriate system. Another advantage is there is no need additional infrastructure at the intersection, so the vehicles are able to negotiate the access of any intersection.

From security perspective, there is an assumption that there is no collision occurs. Actually, the decentralized approaches generally ignore the major communication problems. For example, if a vehicle could not instantaneously obtain any information from other vehicles, a major reason is the saturation of bandwidth of the communication system, it will think that it got the right of accessing the conflict zone. Therefore, when traversing the intersection, it may encounter any possible risk of collision. A test with mini-robots has shown the limitations of decentralized architecture [100]. In order to decrease the

non-detecting of other vehicles, one way is to import additional detectors. In case of an addition of detector on vehicle, for example such as an optical sensor, the other obstacles (not vehicle, such as buildings) may hide the presence of other vehicles. If install detectors at intersection, then it should not be called decentralized architecture. So in the literature, it's a general opinion that the decentralized architecture is not reliable enough.

#### 2.4.2.2/ CENTRALIZED ARCHITECTURE

Different from the decentralized architecture that only consists of vehicles, the centralized architecture includes a controller installed at respective intersection and a control policy [81, 90, 97, 114, 125, 124, 144, 165, 174, 179]. In this architecture there is only the V2I communication, see Figure 2.11. Basing on collected informations from vehicles, the controller could monitor the enter and exit of all vehicles and then is able to implement any control policy of vehicles for traffic safety and efficiency. Some test with mini-robots has shown the interest of an centralized architecture, in which the central server must treat all the request of passage [174, 179]. For safety, it's possible to consider that all the vehicles by default has no right of accessing the conflict zone. In other words, if a vehicle did not obtain the right or way, it will stop before traversing the intersection. Thus, a failure of communication system won't lead to any risk of collision and only cause a total blockage of the intersection. Meanwhile, the communication delay only simply reduce the efficiency of intersection. With the ability of averting the risk of collision, the release of a blocked intersection and the improvement of time delay will only depend on the definition of control protocols.

#### 2.4.2.3/ SEMI-CENTRALIZED ARCHITECTURE

As the communication could occurs between vehicles and meanwhile between vehicle and infrastructure, it's easy to imagine a communication architecture including the two communication mode V2I and V2V, see Figure 2.11. As far as we know, there is no such a protocol named semi-centralized architecture has already been proposed. Actually, the simultaneous use of the two communication modes will certainly complicate the definition of control protocol. In addition, the studies of MANETs show that the transmission of a message through several intermediates will cause many problems. Because there is a central controller in this architecture, so as the centralized architecture, the controller will be the only responsible one to the security of intersection. Based on a set of ITS standards, a way of practical implementation of semi-centralized architecture has been presented [203]. The semi-centralized architecture needs to be tested in real world to show its feasibility of security and to prove the possibility of improving the intersection control.

#### 2.4.2.4/ CONCLUSION

From the above descriptions, it's obvious that the centralized architecture has the most potential of improving the control of isolated intersection. So the following introduction of control protocols and control policies will focus on the centralized architecture.

### 2.4.3/ CONTROL PROTOCOLS

A control protocol created basing on the communication architecture allows to define the form of right-of-way as well as the rules which describe the manner that how the right-of-way is negotiated and assigned. There are already, in the literature, many protocols about the centralized architecture. Between these protocols, it is possible to identify three principle concepts which have also many variants. So in this section, we will focusing on the three protocols: reservation protocol, protocol of cooperative control of velocity for intersections and sequence-based protocol.

#### 2.4.3.1/ RESERVATION PROTOCOL

In 2004, the first principle of reservation was proposed [81] and then was developed in many works [90, 97, 114, 125, 124, 165]. In this type of protocol, a request of right-of-way is a demand of reserving space or time of passing the intersection. There are only two result of this request: accepted or refused by the control server located at respective intersection. All the requests of passage must only be accepted by the server. In other way, there is only the server have the right to distribute the right-of-way. The efficiency of a protocol depends on the capability of a fully controlled vehicle could pass the intersection within the least possible time. The conflict zone is described in form of a grid of small conflict zone with a certain granularity for increasing the flexibility of reservation of space.

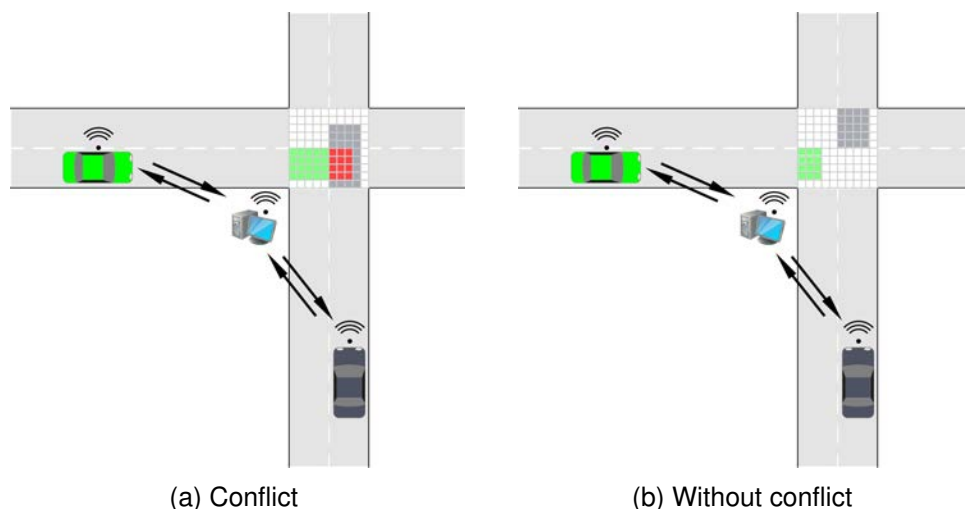


Figure 2.12: Conservation protocol

Figure 2.12 shows an example of reserving space for two approaching vehicles between whose movements there is a conflict zone. In the case of Figure 2.12a, the two vehicles both need to occupy the conflict zone at that moment. If the server reserves the conflict zone for right vehicle, the left one's request of reservation will be refused by the controller. Figure 2.12b presents that the right vehicle has left the conflict zone while the left one has not arrived the conflict zone. in this case, the left one gains right-of-way.

The simulations basing on this protocol have shown its advantages comparing with the tricolor traffic lights. These simulations were implemented basing on some assumptions, for example there is no delay of communication between vehicle and infrastructure and the vehicle has ability of traversing the conflict zone within the reservation time. From



opposite point of view, these assumptions show the difficulties of applying the reservation protocol in real world [156, 148, 179]:

- **The precision of vehicle's movement:** In real environment, very vehicle has a limitation of precision of reacting to movement demands. In other words, a full controlled vehicle could not actuate as expect in high precise environment. For safety, it is necessary to add a security margin. Sadly, this addition will increase the distance and/or time gap between two successive vehicles and consequently decrease the intersection's efficiency.

On the other hand, a vehicle who has respected the reservation precisely may could not avoid another vehicle which may stop at the exit of an intersection because of possible congestion in downstream.

- **The delay of communication:** The communication delay absolutely causes the delay that the vehicle gets the right-of-way. If the delay is too large, for safety, the vehicle must stop before the stop-line.
- **The limitation of infrastructure:** Too many request of right-of-way may overload the controller. Because of communication bandwidth or capability of computer, too many of reservation demands, for example in congestion, occurred at same time will overload the server until a small percent of requests are accepted. This overload will cause that all vehicles wait in the storage zone, see Figure 2.2a.

#### 2.4.3.2/ PROTOCOL OF COOPERATIVE CONTROL OF VELOCITY FOR INTERSECTIONS

The protocol of cooperative control of velocity for intersection is based on the capacity of vehicle to carry out of the variant of velocity for the vehicle to traverse the intersection as quickly as possible [187, 186, 180, 198, 202]. From this point of view, it is close to the reservation protocol. One of differences from the reservation protocol is that the vehicle dose not need to respect to time/space reservation.

In this protocol, the controller of intersection search all possible conflicts between the trajectory of one vehicle and of the others so as to avoid collision between ego-vehicle and others. Basing on the estimation of conflict zone occupancy time of vehicles which already got the right of way, the controller sends indication of velocity adaptation to the approaching vehicles. With the suggestion of velocity, the autonomous vehicle adapts its velocity in order to achieve a possible maximum speed when traversing the intersection. In article [186], the authors proposed a zone located before the entrance of intersection where the vehicle automatically adapts, basing on the indication from controller, its velocity so as to achieve maximum speed when it enters the intersection.

This protocol is more flexible than the reservation protocol. An reservation must be respected or be ignored by vehicle in reservation protocol, while in this protocol, it is possible to gradually adapt the vehicle's speed before the vehicle arrive at the conflict zone.

The main principle that the vehicle will always traverse the intersection at maximum velocity may also possibly leads to a negative performance. The limitation of vehicle control and the problems of communication or positioning may significantly degrade the efficiency of intersection especially in case of large volume of traffic.

### 2.4.3.3/ SEQUENCE-BASED PROTOCOL

Different from the other protocols, sequencing the approaching vehicles is the main characteristic of this protocol [174, 194, 172]. It accepts autonomous vehicles or human driving vehicles. The autonomous vehicle must be equipped at least a communication system and a positioning system. While for the human driving vehicle, an indicator is necessary for indicating the driver the authorization of traversing the intersection. So it is simple to extend this protocol to a hybrid control protocol accepting semi-controlled and fully controlled vehicles.

The main principle of this protocol is to decide an exact sequence of passage of vehicles. Once the sequence is well decided, the sequence will be transmitted to all concerned vehicles with the right of passage with respect to the conflicts between the movements in order to avoid the collisions.

The test with mini-robots described in [174] has shown the improved security of intersection, even though there are communication problems such as time delay. But the test has also revealed that the positioning error not only leads to collision but also causes deadlock at intersection.

In this dissertation, for the reasons mentioned above, we choose the sequence-based protocol.

### 2.4.4/ CONTROL POLICY

The control policy depends on the control protocol and takes the advantage of control protocol to improve the efficiency of intersection. Here, we focus on the **First Come First Served** (FCFS) policy and **Sequencing Algorithm** (SA).

#### 2.4.4.1/ FIRST COME FIRST SERVED POLICY

Many research works using the reservation protocol consider the FCFS as an important policy [97, 133, 144]. In [97], the authors described precisely the implementation of FCFS on an intersection whose conflict zone have been divided into a grid of small conflict zone (tile) with the reservation protocol. Every tile could only be occupied by one reservation. The second vehicle can get the reservation of one tile until the previous vehicle release the occupancy of same tile. The efficiency of this policy is therefore mainly depends on the capability of vehicle to pass the conflict zone as quickly as possible so as to decrease the total occupancy time of a tile. They concluded that after testing several intersection control policy the most efficient policies are based on a FCFS algorithm [125].

#### 2.4.4.2/ SEQUENCING ALGORITHM

Just as what the name implies, this policy is created basing on the sequence-based protocol. Taking into account the vehicle's information and some optimization algorithm it is able to establish an optimized passage sequence of vehicles at an intersection.

- **Priority function:** The intersection server calculate the given priority function for every individual vehicle in order to decide a vehicle's priority of passing the conflict

zone in relation to others [198, 202]. Thus, the server is able to define the sequence. Comparing with the decentralized communication architecture, in which a vehicle calculates its priority by itself (the priority function might be different from others) and negotiate with other vehicles to earn the right-of-way, this policy treats all the vehicles with same priority function and consequently decide the sequence directly by itself.

- **optimization algorithm:** In the FCFS policy, every vehicle is equally treated. Its order of passing the conflict zone only depends on the time that it requests the reservation of a tile. Different from the FCFS policy, the sequencing algorithm policy could give a earlier reservation, basing on basic rules, for a vehicle even if it requests late than others, for example grouping some vehicles so as they could traverse the intersection together. This could be considered as a combination problem and could be solved through some accurate methods such as the dynamic programming [141], the trajectory planning algorithms such as the ant colony optimization [172] or the genetic algorithm. These methods are normally very cost in terms of computing time, thus are not acceptable in real-time control. So we use this approach as a comparative tool with the real-time approaches. Moreover, this approach dose not takes into account the vehicle's exact dynamics since the problem is treated sequentially.

#### 2.4.5/ CONCLUSION

With the development of techniques, there is a rapid increase of market penetration of vehicles with capacity of communication with others and limit autonomous driving such Adaptive Cruise Control system [197]. At macro level, the european project **AutoNet2030** predicts that, given the latest developments in the standardization of vehicular communications, most of vehicles will soon be wirelessly connected so as to be enable to cooperate among them and with the infrastructure. Precisely at micro level, the Cooperative Adaptive Cruise Control of vehicles will evolve to autonomous driving in terms of Advance Driving Assistance System. So, based on these estimations and high possibility in recent years, it proposes that the cooperative control intersections should be developed from now.

Through giving some great principles, many works have achieved grand success on the cooperative control of intersection concerning the infrastructure as well the methods of negotiation and the distribution of right of passage.

From the above descriptions, the centralized communication architecture seems be able to provide better security of traffic and more efficiency than the other two communication architectures. It needs the installation of a controller at an intersection instead of implementation of numbers of detectors both on vehicles and at infrastructures. The research about reservation protocols and the protocols basing on cooperative control of velocity at intersection have shown very promising results which mainly depends on the high punctual capacity of the autonomous vehicles.

Different from the macro control of one intersection, many other researchers focus on the improvement of precise control of individual vehicle [144, 202]. On one hand, basing on wireless communication, most works are carried out for increasing the capability of precisely respecting to speed indications. On the other hand, some works contributed on the trajectory following [62].

At present, the sequence-based protocol looks like the most suitable resolution for intersection management because it could accept the vehicles are equipped only the positioning systems and wireless communication systems. This type vehicle could be fully controlled by human which won't disappear in a foreseeable long time. Further more, the protocols basing on sequence allow to import real-time algorithms to compose an optimized passage order with respect to the physical constraints such as communication delay and computing capability of intersection manager.

In fact, the human driving vehicles without any communication capability with infrastructure will remain for a long time. Some works have taken into account the legacy vehicles into their theory [189, 114, 202]. On one side, the existence of autonomous vehicle at classic intersection and moving among human driving vehicles may lead to high risk. On the other side, the existence of human driving vehicles, even if a small percentage, the performance of protocols will decrease significantly.

## 2.5/ CONCLUSION

This chapter recalled the two main control systems of an isolated intersection: tricolor traffic lights system and cooperative control system. Under the assumption that all vehicles are equal, the traffic lights system could satisfy most of traffic situations. The previewed widespread of autonomous vehicles in near future has motivated and is still attracting more researches on the development of cooperative intersection control system for facing the problems of energy and environment as well as the increasing special transportations especially urgent traffic. We also proposed a classification of work done around this issue by distinguishing the protocols of the regulation policy.



# REACTION-TIME BASED COOPERATIVE ADAPTIVE CRUISE CONTROL AND IMPLEMENTATION

## 3.1/ INTRODUCTION

In Chapter 1, we have discussed that the demands of dealing with increasing number of vehicles and of improving the efficiency of utilization of traffic resource require more precise control system of intersection than the tricolor traffic lights system. Meanwhile, the rapid development of technologies, for example wireless communication, positioning system and advanced vehicle control, encourage researchers to apply these new technologies into the study of controlling traffic flow at intersection. Some researchers try to enhance the tricolor traffic lights by exploring the additional communicated data with some optimization algorithms [169, 131, 207]. Different from this, basing on the new technologies [188, 187, 181, 177, 172, 148, 155, 81, 37] mentioned in previous section, a new approach of controlling the intersection is attracting more and more attentions. The new approach named **Cooperative Intersection Control** (CIM) is neither a cooperative collision warning system nor a cooperative traffic lights system [108].

As discussed before (see Section 2.4.2.2), the centralized communication architecture has the most potential of improving the control of isolated intersection with more efficiency and more security. So in this dissertation, there is only communication between the vehicles and the infrastructure. Basing on the V2I communication, the vehicles and the infrastructure are able to communicate together for negotiating the access of each individual vehicle to the intersection. The vehicle could be both human driving vehicles and/or autonomous vehicles. In addition to the communication architecture, the CIM is also based on both control protocol and control policy that need to be correctly defined.

The protocol determines the way in which the potential zones of collision are shared by conflicting vehicles or flows. Theoretically, time can be saved if the two conflicting vehicles cross the intersection within a tight interval of time. In other words, the efficiency of control system mainly depends on the precision of vehicle's movement. Nevertheless, the required time for freeing the potential zones of collision from a conflicting vehicle cannot be underestimated without increasing the risks of collision. This collision risk depends not only on the control of vehicle's motion but also on the accuracy of positioning system, sampling times, communication delays and so on.

In order to prevent a potential collision caused by the physical limitations mentioned above, the improvement could be applied on the controller side or the control system installed on ego-vehicle. In this section, a new car following control approach is firstly proposed. Then, in order to recognize the factors of intersection that are involved in final control approach, we introduce an implementation of cooperative controlled intersection and corresponding control protocol named **Transparent Intersection Management (MIT)**. After, basing on the proposed car following control approach which is enhanced with the protocol MIT, a new control policy named reaction-time based cooperative cruise control is introduced. At last, some experiments on the proposed method are conducted at the studied intersection.

### 3.2/ REACTION-TIME BASED COOPERATIVE VELOCITY CONTROL APPROACH

As far as we know, taking advantage of communication and measurement and using these advantages in longitudinal control of vehicles was firstly introduced in [20]. Since then, the **Adaptive Cruise Control (ACC)** that taking into account additional information gathering from other vehicles (not only the previous of ego-vehicle) is named as **Cooperative Adaptive Cruise Control (CACC)**.

Recent years, the CACC has been used loosely with visualizing different functions and capabilities. There are two primary transportation system motivations for the development of CACC: improving traffic flow and decreasing fuel consumption; further more for safety, comfort, convenience and customer satisfaction. At the heart, each of CACC concept combines the longitudinal control of ego-vehicle with the additional information gathering through V2I and/or V2V communication 2.3.2.

From the point of view of platooning vehicle, the CACC allows to reduce traffic congestion by improving highway capacity and throughput and by attenuating traffic flow disturbances. With information from V2V, it allows to significantly reduce the mean following time gap which results in an increasing of lane capacity [154, 61, 70, 185]. On the other hand, the CACC could also be used to reduce fuel consumption. Because, high speed ego-vehicle's fuel consumption is significantly influenced by air resistance, tightly-coupled platooning of vehicles can potentially improve fuel economy for both large trucks [170, 142, 171] and passenger vehicles [159].

Another main motivation of implementing the CACC is improving the traffic flow at intersection. In other words, by importing the information about the intersection gathered through V2I communication into its control strategy, ego-vehicle equipped with an CACC system is able to optimize its motion: stop, brake or accelerate. The traffic control at isolated intersection falls into two basic categories: traffic lights timing based traffic signal control and traffic control without traffic light.

The control concept with traffic light could be divided into two types: pre-timed control, semi- and fully- traffic actuated control. Different from traditional timing green wave control (the pre-timed control), whose predetermined cycle, split and offset can not adapt for the dynamical real-time traffic flow, the traffic actuated control does not have a pre-timed cycle, signal sequence and green signal displays, but can accordingly adapt to the volumes of vehicles that are approaching the intersection. In some of the traffic actuated controls, for example the arterial coordinated start concept [208], the vehicles, that are

equipped with CACC system and are waiting at a red traffic signal, would be instructed to begin accelerating in a coordinated fashion once the traffic signal turns green. This coordinated start could allow more vehicles to pass through a congested intersection on a green cycle than manual driving.

More popular application of CACC is at the intersection controlled without traffic lights, as we have discussed in the Section 2.4. There are many obstacles may cause traffic safety problems, for example positioning errors, traveling mechanism, communication delay or even human factors (in case that the sequence protocol dealing with human driving vehicles at intersection).

- The efficiency of reservation protocol (see Section 2.4.3.1) and protocol of cooperation control velocity for intersection (see Section 2.4.3.2) mainly depends on the implementation capacity of full-controlled vehicle. The obstacles might cause that a conflict zone (for example a tile, see Figure 2.12; a conflict point, see Figure 2.2b), which has been declared in the last received message that it could be accessed by ego-vehicle at current point of time, is still occupied by other vehicles in the message that has been just received by ego-vehicle. In this serious case, the ego-vehicle need to brake immediately so as to avoid collision.
- As describe in Section 2.4.3.3, the sequence protocol could be extended to a hybrid control protocol which accepts semi-controlled vehicles. In some case, the movement of previous fully controlled vehicle may cause the human driver to brake so as to avoid collision even if, basing on the automatic controller's estimation, there is no potential collision between ego-vehicle and previous vehicle. The successive fully controlled vehicle equipped with CACC system should deal with unforeseen motion safely.

In the rest of this section, a new car following control approach named **Reaction Time based Cooperative Velocity Control** (RT-CVC) is proposed to help ego-vehicle to deal with the potential brake of previous vehicle.

As we just discussed, the new approach is developed to dealing with occupancy of a conflict zone. If we consider the problem at the point of view of car following, the conflict zone could be considered as a location on road before the following vehicle in car following model. If we consider the problem at the most serious case, in which the conflict zone will be occupied for a long time, this location could be considered as the stand of the leader vehicle in car following model. So above problem could be describe as a car following scenario:

1. At current sample point of time, the leader vehicle begin to brake with maximal deceleration capacity until it stands. The following vehicle does not notice leader vehicle's action and takes an acceleration which is the solution of RT-CVC.
2. At the next sample point of time, basing on the assumption that the leader continues brake until stop if it has not stopped yet, the follower begins to accelerate with its maximal deceleration capacity so as to make sure that it will stop behind the leader and the final distance gap is the specified minimal distance headway.

Before giving the equation about the scenario, it is necessary to give the variable parameters of vehicle that will be used in following, see Table 3.1.



Table 3.1: Parameters of Reaction-Time base Cooperative Velocity Control

| Parameters | Meaning  | Unit             |
|------------|--|------------------|
| $l$        | length of vehicle  | m                |
| $v_0$      | preset maximal velocity of vehicle                       | $\text{ms}^{-1}$ |
| $s_0$      | minimal distance headway between two successive vehicles | m                |
| $a$        | maximal acceleration capacity                            | $\text{ms}^{-2}$ |
| $b$        | maximal deceleration capacity                            | $\text{ms}^{-2}$ |
| $v$        | velocity of vehicle                                      | $\text{ms}^{-1}$ |
| $\tau_v$   | vehicle's sample interval                                | s                |
| $\tau$     | reaction time  | s                |
| $s$        | distance headway without the $s_0$                       | m                |
| $h$        | brake distance   | m                |
| $x$        | vehicle's distance from start of storage zone            | m                |

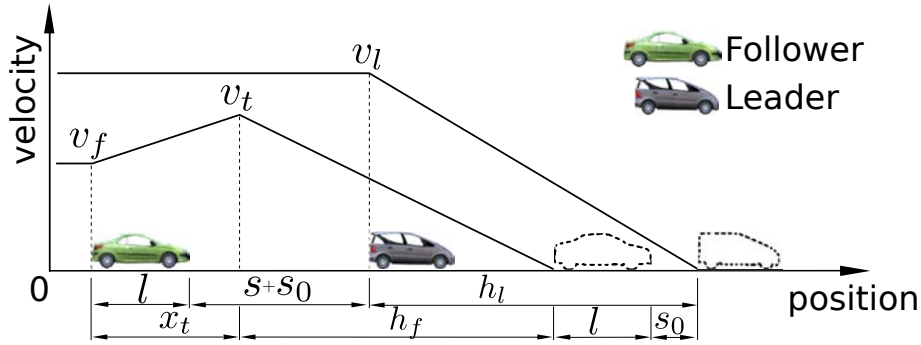


Figure 3.1: Principle of Reaction-Time based Cooperative Velocity Control

Figure 3.1 illustrates above car following scenario. In this illustration,  $v_f$  and  $v_l$  are respectively current velocity of leader vehicle and follower vehicle at current sample point of time.  $s + s_0$  represents the distance gap at current point of time.  $x_t, v_t$  are respectively moved distance during next sample interval and final velocity at next sample point of time.  $h_l, h_f$  represent respectively the deceleration distance of leader and follower until they stopped.

By simple deduction, the principle shown in Figure 3.1 could be formulated as following relations:

$$\begin{cases} v_t = v_f + a_r \tau \\ x_t = \frac{\tau}{2}(v_f + v_t) \\ h_l = -\frac{v_l^2}{2b_l} \\ h_f = -\frac{v_t^2}{2b_f} \\ 0 = (h_l + s + s_0 + l) - (x_t + h_f + l + s_0) \end{cases} \quad (3.1)$$

where,  $b_l, b_f$  are respectively the maximal deceleration of leader and follower,  $a_r$  is the acceleration that follower will take during the next step  $\tau_v$ . We draw the reader attention to the fact that for safety reasons,  $\tau$  is bigger than  $\tau_v$  and  $RTT_{v2i}$ . The  $RTT_{v2i}$  is the round-trip delay time of wireless communication between vehicle and infrastructure. In the following we consider that  $\tau = 1.2 \max(\tau_v, RTT_{v2i})$ .

Then we have the acceleration, from equation 3.1, that the follower should take during

the next  $\tau_v$ ,

$$a_r = \frac{b_f \tau - 2v_f \pm 2b_f \sqrt{\frac{b_f b_l \tau^2 + 4b_l v_f \tau + 4v_l^2 - 8b_l s}{4b_f b_l}}}{2\tau} \quad (3.2)$$

In some unusual case, the bumper-to-bumper distance may be less than the minimal distance headway  $s_0$ . Taking into account this case, the final control approach is:

$$a_r(v_f, v_l, s) = \begin{cases} b_f, & \text{for } s < 0 \\ \frac{b_f \tau - 2v_f - 2b_f a^*}{2\tau}, & \text{for } s \geq 0 \end{cases} \quad (3.3)$$

where,

$$a^*(v_f, v_l, s) = \sqrt{\frac{b_f b_l \tau^2 + 4b_l v_f \tau + 4v_l^2 - 8b_l s}{4b_f b_l}}$$

The platoon of vehicles requires that there is a steady state between successive vehicles. The steady state could be represented by following:

- the acceleration of follower is 0 at any moment,
- the headway is constant,
- the two vehicles have same speed.

From Equation 3.3, we could have the headway of follower of the steady state.

$$s = \frac{b_f v_l^2 + 2b_l b_f \tau v_f - b_l v_f^2}{2b_f b_l} \quad (3.4)$$

where,  $s$  does not contains the minimal headway  $s_0$ .

Figure 3.2 shows the simulation of a normal car following scenario of two vehicles. The initial headway between the vehicles, velocity of the two vehicles are respective 8 m, 0  $\text{ms}^{-1}$ . The range of follower's acceleration capacity is  $[-4, +4] \text{ms}^{-2}$ . The follower's reaction time  $\tau$  is 2 s. Maximal velocities of the two vehicles are same, 20  $\text{ms}^{-1}$ ; In the simulation, the leader vehicle brakes frequently with maximal deceleration capacity  $-15 \text{ms}^{-2}$ .

Figure 3.3 shows the comparison of 4 car following scenario described in Figure 3.2. The difference between the 4 followers is the reaction time  $\tau$ . The legend *Follower-0.5 s* indicates the reaction time of follower is 0.5 s.

### 3.3/ COMPARISON

As we discussed before, one of reasons of proposing the RT-CVC is to deal with possible huge time interval between two successive actions of controller. There are many reasons could cause huge time interval, for example, package lost in wireless communication, low reaction time of positioning system and so on. In my opinion, the low precision of positioning system or temporal functional failure of front radar could also be partly considered as a delay on sample interval. So the RT-CVC imports the reaction time into the algorithm to try to face these problems. Normal longitudinal control algorithms of vehicle are

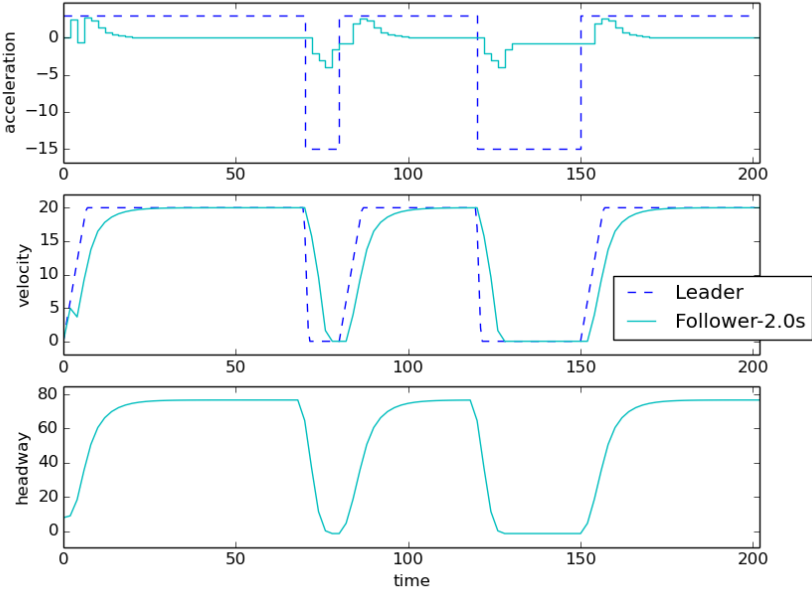


Figure 3.2: Sample scenario that leader vehicle brakes frequently with maximal deceleration capacity

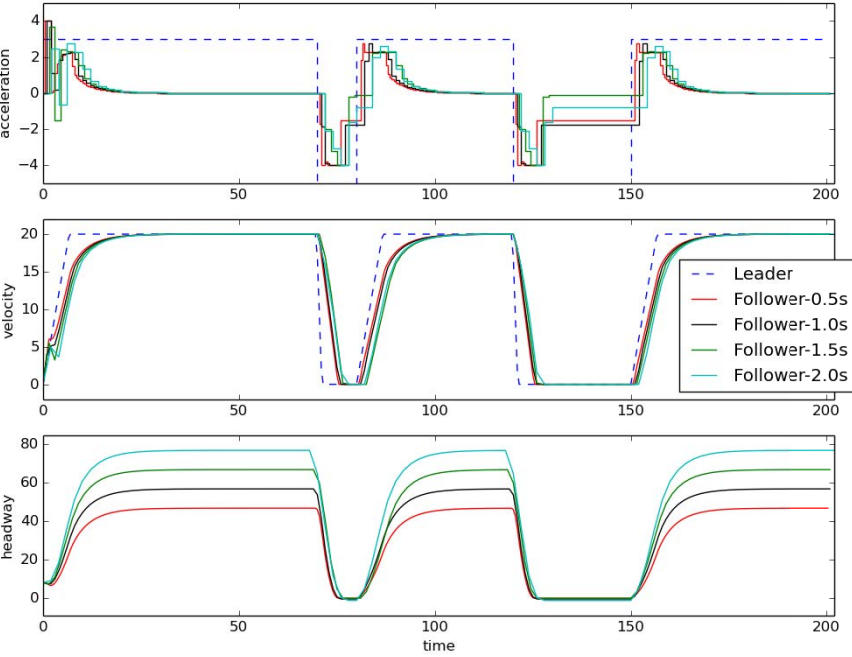


Figure 3.3: Sample scenario that leader vehicle brakes frequently with maximal deceleration capacity

developed based on assumption of small reaction time interval, for example the [151]. In this section, the comparison between the Intelligent Drive Model (IDM) and the proposed algorithm RT-CVC is presented to show influence of reaction time.

In order to focus on the motion relationships between successive vehicles, a scenario is designed as a platoon of vehicles running on straight lane, see Figure 3.4. The motion of vehicles in a platoon could partly represents the stability of a longitudinal control algorithm. In the figure, the number labels represent the vehicle's order in the platoon sequence. The vehicle with number 1 is the leader of the platoon. Because the abrupt brake of previous vehicle is a normal reason of collision, like the leader vehicle's action in Figure 3.2, the leader vehicle's deceleration capacity is different from the other vehicles (followers) in the platoon, in order to observe the influence of abrupt brake of previous vehicle to the following vehicles. The leader vehicle is controlled by preset actions: at the beginning it speeds up, then runs at constant desired velocity  $v_0$  for a while and finally brakes to stop. As we just have interest on the longitudinal motion of followers, all vehicles move exactly along the center line of lane.

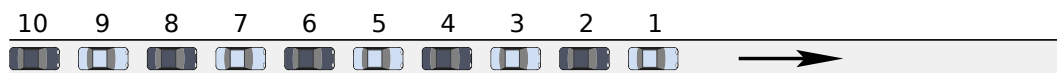


Figure 3.4: Scenario: platoon of 10 vehicles

Before starting the simulation, the vehicles are located at the beginning of the straight lane. Their initial velocity is  $0 \text{ ms}^{-1}$ . The gap between two adjacent vehicles is the minimal distance with respect to the initial velocity. In the platoon, every vehicle just reacts to the motion of its previous vehicle.

In order to look into the reactions of the two algorithms, the simulation is implemented under two set of parameters of vehicles. One is the the parameters used in [151]. In the other set, the acceleration is bigger to simulate the reactions of vehicles travels in complex urban environment. As shown in Figure 3.2 and 3.3, the following simulations will only be implemented to observe the characteristics of the two algorithms during the first speeding up process and braking process.

### 3.3.1/ SCENARIO I: PARAMETERS FROM ARTICLE [151]

In the scenario, we simulated the IDM algorithm and the RT-CVC algorithm under different maximal deceleration of leader and different reaction time to see the relationships between the reaction time and abrupt braking action. Except the maximal velocity of vehicle and the maximal deceleration of leader, all the simulating parameters of vehicles are set according to the Table 1 in [151]. The preset maximal acceleration and deceleration are respective  $a = 1.4 \text{ ms}^{-2}$  and  $b = 2.0 \text{ ms}^{-2}$ . The minimal distance between two successive vehicle is  $s_0 = 2.0 \text{ m}$ . The desired time gap is  $T = 1.5 \text{ s}$ . The free acceleration exponent  $\delta$  is 4. Different from the settings in [151] where the desired velocity is  $v_0 = 120 \text{ ms}^{-1}$ , the maximal speed of all vehicles is  $v_0 = 15 \text{ ms}^{-1}$ . As the abruptness is relative to the value of maximal deceleration and reaction time, the simulations are carried out with varying one of two variables while another one keeps constant.

## 3.3.1.1/ IDM

Figure 3.5 shows a simulation result of the IDM algorithm, with proposed parameters of vehicle in article [151]. It shows that under the maximal deceleration  $b = 2.0 \text{ ms}^{-2}$  of leader vehicle, the braking process of every follower is still perfect with the sample interval 0.7 s.

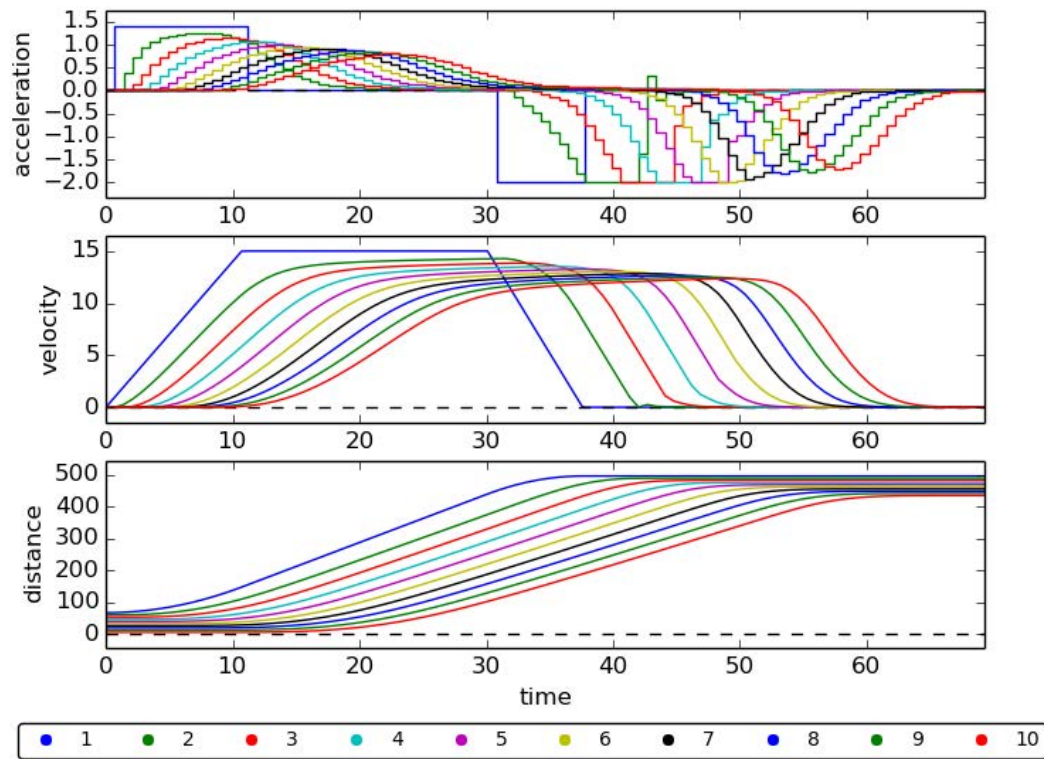


Figure 3.5: Scenario I: IDM algorithm, leader brakes at  $2.0 \text{ ms}^{-2}$  the reaction time follower is 0.7 s

In the simulations under constant deceleration,  $b = 2.0 \text{ ms}^{-2}$  of leader, the increasing reaction time causes the stability of braking process of followers gets worse. In Figure 3.5, the velocity of vehicle at the end of braking process steadily converges to  $0 \text{ ms}^{-1}$ . The action times that are bigger than 0.7 s and are less than 2.0 s cause short speeding up before ego-vehicle stops behind its previous vehicle. As we did not consider the collision checking, when the reaction time is 2.0 s, the followers could not stop behind their previous vehicle and finally cross the position of leader, as shown in Figure 3.6.

From the simulations with different maximal deceleration capacity of leader vehicle and different reaction time of follower, we observed that bigger deceleration of leader leads to smaller maximal acceptable reaction time of followers for stability and safety. When the leader's deceleration is  $4.0 \text{ ms}^{-2}$ , the reaction time 1.2 s causes the result shown in Figure 3.6. When the leader's deceleration is  $5.0 \text{ ms}^{-2}$ , the reaction time 0.9 s causes same result. If the leader brakes with deceleration  $15 \text{ ms}^{-2}$ , the same result appears when the reaction time is 0.5 s.

We also simulated the Enhanced Intelligent Drive Model (EIDM) (see [151]) with same parameter conditions and the cool factor  $c = 0.99$ , we observed that it works better than

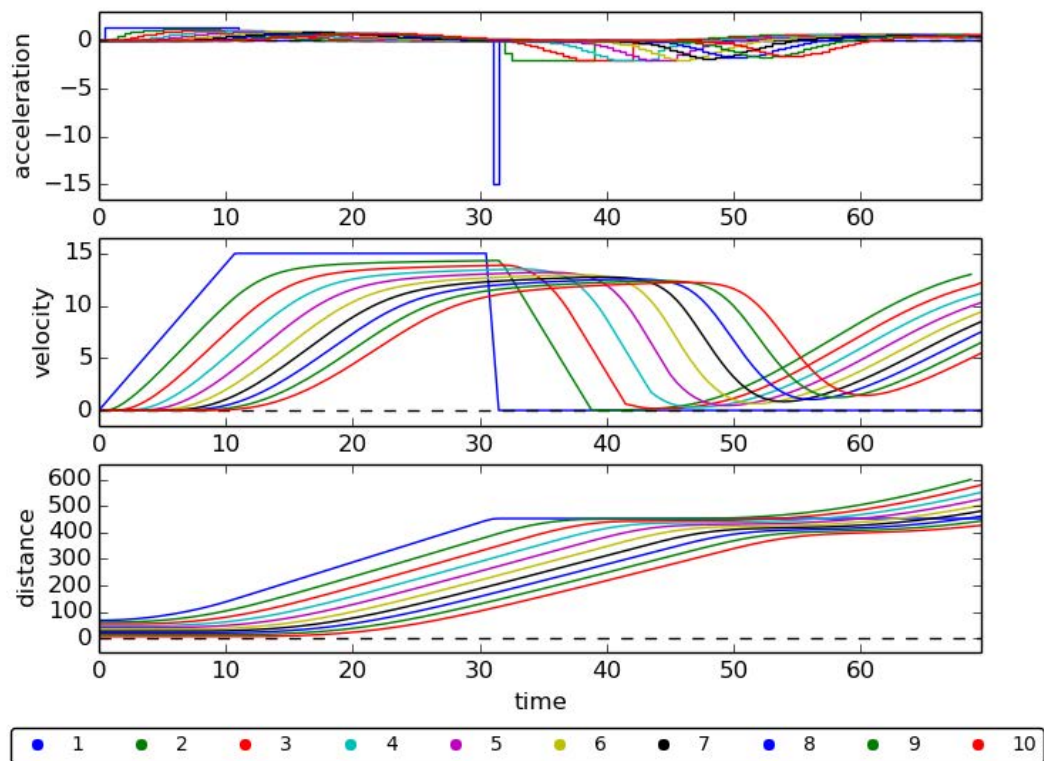


Figure 3.6: Scenario I: IDM algorithm, leader brakes at  $15.0 \text{ ms}^{-2}$ , the reaction time follower is  $0.5 \text{ s}$

the IDM algorithm. Until  $0.8 \text{ s}$  of reaction time, the braking process of follower is stable. With  $0.9 \text{ s}$  of reaction time, the followers could stop behind their previous vehicle even though there is a velocity saltation in the end of braking process. The reaction time  $1.0 \text{ s}$  causes same result as shown in Figure 3.6.

### 3.3.1.2/ RT-CVC

Figure 3.7 shows the movement of the platoon of vehicles equipped the RT-CVC algorithm. Their parameters are same to that in the experiments of IDM in previous section. The reaction time of every follower is  $1.5 \text{ s}$ .

In the simulations, even if the reaction time increases from  $0.1 \text{ s}$  to  $4.0 \text{ s}$ , the final braking process of followers keeps stable. An obvious difference between the IDM and RT-CVC algorithm is the speeding up process, see the region in the red rectangle of subplot *time-velocity* in Figure 3.7. There is a brake during the speeding up process of every follower vehicle, before they reach their maximal velocity. The first follower brakes because of the leader changed its motion from accelerating to running at constant velocity. After the adaptation, the follower continues speeding up but with a decreasing acceleration. The subsequent followers make same adaptation to react to the motion change of each one's first previous vehicle. The follower which has a bigger distance from the leader vehicle takes a smoother adaptation than its previous vehicle. In other words, the brake wave of follower in the platoon damps during the transmission from first follower to the last one of

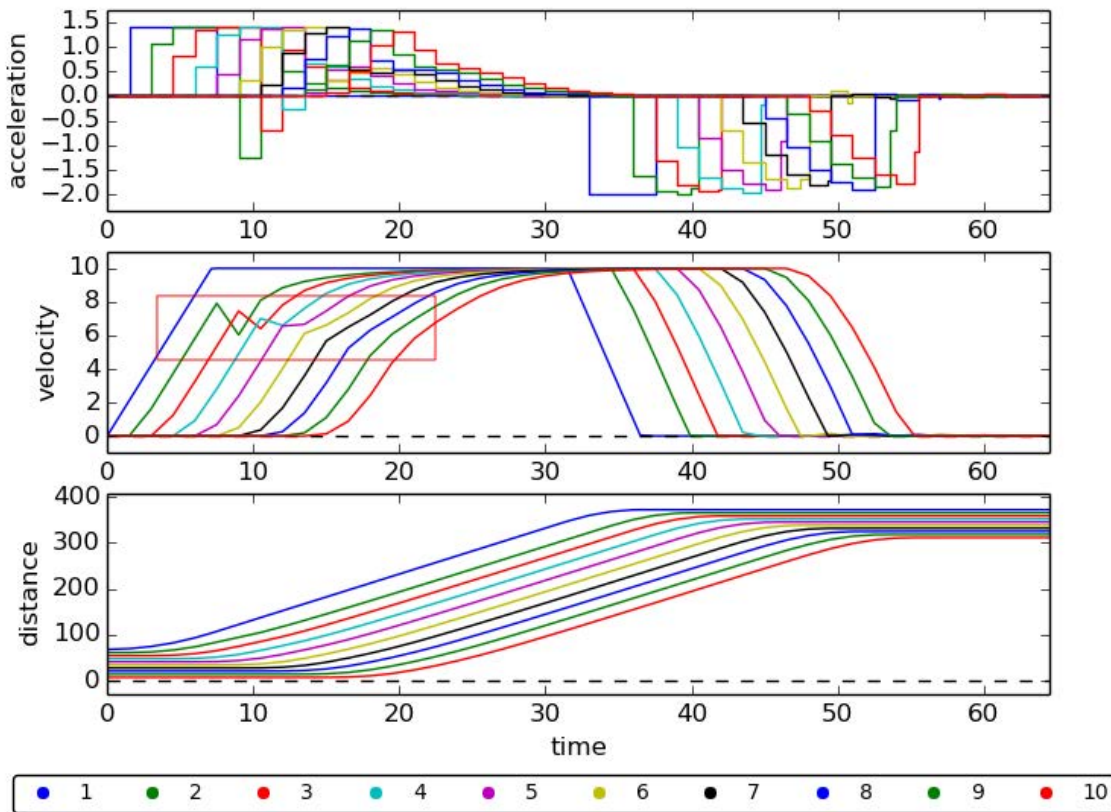


Figure 3.7: Scenario I: RT-CVC algorithm, leader brakes at  $2.0 \text{ ms}^{-2}$ , the reaction time follower is  $1.5 \text{ s}$

platoon. The increasing of reaction time leads to consequent increasing of amplitude of the adaptation wave of follower. But the amplitude of adaptation wave steadily converges to 0, during its transmission from first follower to the end of platoon.

Continuing increasing the reaction time leads to second adaptation wave occurs at the reaction time  $2.1 \text{ s}$ . The second wave keeps damping. Figure 3.8 shows the simulation result of RT-CVC at the reaction time  $4.0 \text{ s}$ . The three brake waves all steadily converge to 0.

On the other side, with same reaction time, bigger deceleration capacity of leader vehicle leads to the earlier occurrence of adaptation wave, see Figure 3.7 and Figure 3.9.

### 3.3.2/ SCENARIO II

In this scenario, except the deceleration of leader is  $b = 15.0 \text{ ms}^{-2}$ , the acceleration and deceleration of all vehicles are set to  $4.0 \text{ ms}^{-2}$ . The other parameters are same with the ones in Scenario I.

Figure 3.10 shows the movement of platoon under the control of IDM algorithm. We observed that start from  $0.4 \text{ s}$  of reaction time, there are frequent small accelerating-braking process at the beginning of speeding up and the end of braking.

Figure 3.11 shows that the RT-CVC keeps stable when the reaction time is  $0.8 \text{ s}$ . During

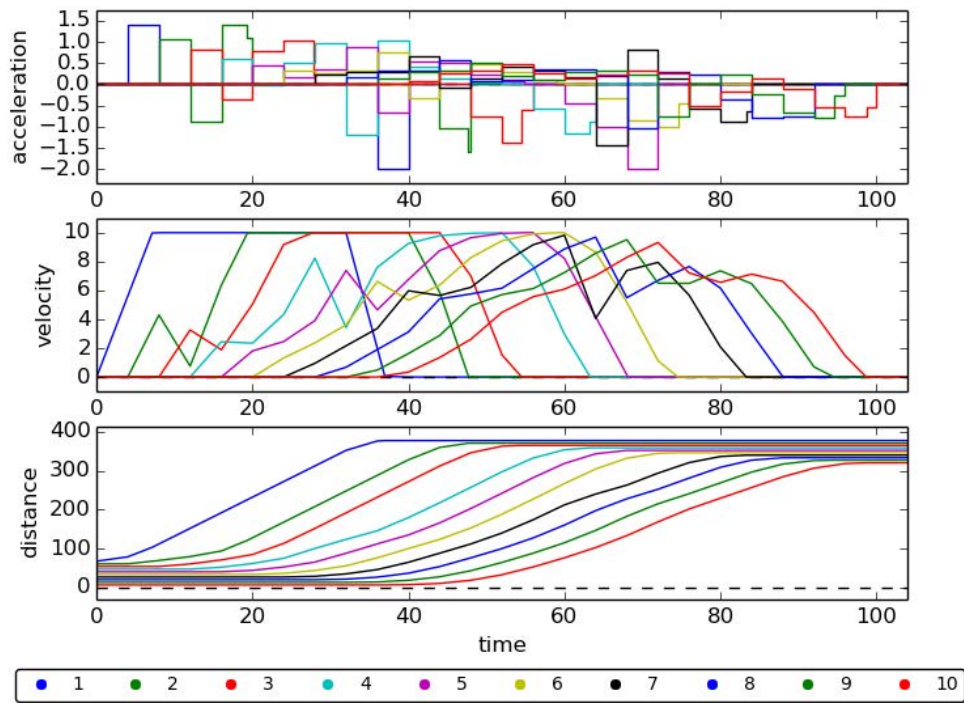


Figure 3.8: Scenario I: RT-CVC algorithm, leader brakes at  $2.0 \text{ ms}^{-2}$ , the reaction time follower is  $4.0 \text{ s}$

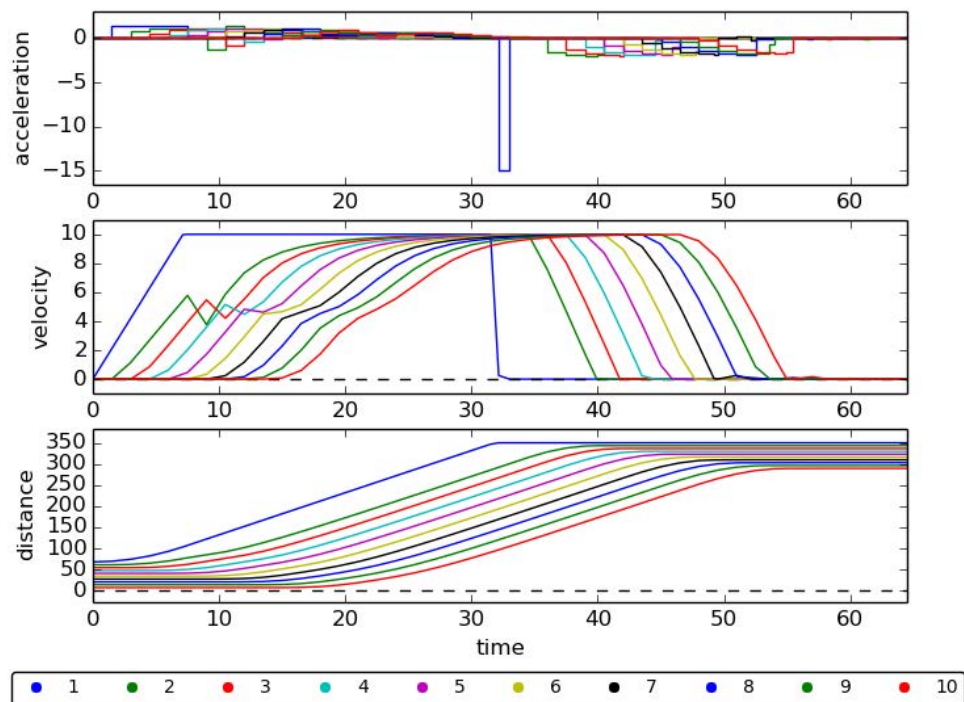


Figure 3.9: Scenario I: RT-CVC algorithm, leader brakes at  $15.0 \text{ ms}^{-2}$ , the reaction time follower is  $1.5 \text{ s}$



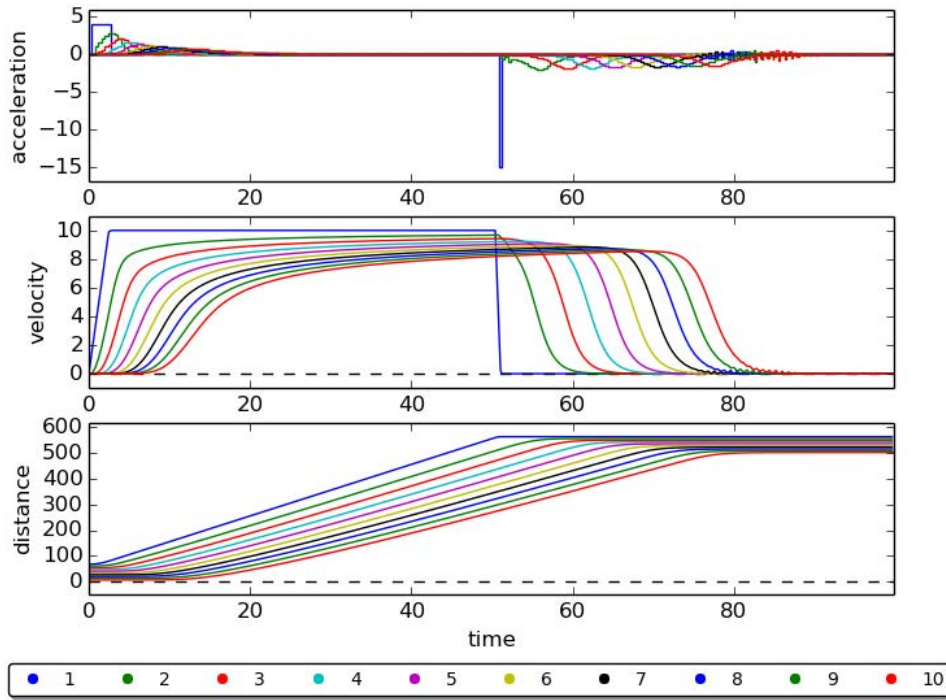


Figure 3.10: Scenario II: IDM algorithm, leader brakes at  $15.0 \text{ ms}^{-2}$ , the reaction time follower is  $0.4 \text{ s}$

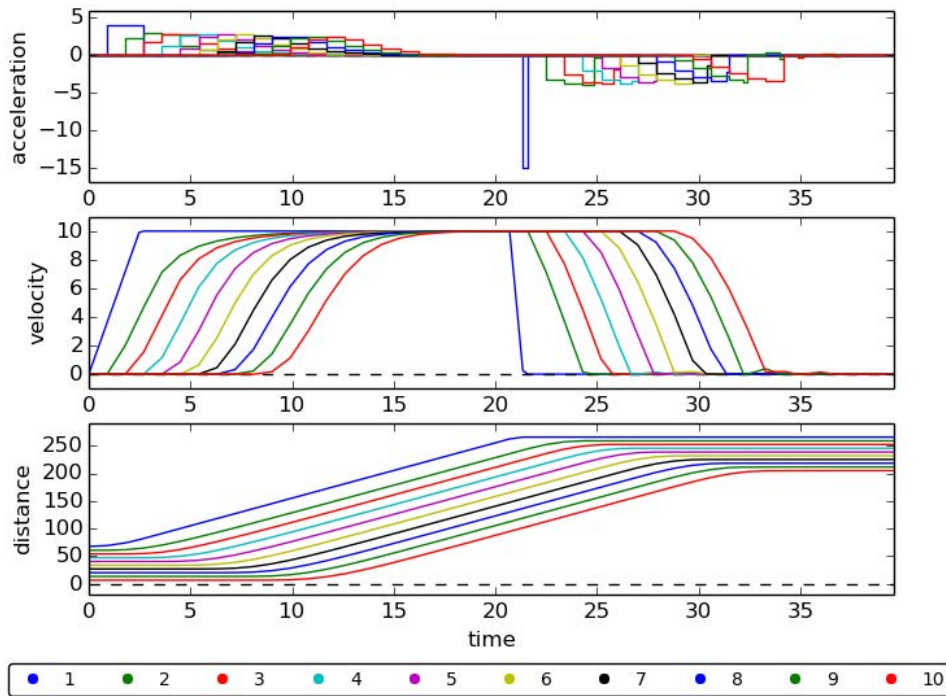


Figure 3.11: Scenario II: RT-CVC algorithm, leader brakes at  $15.0 \text{ ms}^{-2}$ , the reaction time follower is  $0.8 \text{ s}$

the simulations, we observed that when the reaction time is bigger than 0.8 s, the brake wave appears and the braking process still keeps stable.

### 3.3.3/ CONCLUSION

From the simulations of the two scenarios, we could observe that the RT-CVC algorithm keeps stable during the braking process even if the deceleration and reaction time are big. The adaptation wave that occurs during the accelerating process damps during the transmission from the first follower to the end of platoon. So, in my view, the RT-CVC could be used to control the vehicle in urban environment.

## 3.4/ IMPLEMENTATION OF INTERSECTION

The intersection for testing the reaction-time base cooperative velocity control is a cooperative isolated intersection. A control protocol named **Transparent Intersection Management** (TIM) [193, 194] is adopted. It is based on sequence-based protocol (see section 2.4.3.3) for solving the problems that the authors encountered in their previous works [181].

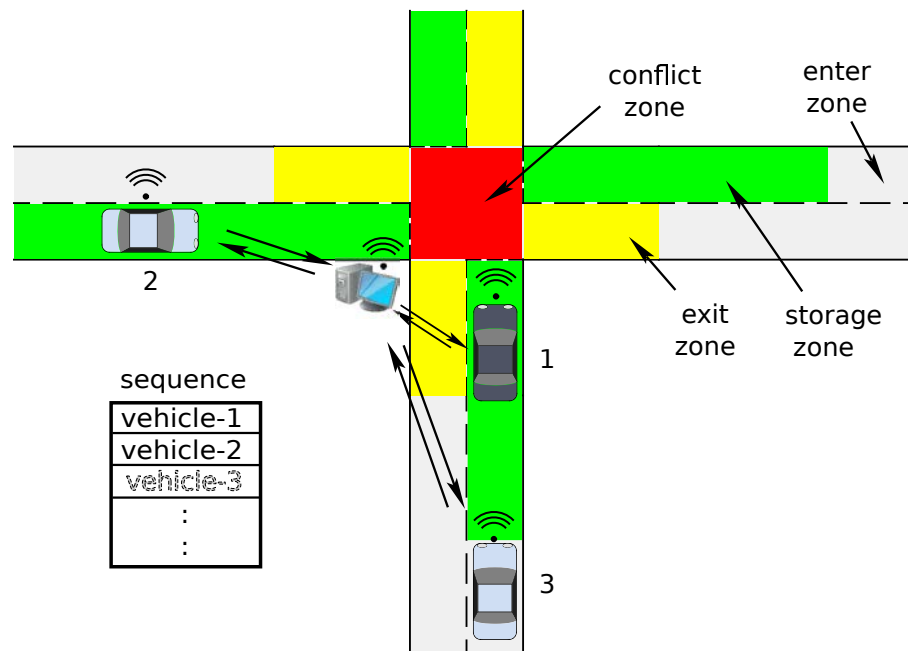


Figure 3.12: Implementation of Transparent Intersection Management

### 3.4.1/ ZONING THE INTERSECTION

The principle of zoning the conflict zone is shown in Figure 3.12. the intersection is zoned into three types of area:

- **Global Conflict Zone:** As the joint connecting all lanes concerns the intersection, the **Global Conflict Zone (GCZ)** (red area in Figure 3.12) is the most important area that the intersection manager concerns. It is divided into small areas for precisely controlling vehicle's movement. The small area that is covered by more than one vehicle's movement is named as **Local Conflict Zone (LCZ)** ( see the red small areas shown in Figure 3.13). For safety, at each one point of time, one LCZ could only be occupied by one vehicle's movement.
- **Storage zone:** The storage zone (blue zone in Figure 3.12) is located on the enter lane of intersection. Each enter lane owns a storage zone. It has a predefined length. Basing the positioning and/or navigation system installed on vehicle and the communication delay between vehicle and intersection manager, it is able to obtain the distance between vehicle and conflict zone. Once the vehicle enters the storage zone, it negotiates, through V2I communication, with the intersection manager for the right-of-way of traversing the conflict zone. Before have got the authorization, the vehicle must stay by default in the storage zone.
- **Exit zone:** When a vehicle has entirely entered the exit zone (yellow zone in Figure 3.12), it sends a message to notice the manager that it has left the GCZ. Once the manager receives this message, it makes some clean works and assigns the authorization of accessing the same LCZ, the sender vehicle has just left, to other vehicles that are waiting in the storage zone.

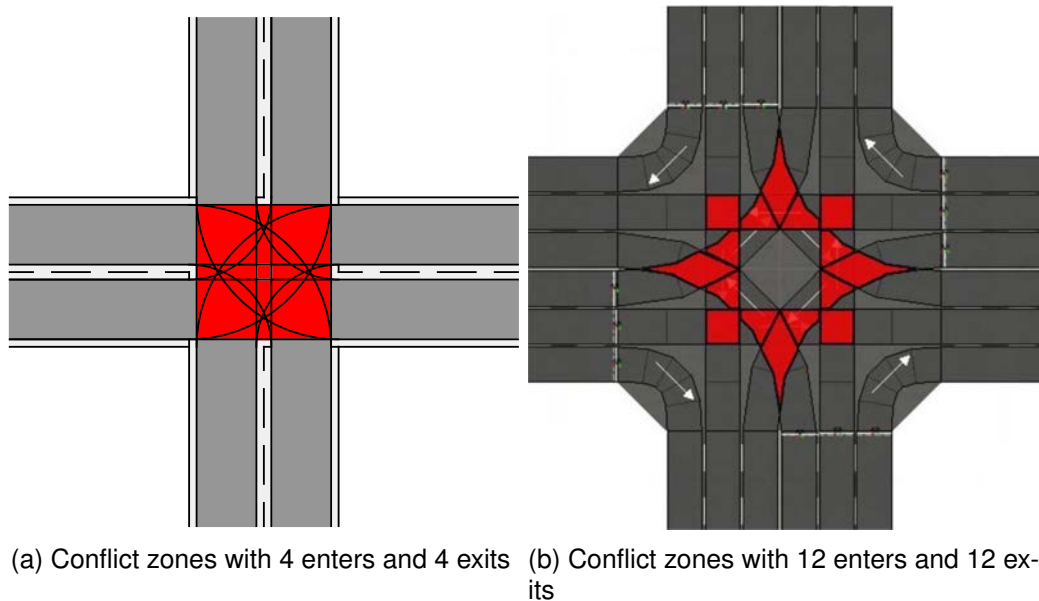


Figure 3.13: Example of Zoning an intersection

It is necessary to note that the GCZ could be zoned with different forms, depending on the movement angles and different size. Indeed, the GCZ must exactly cover the critical area to maximize the use of space. Furthermore, we consider that each vehicle must know the conflict between the movements and the GCZ, so as to be able to stop before any GCZ.

### 3.4.2/ COMMUNICATION ARCHITECTURE

As introduced before, the communication architecture describes the mode of communication between vehicle and vehicle (V2V) or vehicle and infrastructure (V2I). The negotiation of right-of-way is wholly based on the centralized communication architecture (see section 2.4.2.2). This demands that every vehicle, considered by this protocol, must be equipped an on-board communication system in order to communicate with the intersection manager. The Figure 3.14 represents the details of communication between vehicle and manager. An enter lane consists of two parts: the storage zone and the rest which is named as enter zone. This type of zone is not taken into account in this protocol. Actually, this zone could help to provide additional security to vehicle and to especially enhance the intersection management. When traveling in this area, the vehicle (see *Vehicle-3* in Figure 3.12) try to communicate with the server. With the received message, the server could register the vehicle into the sequence at proper point of time so as to start the actual communication with the vehicle. As shown in Figure 3.14, there are three components concerned in this protocol.

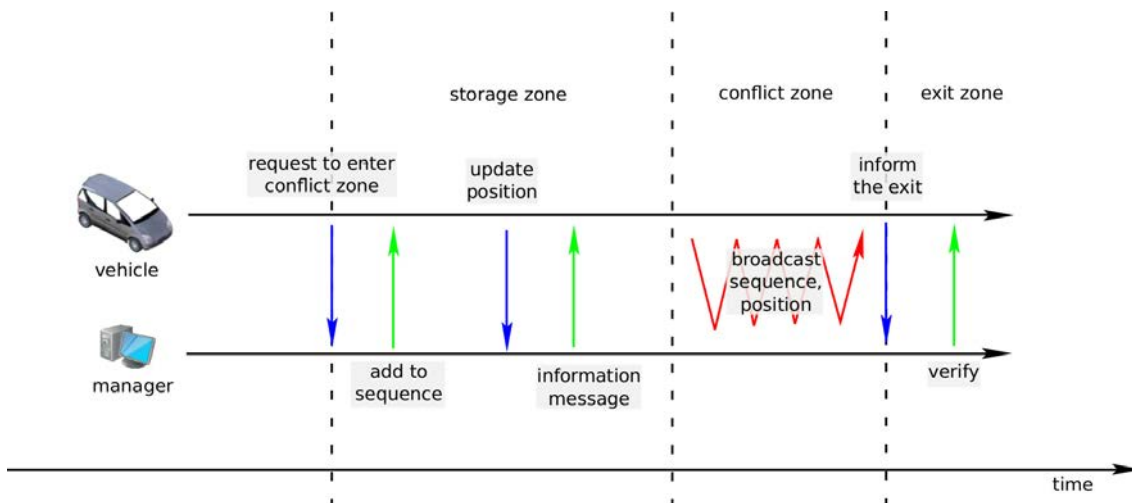


Figure 3.14: Communication architecture of the TIM protocol

#### 3.4.2.1/ MANAGER

Basing on the information collected from vehicles that are already registered on it, the manager maintains a sequence of vehicles (see Figure 3.12). With some optimization algorithms, it assigns the authorization of passing the conflict zone to ensure the safety of vehicles and to improve the efficiency of intersection. At each sample point of time, the manager sends the sequence with authorizations to all vehicles listed in the sequence. Once received a message from vehicle, which indicates that the vehicle has already entirely entered the exit zone, the manager removes the vehicle from the sequence and sends a confirmed message to the vehicle. The safety of vehicles that are already running in the conflict zone is the most important factor that the manager considers when it distributes an authorization of entering the conflict zone to a vehicle.

In order to assign right-of-way to different vehicle, basing on the occupancy of conflict

zone, the manager refers a conflict matrix table. The table is defined based on the pattern of intersection. Every possible movement is considered as an item in the table. Figure 3.15 shows the table of conflict matrix of the movements in typical four legs intersection as shown in Figure 2.2b. Each item  $c_{i,j}$  of the table represents the conflict information between movement  $i$  and movement  $j$ . For example,  $i_{1,5} = 1$  represents that the turning right movement 1 and go straight movement 5 has conflict and  $i_{1,4} = 0$  indicates that there is no conflict between movement 1 and turning right movement 4.

|    | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|----|---|---|---|---|---|---|---|---|---|----|----|----|
| 1  | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0  | 0  | 0  |
| 2  | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 1  | 1  | 1  |
| 3  | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 0 | 0  | 1  | 1  |
| 4  | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0  | 0  | 1  |
| 5  | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 1 | 1 | 0  | 0  | 1  |
| 6  | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 1 | 1 | 1  | 1  | 0  |
| 7  | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0  | 1  | 0  |
| 8  | 0 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0  | 1  | 1  |
| 9  | 1 | 1 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0  | 1  | 1  |
| 10 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0  | 0  | 0  |
| 11 | 0 | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 1 | 0  | 0  | 0  |
| 12 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 0  | 0  | 0  |

Figure 3.15: Conflict matrix table of intersection 2.2b

### 3.4.2.2/ VEHICLE

When running in an enter zone, the vehicle sends messages to the intersection manager for registering itself on the manager. It incessantly sends the demanding message until it is registered successfully on the server. Then the communication between the vehicle and server continues until the vehicle has been removed from the sequence on server. Once the vehicle has entered the storage zone, the manager adds it to the sequence so as to assign the authorization to it at a proper moment, see *vehicle-3* in Figure 3.12. When moving in the storage zone, based on the equipped control approach, the vehicle may adapt its velocity to optimize its movement. Ego-vehicle's adaptation depends on its order in the sequence, its position and the movements of its previous vehicles which are located in the sequence. So ego-vehicle needs to update its information as much as possible to the manager. By default, the vehicle has no right of occupying the LCZs that its movement covers. In other words, without an authorization, it will stop in the storage zone. Once it gains the right of passing the intersection, it traverses the LCZs. Finally, when it entirely arrives at the exit zone, it reports to the manager until it is verified by the manager that it has been removed from the sequence.

### 3.4.2.3/ PRIORITY OF MESSAGE

The traffic safety of the managed intersection mainly depends on the communication architecture and the rules which define the control protocol. The communication delay is an important factor that reduces the intersection's efficiency. But, it does not increase directly the risk of collision. As mentioned before, the sequence-base protocol allows human driver appears in its control region. This is important when there are still non-fully driven vehicles running on the road. A human driver might make a dangerous behavior. Once the manager detected the danger, it could send a warning to the driver. Meanwhile, it could also alert the other vehicles which have a later order of passing the intersection. For safety, each vehicle in the sequence only considers the last received message so as to be able to react to the danger as quickly as possible. If a vehicle could not report its exit from the conflict zone, a deadlock may occur. Because of the reasons discussed above, it is necessary to give different priority to message. Here, the communication system considers 4 levels of priority:

- **Level-3:** vehicle with dangerous behavior
- **Level-2:** vehicle has exited the conflict zone
- **Level-1:** communication delay
- **Level-0:** other messages

## 3.5/ CONTROL STRATEGY

The safety and efficiency of an intersection management depend mainly on the distribution of the authorization of a LCZ to different vehicles. After successively occupied same LCZ, the two vehicles either run on same lane (merging of vehicles) or on two different lanes (cross of trajectories of two vehicles). Normally, the cross control needs that the two successive vehicles adapt their velocity so as to pass the LCZ safely and efficiently. The merging control of vehicles is more complex than the cross control. In addition to the safety and efficiency, it should also consider seriously the movements of the vehicles after they pass the LCZ successively for safety and the fluidity of traffic flow in the downstream lane of the intersection.

So general principle of proposed control strategy of an intersection is to assimilate the two successive vehicles, which will pass same conflict zone, to a conventional motion on same lane. Basing on the principle, we could consider the two vehicles, which will successively pass same conflict zone (as shown in Figure 3.16), as a leader vehicle and a follower vehicle that are running on an imaged lane. In the TIM protocol, the follower vehicle should adapt its velocity in accordance with the position and velocity information of the leader vehicle. So every vehicle must have the order of passing the LCZ that it must respect to, the position and velocity of preceding vehicles that will pass the same LCZ before it. From the car following principle, the acceleration and deceleration of a vehicle must not exceed a preset threshold even if it needs to stop as quickly as possible. As we discussed before, in order to increase the efficiency of a control policy, the vehicle needs to pass the conflict zone as quickly as possible. But, meanwhile, the high speed will lead to potential collision. So there should be a compromise between the efficiency and the safety.

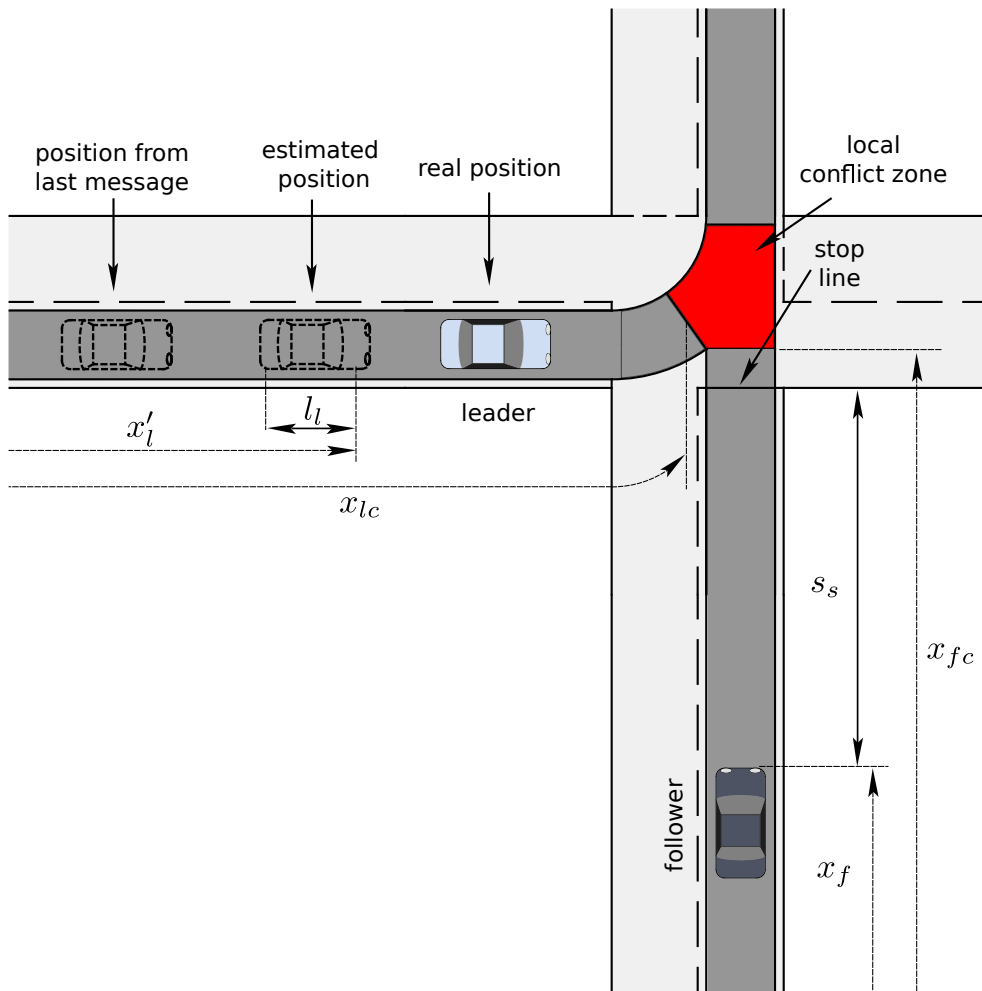


Figure 3.16: Sample merging scenario

In the TIM protocol, the follower vehicle needs to consider two types of information. On a macro level, the ego-vehicle should consider different types of vehicle, running exactly before it or on other lane but has a high order to pass the conflict zone, and the stop line if it is denied to pass the conflict zone. On micro level, because of communication delay, it is necessary to estimate the position and velocity of preceding vehicle.

### 3.5.1/ ESTIMATION OF POSITION AND VELOCITY

Because of the communication delay, the information that a vehicle has just received is not the actual information, especially in a control strategy that is mainly basing on the velocity and position of vehicle, for example the approach in [97]. So a vehicle must always consider the last received information of position and velocity. Indeed, for security reason, ego-vehicle must always assume a worst case that the previous vehicle, that ego-vehicle concerns, has braked from the point of time of the last message that it received. So the estimation of velocity and position should be calculated basing on the braking of concerned vehicle with maximal deceleration capacity:

- **velocity:**  $v' = \max(0, v + b\tau_v)$ , where  $v$  and  $v'$  are respectively the velocity contained in the last message and the estimated velocity of the concerned vehicle.
- **position:**  $x' = x + \frac{(v+v')\tau_v}{2}$ , where  $x$  and  $x'$  are respective the position contained in the last received message and the estimated position.

### 3.5.2/ OBSTACLES

In the MIT protocol, ego-vehicle should consider three types of obstacle that will affect its motion decision. Mapping the *vehicle-2* onto the lane of *vehicle-1* and *vehicle-3* basing on the *sequence* in Figure 3.12, the merging scenario could be represented as the Figure 3.17. We consider the *vehicle-3* as the ego-vehicle that we would like to control. The stop line and the conflict zone are respectively the end of lane that ego-vehicle is running on and the conflict zone that ego-vehicle will traverse.

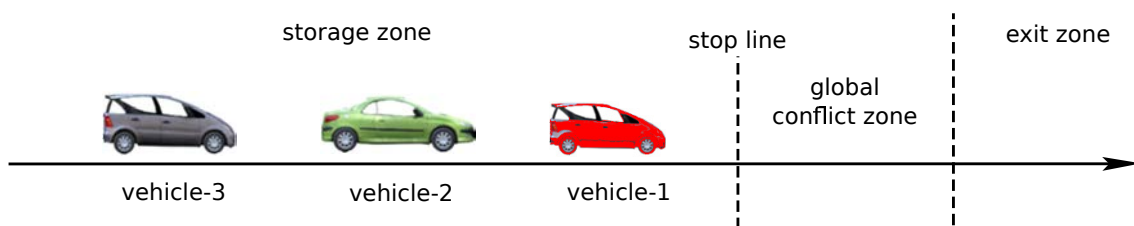


Figure 3.17: Sample merging scenario

Basing on the car following control and ego-vehicle's potential stop before the conflict zone, the three types of obstacle are:

- **Real obstacle:** The real obstacle is the exact preceding vehicle running on same lane. It's the preceding vehicle considered in traditional car following model. Before entering the conflict zone, this is the first important obstacle that ego-vehicle needs to take into account. Ego-vehicle detects this obstacle with sensors equipped in front of it, such as radar.
- **Virtual obstacle:** There are two types of virtual obstacle:
  - **Virtual preceding vehicle:** The virtual preceding vehicle of ego-vehicle listed in the *sequence* and has a higher order of passing the intersection. The control strategy of ego-vehicle only needs to make sure the safety of passing the local conflict zone covered by the movements of the ego-vehicle and this virtual obstacle. On the promise of safety, ego-vehicle should also traverse the LCZ as quickly as possible for efficiency. This type of obstacle could be detected from the sequence information received from the intersection manager.
  - **Stop line:** The stop line is considered as another type virtual obstacle only when ego-vehicle has been denied to pass the intersection. Some researchers consider the beginning of the LCZ on ego-vehicle's trajectory as this obstacle. This setting could help to improve the usage efficiency of the infrastructure. But considering a complex intersection which has many movements, such as the one shown in Figure 3.13b, the stop of ego-vehicle near the local conflict



zone might cause a human driver makes wrong reaction. This action may consequently lead to potential risk of collision. So here, for safety, we consider the beginning of the global conflict zone as the stop line. In order to import this obstacle into the car following control approach, we consider it as a vehicle who has same properties and parameters with ego-vehicle. This virtual vehicle stopped at the stop line. The position of stop line is detected basing on the positioning systems equipped on ego-vehicle.

### 3.6/ REACTION-TIME BASED COOPERATIVE ADAPTIVE CRUISE CONTROL FOR INTERSECTION

Equation 3.3 represents that the calculation of acceleration is only relative to the distance to leader vehicle, if the reaction time  $\tau$  is constant. For combining the three types of obstacles, it's necessary to define the distance between ego-vehicle and respective obstacle.

- $s_r$ : distance from the real obstacle. It is measured with ego-vehicle's front radar.
- $s_p$ : distance from the virtual preceding vehicle. It is calculated through the estimated position of virtual preceding vehicle that have been discussed in previous section. In order to calculate the distance, we assume that the last message received from the intersection manager contains the distance of virtual obstacle from the start of storage zone that the obstacle vehicle is running on. Actually, there is also another necessary condition that the time stamps of the intersection manager and of the concerned vehicles have already been synchronized.

$$s_p = (x_{fc} - x_f) - (x_{lc} - x'_l + l_l)$$

It's obvious that the value of  $s_p$  may be less than the minimal distance headway  $s_0$ , even be negative.

- $s_c$ : the calculation of this distance depends on the length of storage zone that ego-vehicle is running on, current position of ego-vehicle in relation to start of storage zone and ego-vehicle's length, see Figure 3.16.

From above description, it's clear that the precision of distance mainly depends on the quality of vehicle's positioning system.

In case that the virtual preceding vehicle and ego-vehicle are not running on same lane, the distance of leader from start of local conflict zone may be greater than that of ego-vehicle, see Figure 3.18. In other words, the distance  $s_p$  might be negative. We could also get the Equation 3.2 from this scenario which is impossible in car following model.

So the calculation of ego-vehicle's acceleration is based on all three types of accelerations with respect to the three types of obstacle:

- $a_r$ : The acceleration depended on the detected real obstacle, in other words, the distance obtained from the front radar.
- $a_p$ : The acceleration computed basing on the motion of ego-vehicle's virtual obstacle listed in the sequence.

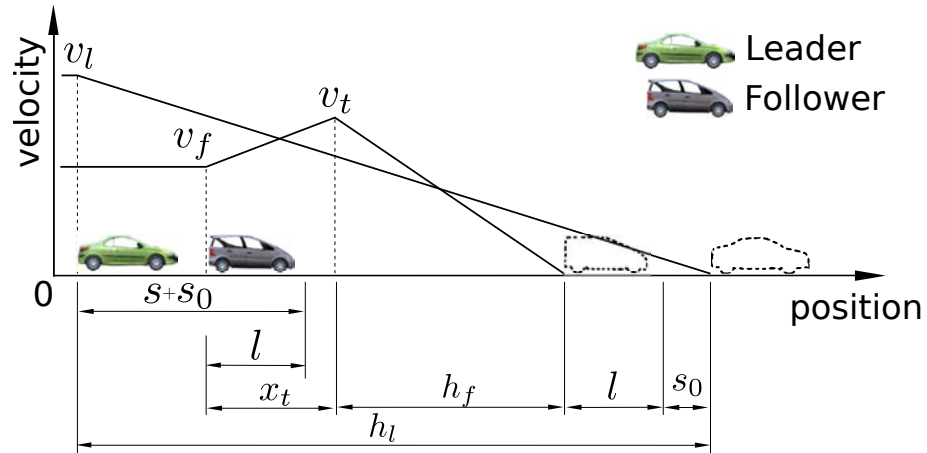


Figure 3.18: Principle of Reaction-Time based Cooperative Adaptive Cruise Control: follower is running before the leader

- $a_c$ : If the vehicle has gained the right-of-way, the value of  $a_c$  is the vehicle's maximal acceleration  $a$ . Otherwise, it is calculated with the virtual obstacle, stop-line.

Firstly, we combine the two types of virtual obstacles to get an acceleration  $a_v$  of virtual obstacle:

$$a_v(v_f, v_l, s_p, s_c) = \begin{cases} a_p, & \text{for } s_p < 0 \text{ or } a_p \leq a_c \\ a_c, & \text{otherwise} \end{cases}$$

where,

$$\begin{aligned} a_c &= a_r(v_f, 0, s_c), \\ a_p &= a_r(v_f, v_l, s_p). \end{aligned}$$

Then we have the final approach named **Reaction-Time based Cooperative Adaptive Cruise Control (RT-CACC)** for vehicle that are approaching the studying intersection:

$$a_f = \min(a_r, a_v) \quad (3.5)$$

In the Equation 3.5, the smallest value will be taken by the follower vehicle. This indicates that, once the distance of virtual preceding vehicle from its respective stop line is larger than that of ego-vehicle, the follower will immediately brake to achieve a safe distance, even if they are running on different lane. In the case that they arrive their respective storages zone at same time and the two storage zones have same length, the follower must brake at the beginning. This leads its following vehicles brake too and consequently decrease the usage of the storage zone.

In order to avoid this lost, another strategy is adapting the follower's velocity when it is near the stop line. Before do this, the follower runs as fast as possible in the storage zone. Figure 3.19 shows the experiment result of this strategy in the scenario shown in Figure 3.16. The result shows an increase of usage of the storage zone. But the follower needs take more time to cross the intersection, because it brakes at the stop line. The process that the follower passes the intersection is also its speeding up process.

The two strategies that the follower vehicle adapts its velocity basing on its virtual preceding vehicle and that the follower reacts with respect to the stop line are not good enough

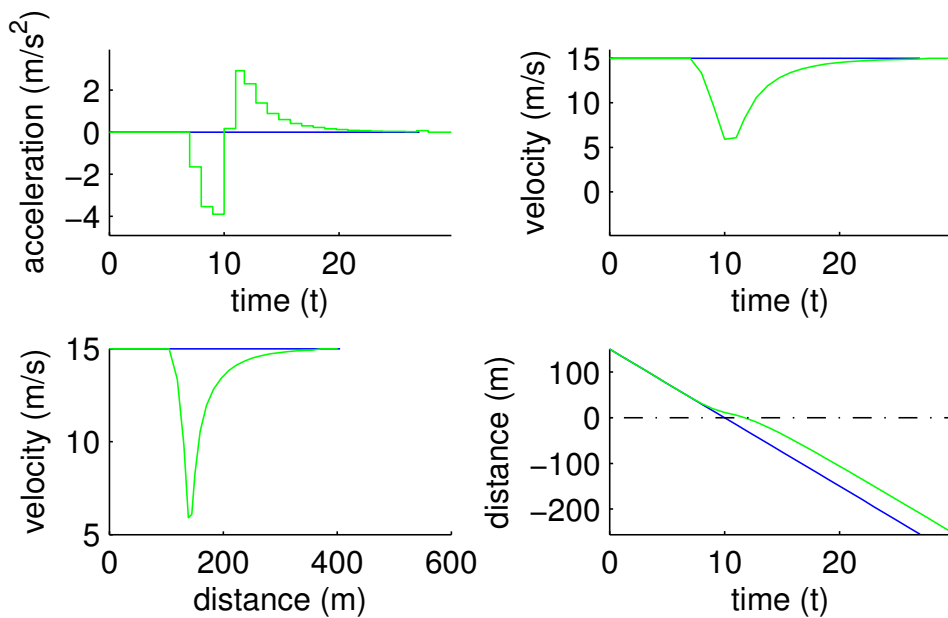


Figure 3.19: Simulation of RT-CACC in the scenario shown in Figure 3.16

in considering both the usage of storage zone and the usage of the conflict zone. In following section, a strategy is proposed to balance both the usage of storage zone and of the conflict zone.

### 3.7/ SMOOTHNESS STRATEGY

#### 3.7.1/ DESCRIPTION OF PROBLEM

As discussed before (see Section 2.4.3), the increase of efficiency of an intersection partly depends on the decrease of the time occupancy of the conflict zone [186]. One of other factors that affects the efficiency of an intersection is the usage of the storage zone.

For sequencing the incoming vehicles, we adapt the simple control policy FCFS (see 2.4.4.1). In the scenario that two vehicles enter two storage zones at same time, according to the FCFS policy, the two vehicles are successively sequenced in the control list that are maintained by the intersection manager (see the *sequence* in Figure 3.12). If the lengths of the two storage zones are same, the two vehicles have the same distance from the beginning of conflict zone. If the lengths are different, the firstly served vehicle might have longer distance from the stop line than the secondly served vehicle. In above cases, in accordance with the strategy Equation 3.5, the second vehicle reacts immediately to achieve a virtual safe distance from the first vehicle, even if they are running on different lane. This is not helpful to the usage of the storage zone. Figure 3.19 shows the other strategy of adapting the vehicle's velocity in the end of the storage zone. It performs better in increasing the usage of storage zone. But it delays the follower's passage of the conflict zone, because of the lower speed of the vehicle, which consequently decreases the usage of the conflict zone.

Basing on the FCFS control policy and the vehicle control method, it is able to estimate the time that the vehicle will spend when it arrives at the stop line. So the problem could be represented as following, see Figure 3.20a:

- The vehicle needs to travel given distance  $s_s$  in given time interval  $t_e$ . In this dissertation, the distance  $s_s$  is the distance of vehicle's front bumper from the beginning of global conflict zone. The time interval  $t_e$  is estimated basing on the number of vehicles that are listed in the sequence before ego-vehicle and that will pass the same LCZs.
- When ego-vehicle arrives at the desired position, it has the desired velocity  $v_t$ . Here, the velocity is the maximal velocity of ego-vehicle  $v_0$ , in order to make sure that ego-vehicle passes the intersection as quickly as possible.

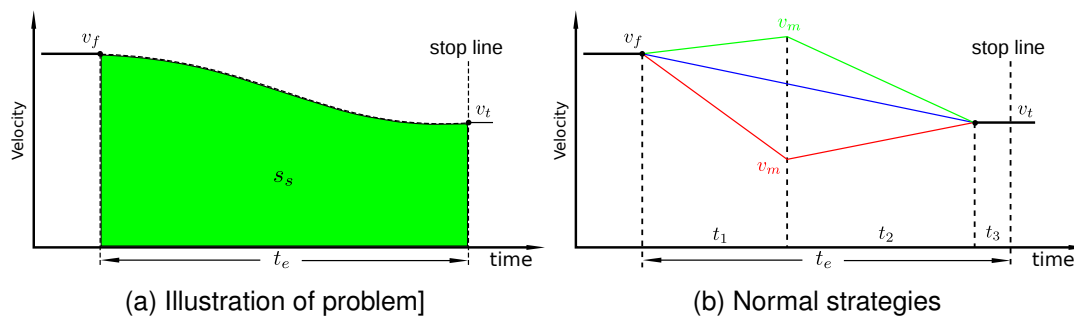


Figure 3.20: Adaptation process in the storage zone

### 3.7.2/ NORMAL SOLUTIONS

In certain case, the ego-vehicle could adapt its velocity at a constant acceleration/deceleration to arrive at the desired position in given time interval and to achieve a desired velocity when it arrives at the desired position (see the blue line in Figure 3.20b). But in general cases, the vehicle could not achieve the two targets during a single adaptation process. The vehicle needs to take two opposite velocity adaptation processes to achieve the two targets simultaneously: accelerate at first and then decelerate to desired velocity (the green line in Figure 3.20b) or brake firstly and then accelerate to the desired speed (the red line in Figure 3.20b). For passenger's comfort, during the adaptation of velocity, the acceleration is generally constant. Here, just the brake-accelerate process is considered.

Because the vehicle has a sample interval  $\tau$ , normally, there is small time interval  $t_3$ , in which the vehicle moves at the desired velocity  $v_t$ , see Figure 3.20b. In some serious scenarios, if the time  $t_e$  is too big and the distance  $s_s$  is too small, the vehicle needs to stop for a while before it arrives at the desired position.

From Figure 3.20b, the relations could be expressed as following:

$$\begin{aligned}
 t_a &= t_1 + t_2 \\
 d_a &= \frac{1}{2}(v_f t_1 + v_t t_2) \\
 t_1 &= \frac{v_f}{-b_f} \\
 t_2 &= \lceil \frac{v_t}{a_f \tau} \rceil \tau \\
 s_s &= (t_e - t_a)v_t + d_a
 \end{aligned}$$

where,  $t_2$  is the acceleration time and is divisible by sample interval  $\tau$ ,  $d_a$  and  $t_a$  are respectively the adaptation distance and the adaptation time,  $a_f$  and  $b_f$  are respectively the acceleration and the deceleration of vehicle during the adaptation process.

For achieving the two targets, as discussed before, there are two simple velocity adaptation ways that are based on when to make the adaptation, see Figure 3.21:

- Adapt at the beginning of storage zone with maximal capacity:  
This strategy could achieve the desired speed  $v_t$  as quickly as possible. After the adaptation, the vehicle moves at the constant velocity until the stop line. Because the vehicle brakes at the beginning, in serious case the vehicle might need to stop for a while, the usage of space between the vehicle and the stop line is low.
- Adapt in the end of storage zone with maximal capacity:  
In this strategy, the vehicle adapts its speed when approaching the stop line. After it obtained the right-of-way, it speeds up to pass the conflict zone. If the vehicle has to stop at the stop line, the efficiency of intersection management will be consequently decreased.

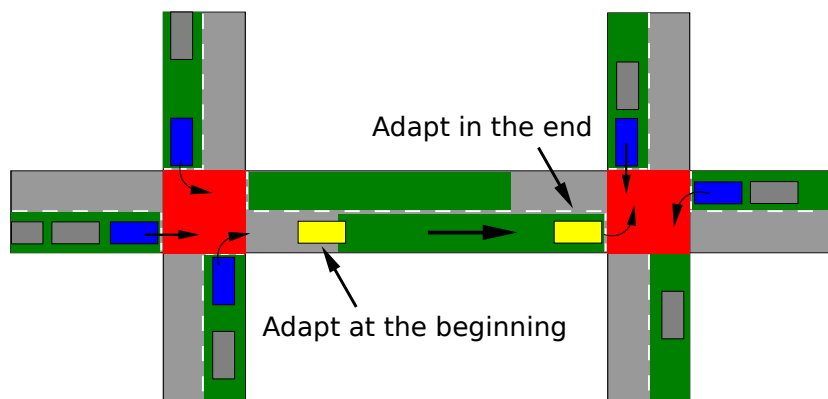


Figure 3.21: Existing two strategies

### 3.7.3/ SMOOTHNESS STRATEGY

In order to increase the usage of storage zone and to partly avoid the stop of a vehicle in the storage zone, we propose a new strategy. The new strategy has two characters: the

speed adaptation process covers ego-vehicle's whole movement in the storage zone, the absolute value of acceleration during the adaptation keeps constant (see Figure 3.22). In this way, the adaptation could be more smooth and could partly improve the usage of storage zone. With smaller deceleration, the space length between vehicle and stop line shortens quickly. A smaller deceleration also helps to improve the passenger's experience. So the new strategy is named as **Smoothness Strategy**.

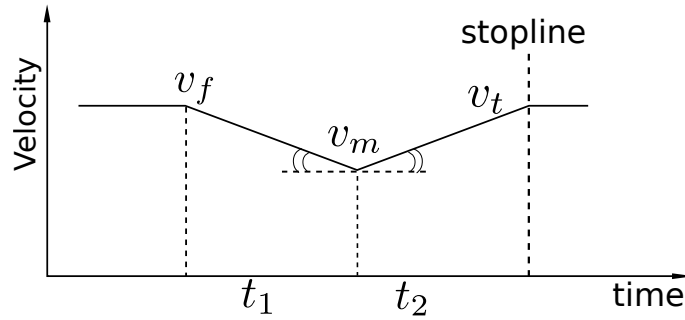


Figure 3.22: Smoothness strategy

From Figure 3.22, we have

$$\begin{cases} v_m = v_f - at_1^* \\ v_t = v_m + at_2^* \\ t_e = t_1^* + t_2^* \\ (v_f + v_m)t_1^* + (v_m + v_t)t_2^* = 2s_s \end{cases} \quad (3.6)$$

where,  $v_m$ ,  $t_1$  and  $t_2$  are respectively the minimal speed during the adaptation process, the brake time and the speeding up time.  $t_e$  is the escape time of ego-vehicle, which is also the estimation time  $t_{el}$  that the leader vehicle will spend for leaving the conflict zone. The calculation of  $t_{el}$  is based on  $t_{el} = \frac{d_{el}}{v_l}$ , where  $d_{el}$  and  $v_l$  are respectively the distance of leader vehicle from the exit point of conflict zone and the current velocity of leader vehicle.

Normally, the follower does not need to stop during the adaptation and has a sample interval  $\tau$ , so the actual braking time should be divisible by  $\tau$ . With the Equation 3.6, the velocity  $v_m$  should be firstly calculated and then the adaptation time  $t_1^*$ . Finally, the possible duration of the first stage could be computed by following equation:

$$t_1 = \lceil \frac{t_1^*}{\tau} \rceil \tau$$

In the first stage, the follower takes the acceleration  $a_1$  that is calculated with  $v_m$  and  $t_1$  until it adapts its velocity to  $v_m$ . In the second stage, the follower considers its distance from the stop line and the expected time that it should arrive at the stop line to adapt its velocity, so as to achieve its maximal speed  $v_0$  when it arrives at the conflict zone.

Figure 3.23 shows the simulation result of smoothness strategy in the scenario described in Figure 3.26 which will be used in the experiment of proposed methods. The simulation just takes a very simple scenario which has two vehicles to show the smoothness strategy. The follower, whose legend is 2, does not consider the right of way. In subplot *absolute-distance*, the dashed line at  $y=100$  is the position of the beginning of storage zone. The dashed line at  $y=200$  is the position of the stop line. The space between the two dashed lines is the storage zone.

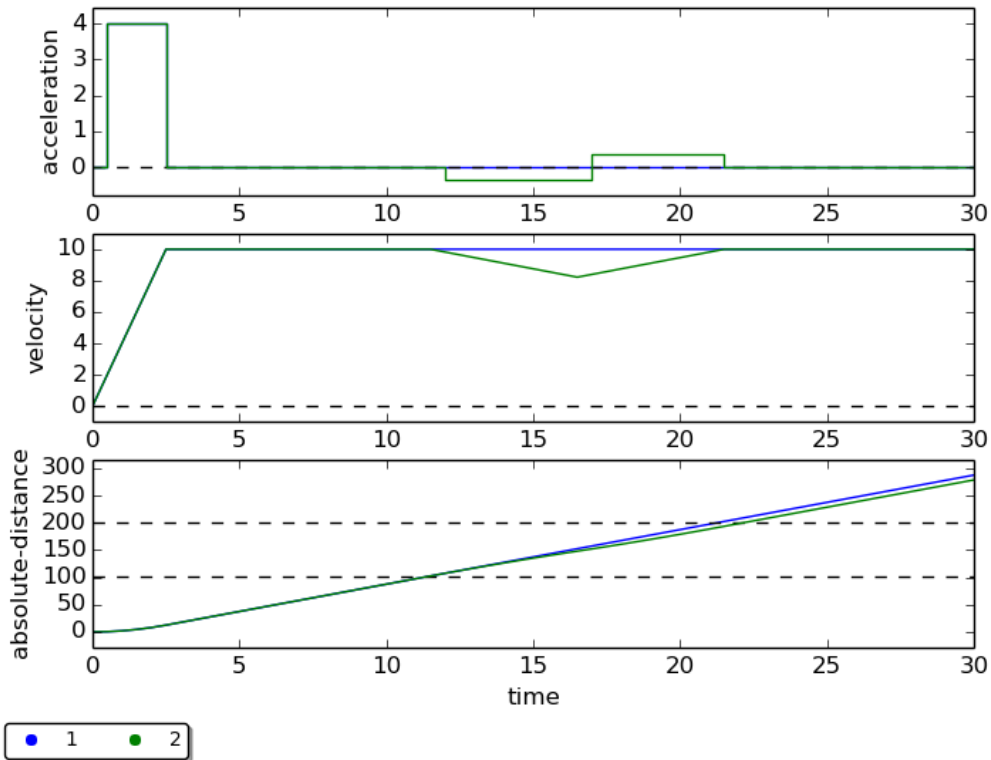


Figure 3.23: Simulation of Smoothness Strategy in the scenario shown in Figure 3.26

The smoothness strategy is combined into the RT-CACC with following strategy:

$$a_f = \begin{cases} \min(a_r, a_{ss}), & a_c > 0 \text{ and stage-1} \\ \min(a_r, a_{ss}, a_p), & a_c > 0, \text{ stage-2 and has right-of-way} \\ \min(a_r, a_{ss}, a_c), & a_c > 0, \text{ stage-2 and has no right-of-way} \\ \min(a_r, a_p), & a_c < 0 \text{ and has right-of-way} \\ \min(a_r, a_{ss}, a_c), & a_c < 0 \text{ and has no right-of-way} \end{cases} \quad (3.7)$$

where,  $a_r$ ,  $a_p$ ,  $a_c$  and  $a_{ss}$  are the accelerations calculated by considering the real preceding vehicle, the virtual preceding vehicle, the stop line and the smoothness strategy. Stage-1 is the first stage of the adaptation basing on the smoothness strategy. Stage-2 is the second stage. For simpleness, the Reaction-Time base Cooperative Adaptive Cruise Control with Smoothness strategy is abbreviated as RT-CACCS in the rest of this chapter.

Figure 3.24 shows the simulation result of RT-CACCS. Before approaching the end of the storage zone, the follower vehicle makes a smooth velocity adaptation. The follower's legend in the figure is 2. In the end, because it has not obtained the right-of-way, it brakes sharply and then accelerates with maximal capacity. When it crosses the stop line, the follower has achieved almost its  $v_0$ .

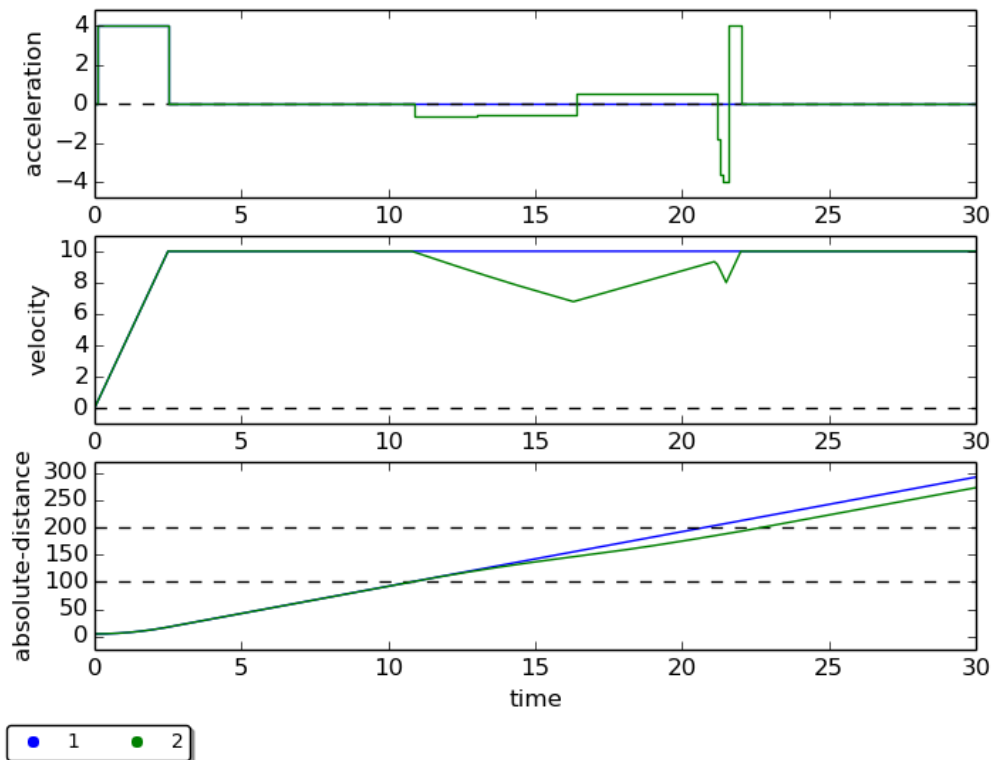


Figure 3.24: Simulation of RT-CACCS in the scenario shown in Figure 3.26

## 3.8/ SIMULATIONS

As discussed in previous sections and shown in the figures of experiment result (such as, Figure 3.19 and Figure 3.24), the longitudinal control method RT-CVC and the strategies of combining the accelerations of different obstacle are proposed to increase ego-vehicle's safety and to synchronize vehicles' velocity. In our opinion, the synchronization of vehicles' velocity helps to improve the transportation system.

In order to observe the motions of vehicle that is controlled by the proposed control method and strategy, we have designed a scenario to simulate the traverse of vehicles at an intersection. We have implemented the test in two forms: under a software simulation platform, with a set of mobile robots.

### 3.8.1/ SIMULATION ON SOFTWARE PLATFORM

In the simulation platform, the test courses is designed as an infinite loop, see Figure 3.25. It consists of two lanes and an intersection. Each vehicle could only take the movement of going straightly at the intersection. The arrows in the figure show the direction of vehicle's movement. At the intersection, there is an intersection manager. It takes the FCFS strategy to serve the vehicles registered in the *sequence*.



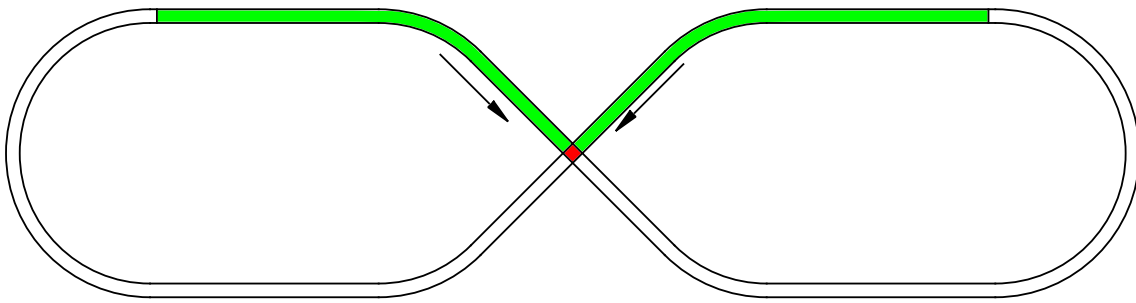


Figure 3.25: Infinite course

A scenario that a cross of two lists of vehicles are approaching the intersection is implemented on this course, see Figure 3.26. There are some assumptions: (1) the only one local conflict zone between the only two movements is the global conflict zone; (2) the lengths of the two storage zones are same; (3) the vehicles have the same initial speed; (4) the platoon of vehicles that are running on same lane has an initial steady state (in other words, the distance between two successive vehicles is a balance gap in accordance with the speed of follower vehicle) before they enter respective storage zone; (5) the vehicles traverse the intersection in accordance with a pre-specified order (see the number labels in the figure). The labels of vehicle indicate that every lane alternately outputs a vehicle to the intersection. In other words, every two successive vehicles, that are listed in the *sequence*, come from different lane.

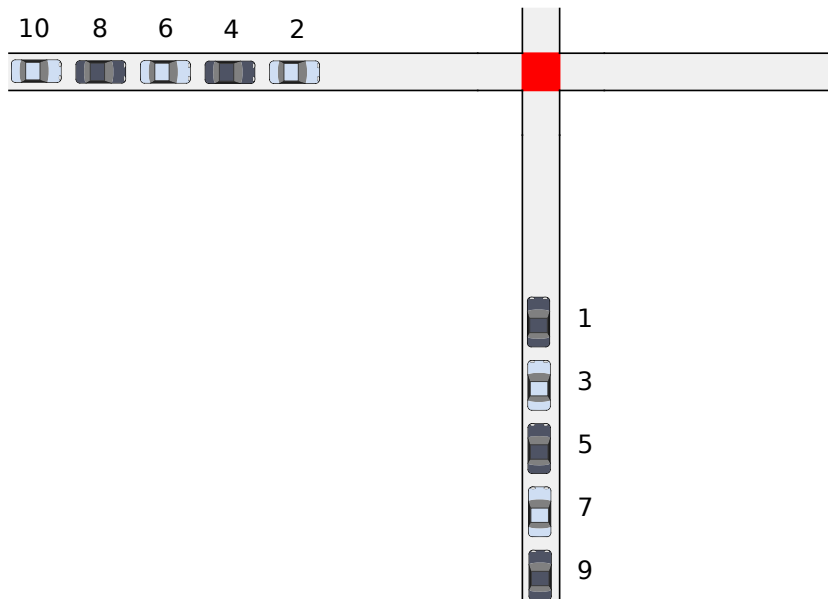


Figure 3.26: Ordered vehicles traverse an intersection

In this section, two types of experiment are conducted. For testing the safety of vehicle, the leader's movement schedule is designed as that it stops at the conflict zone for a while to see the reactions of follower. For the purpose of synchronizing vehicle's speeds, the experiment are conducted with the assumption that each two successive vehicles, for example vehicle-1 and vehicle-2 or vehicle-3 and vehicle-4 in Figure 3.26, enter the

storage zone at same time. In other words, they should be sequenced successively in the *sequence* and have the same distance to the conflict zone.

In following experiments, all vehicles have same acceleration and deceleration capacity:  $a = 4.0 \text{ ms}^{-2}$  and  $b = 4.0 \text{ ms}^{-2}$ . The maximal velocity is  $v_0 = 10 \text{ ms}^{-1}$ . The minimal distance headway is  $s_0 = 2.0 \text{ m}$ . The intersection manager adopts the First Come First Served sequencing policy. Every vehicle adapts its velocity in accordance with the right-of-way, motion of its real preceding vehicle, movement of its virtual preceding vehicle that is listed in the *sequence*. With this adaptation, each vehicle tries to traverse the LCZs at a possible high speed and the specified order. One of the results of this adaptation is that, after the passage of the LCZs, the distance between two successive vehicles that are running on same lane becomes bigger.

### 3.8.1.1/ EXPERIMENT OF SAFETY

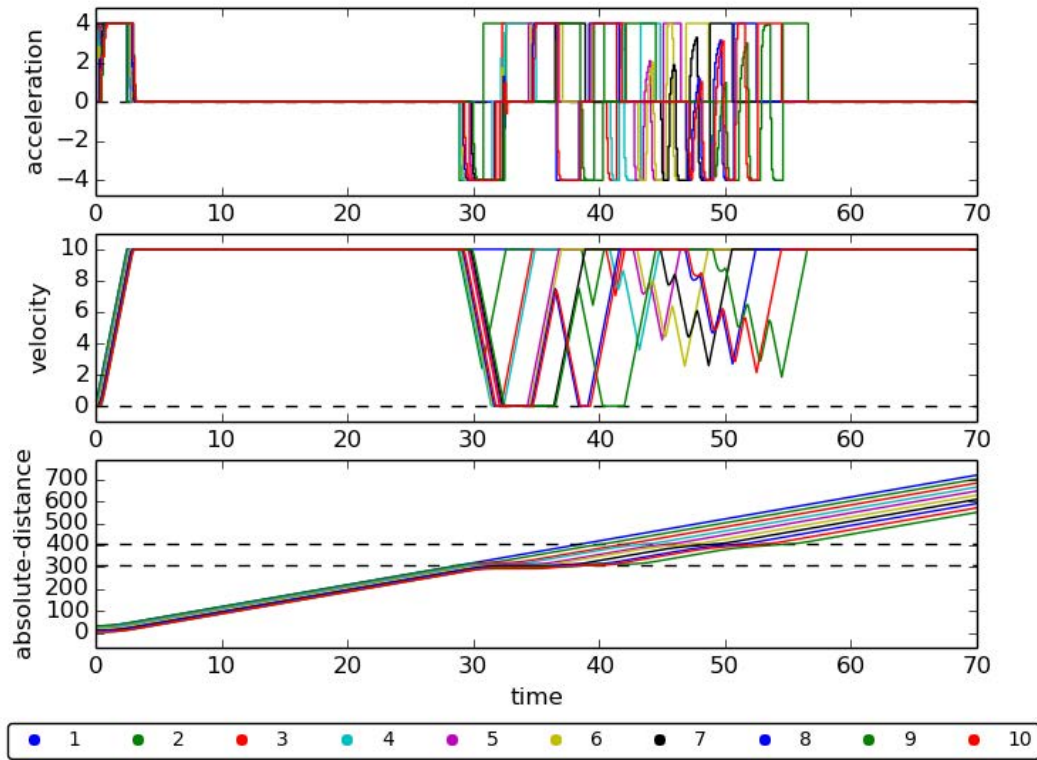
Figure 3.27 shows the simulation of scenario shown in Figure 3.26. All followers are under control of proposed method RT-CACC and they brake immediately once they receive the information of their respective virtual preceding vehicle. The sampling times of all vehicles are same, 0.5 s.

Figure 3.27a shows the experiment result that there is no stop of leader at the conflict zone. In the plot *absolute-distance*, the subplot between the two dashed lines shows the adaptations of the follower in the storage zone. Vehicle's motion depends on the acceleration and the sampling interval. Bigger sampling interval of previous vehicle leads to longer stop of follower before the conflict zone. The control of right-of-way helps to ensure the safety and the specified order of traversing the local conflict zone. Figure 3.27b shows the influence of an unexpected stop of leader vehicle at the conflict zone to the rest vehicles of the *sequence*. In the simulation, the leader vehicle is forced to stop at the conflict zone for a while in order to observe the reactions of follower vehicles. From the experiment result, it is observed that, because of the FSFC control policy, all follower vehicles in the *sequence* stopped in the end of storage zone for waiting the right-of-way. After obtained the right-of-way, the vehicle speeds up and traverse the conflict zone.

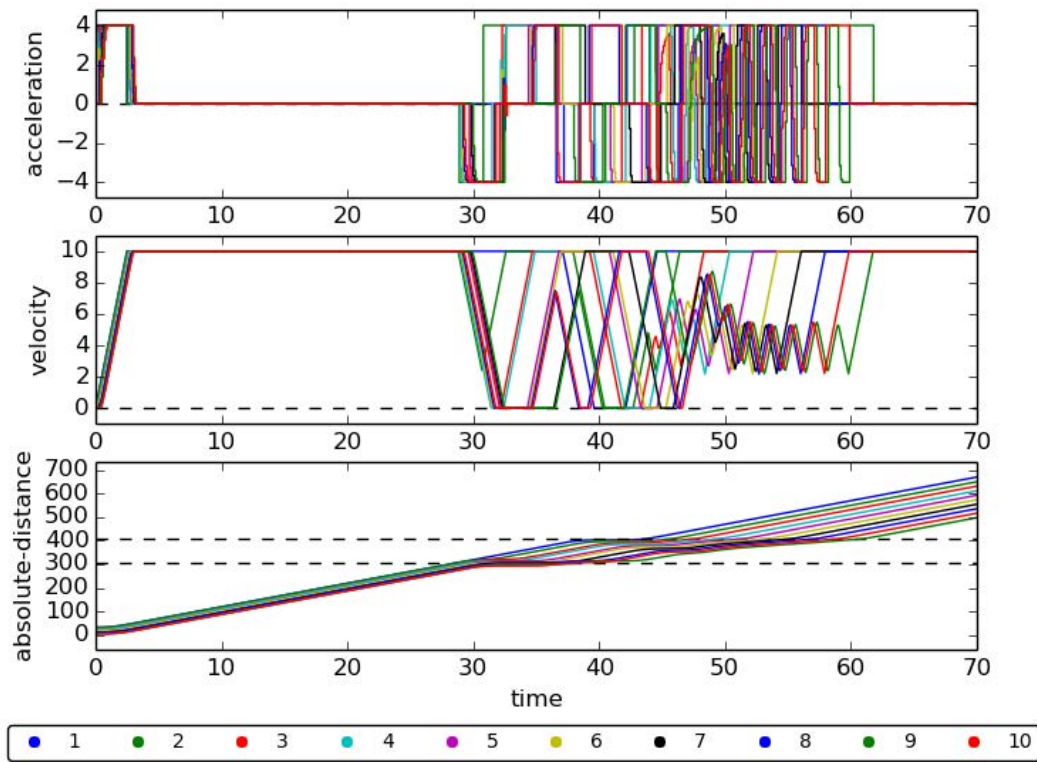
The Comparison of the plots *absolute-distance* of Figure 3.27a and of Figure 3.27b shows that the stop of first vehicle has caused the increase of distance between every two successive vehicles that are running on same lane after they traversed the conflict zone. The brake of followers for waiting the right-of-way is similar to the motion of vehicles that are controlled by the strategy of braking in the end of storage zone.

Figure 3.28 shows the experiment result of the control method RT-CACCS. Except the control method, other parameters are same to the experiment shown in Figure 3.27. Because of the smoothness strategy, all followers adapt their velocity during the whole movement in the storage zone.

Comparing the subplot between the two dashed lines of the plots *absolute-distance* in Figure 3.28 and Figure 3.27, it shows that the smoothness strategy helps to decrease the occupancy of the most part of the storage zone. As discussed in previous section, under the control of smoothness strategy, the follower has to slow down in the end of storage zone if it has no the right-of-way, even if its virtual preceding vehicle has already exited from the conflict zone. This delay of obtaining the right-of-way is mainly caused by the reason that the two successive vehicles arrives at the storage zone at same time. In other

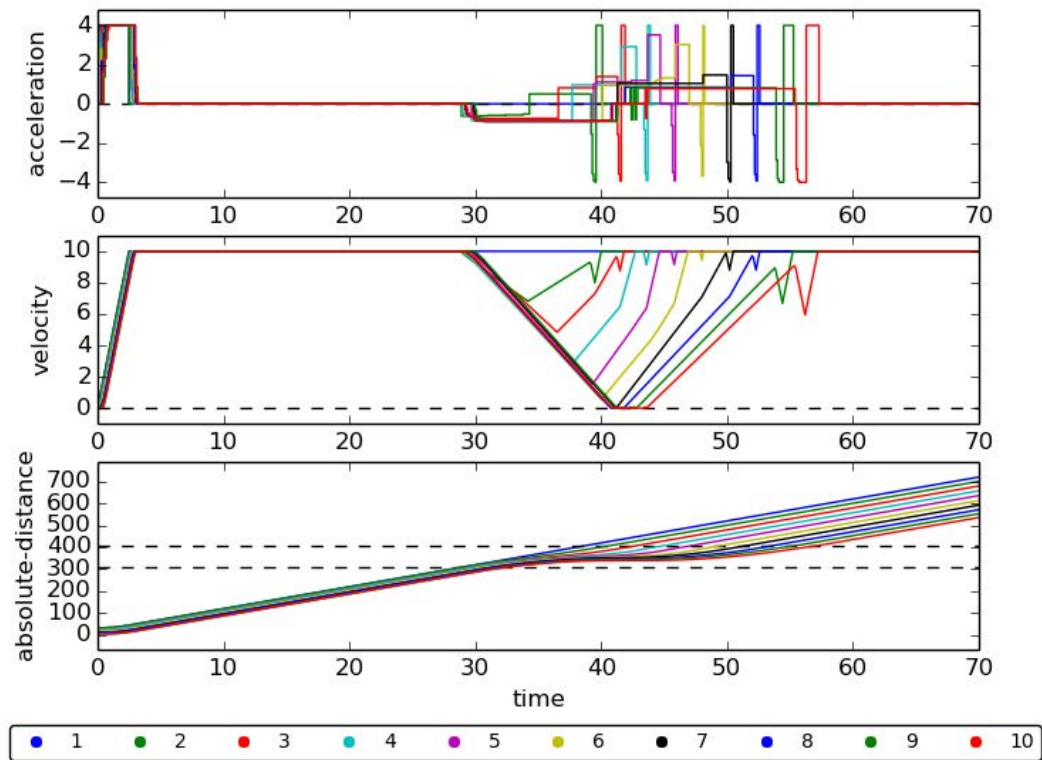


(a) No stop of leader at the intersection

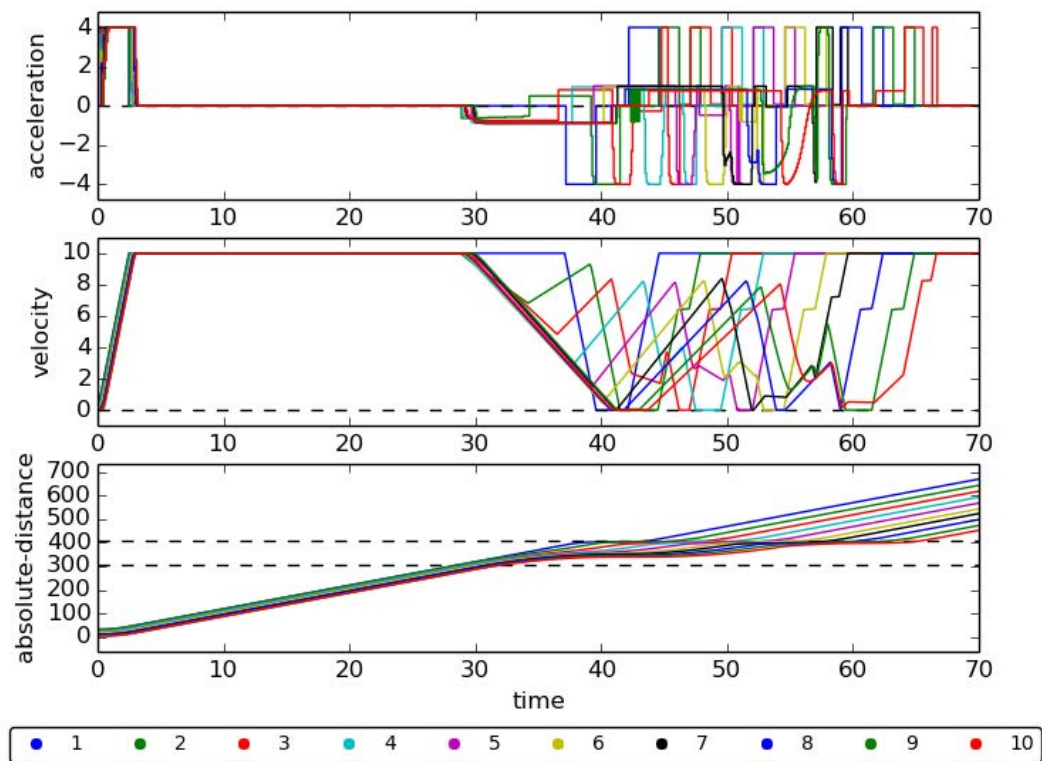


(b) Leader stops at the intersection

Figure 3.27: Experiment of followers' safety under control method RT-CACC and of scenario shown in Figure 3.26



(a) No stop of leader at the intersection



(b) Leader stops at the intersection

Figure 3.28: Experiment of followers' safety under control method RT-CACCS and of scenario shown in Figure 3.26

words, the gap between the two vehicles is less than 0. Because of the synchronization, after the two successive vehicles have passed the intersection, the space between them is almost near to the balance gap. In our opinion, this synchronization helps to improve the flow of vehicles in the transportation network.

### 3.8.1.2/ SYNCHRONIZATION OF VEHICLE'S VELOCITIES

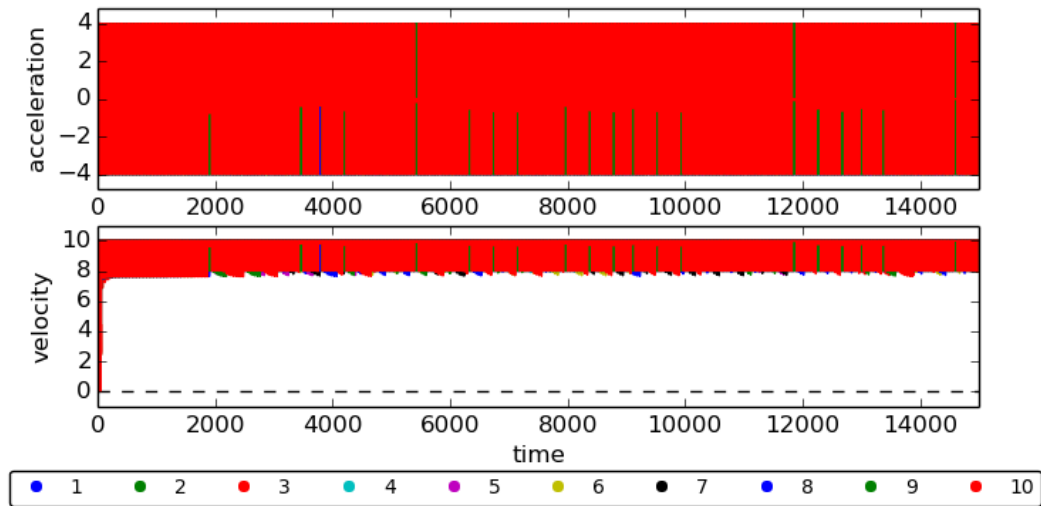
When managing an intersection, an extreme case is that two successive vehicles, that will arrive at the conflict zone of their movements at same time, demand the right-of-way of the conflict zone at same time. Different strategies adapt the follower's speed in different way, for example the three ways discussed in previous sections. They lead to different results of traffic flow in the downstream lanes of the controlled intersection. For example, comparing the Figure 3.27a and Figure 3.28a, the RT-CACC method results a shorter occupancy of the intersection region, including the global conflict zone and the storage zones, and a denser traffic flow than the method RT-CACCS. It helps to increase the usage of the transportation resources. But, in addition to improving the efficiency of an intersection, the intersection management should also consider the influence of ego-intersection's output to the whole transportation network.

The Figure 3.27 and Figure 3.28 shows experiment result of one time of the vehicles' passage at the intersection. In order to observe the synchronization's effect, prolonged experiments of the two proposed methods are conducted to simulate the effects of the two methods to the whole transportation network. Figure 3.29 shows the experiment results.

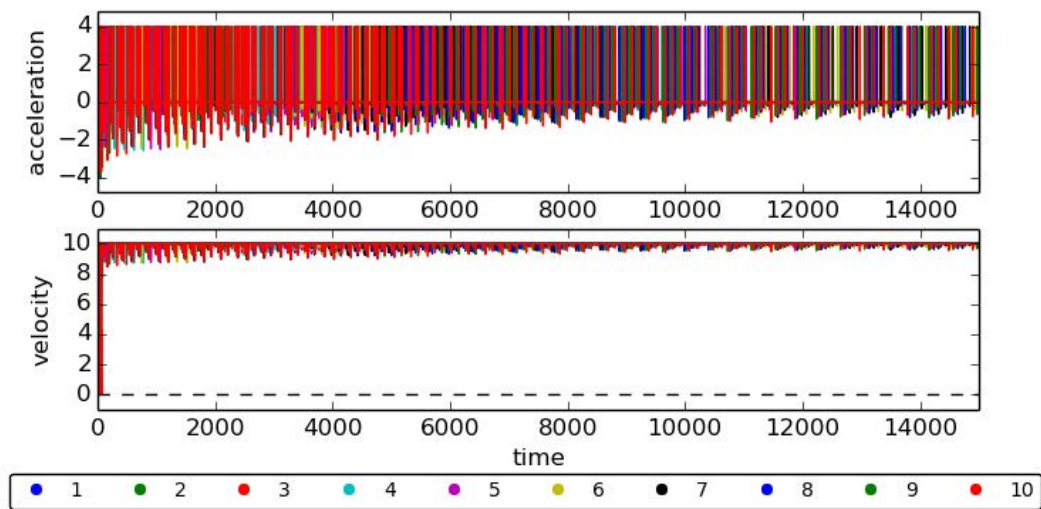
Comparing the two sub figures, it shows that the control method RT-CACCS (see Figure 3.29b and Equation 3.7) makes a better effect on improving the adaptation of follower vehicles' motion during their movements in the storage zone than the RT-CACC method (see Figure 3.29a and Equation 3.5). The RT-CACC method works on the speed of a vehicle at each time the vehicle enters the storage zone. It leads to a constant amplitude of speed adaptation wave, as shown in the plot *velocity* of Figure 3.29b. Meanwhile, the RT-CACCS makes a slow convergence of the amplitude of speed adaptation wave. In our opinion, if a control method could help to improve the movement of a vehicle at an intersection, it is also helpful to the traffic flow of transportation network.

In previous experiments, the adaptation of follower vehicle depends on many factors: the time gap that the two successive vehicles arrive the storage zone, the distance gap between them, the sampling time of follower vehicle and the velocity. The adaptations of the time gap and the distance gap between two successive vehicles are the targets of the proposed methods. Except the two types of gap, the maximal velocity of follower when it leaves the intersection is another target that the proposed methods try to achieve. The RT-CACC with strategy of adapting speed at the beginning of the storage zone and the RT-CACCS both could help the follower to achieve the desired velocity  $v_0$ . So the major factor that affects the result of synchronization is the sampling time of vehicle. Considering the Figure 3.29, the rest of this section is focused on the experiment of the method RT-CACCS with different sampling time. There is also an assumption that the non-storage zone space of each lane is able to contain the synchronized list of vehicles. Because one of the results of synchronization is the enlarged the distance gap between two successive vehicles that are listed in the *sequence*.

Figure 3.30 shows the experiments concerned two vehicles and different sampling time. It shows that smaller sampling time causes a slow but smooth convergence of the ampli-



(a) Prolonged simulation of Figure 3.27a



(b) Prolonged simulation of Figure 3.28a

Figure 3.29: Prolonged simulations

tude of speed adaptation wave. Meanwhile, bigger sampling time helps to converge the adaptation wave to zero quickly. But the speed adaptation wave is not smooth by comparison with result of the smaller sampling time. That is because each follower vehicle reacts to the motion of its preceding vehicle. Each vehicle's adaptation wave spreads one by one in the rest of *sequence*. The superposition of adaptation waves of different vehicle leads to a bigger amplitude of follower's velocity adaptation wave.

Figure 3.31 shows the results of experiment with 10 vehicles. In the experiment of Figure 3.31a, the sampling time is small and the adaptation wave converges almost stably as time goes on. Bigger sampling time leads to quicker convergence of adaptation wave. But, because of the superposition of adaptation waves of different vehicle, the whole wave may be not smooth in a short time range, see the velocities around time 4000s in Fig-

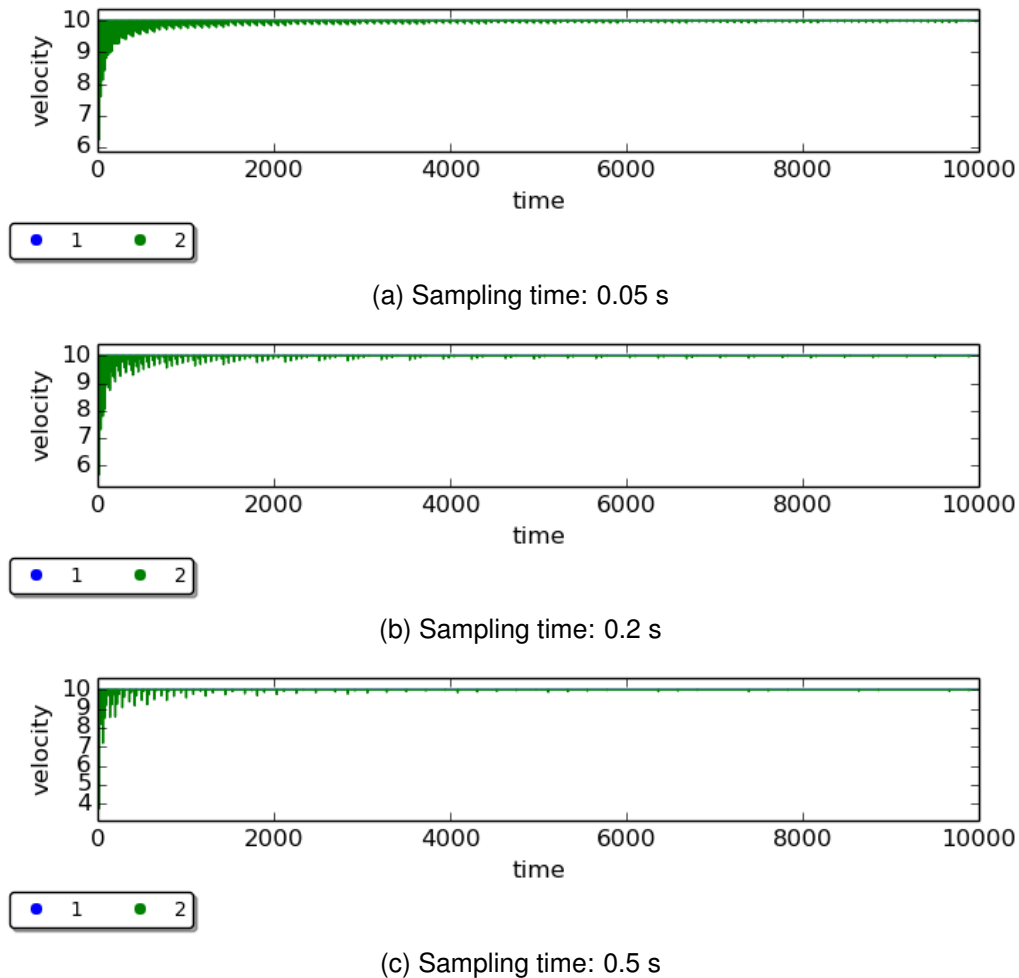
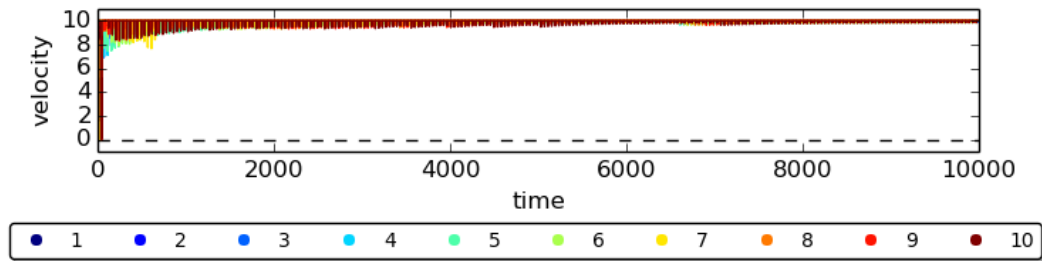


Figure 3.30: Experiment of RT-CACCS with 2 vehicles and different sampling time

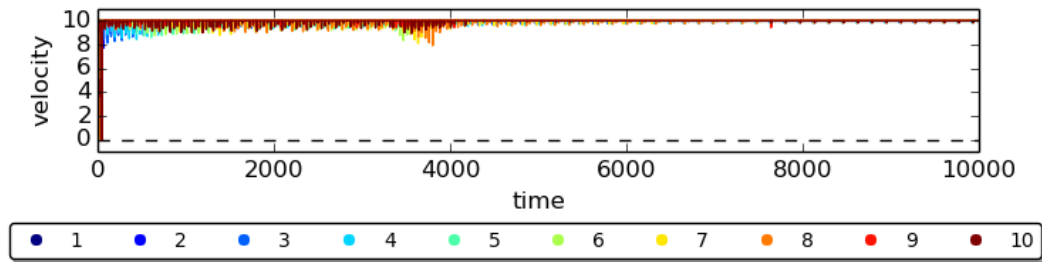
ure 3.31b. Too big sampling time causes to sequence occurrence of the un-smooth wave mentioned above which also slows down the convergence of amplitude of adaptation wave, see Figure 3.31c.

### 3.8.2/ SIMULATION WITH 4 NXT MOBILE ROBOTS

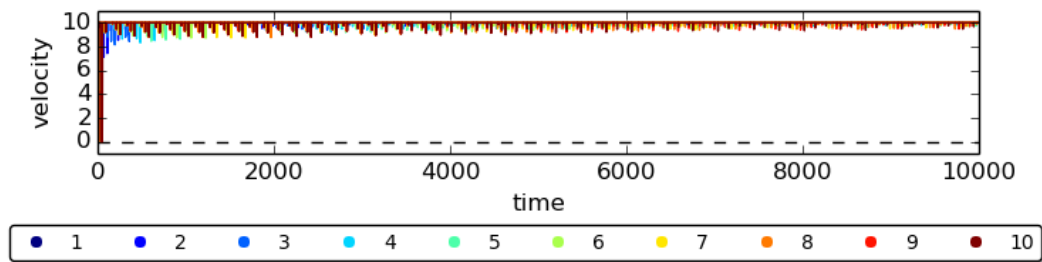
As shown in Figure 3.32, the intersection with NXT robots consists of an intersection which is connected by two lanes, an intersection manager which is an intelligent NXT brick and is not shown in the figure, the 4 NXT robots are considered as 4 vehicles that are approaching the intersection. The black belts represent the two lane. The intersection is located at the cross of the black belts. The blue belts indicate the zones of the intersection. The small red belts indicate the beginnings of respective storage zone. With preset length of storage zone, the size of conflict zone and the on-board positioning system, the robots are able to detect the range of storage zone, the conflict zone and consequently the exit zone. The two short blue belts indicate the enter zones. The manager brick is able to communicate with the 4 robots for distributing the authorization of right-of-way.



(a) Sampling time: 0.05 s



(b) Sampling time: 0.2 s



(c) Sampling time: 0.5 s

Figure 3.31: Experiment of RT-CACCS with 10 vehicles and different sampling time

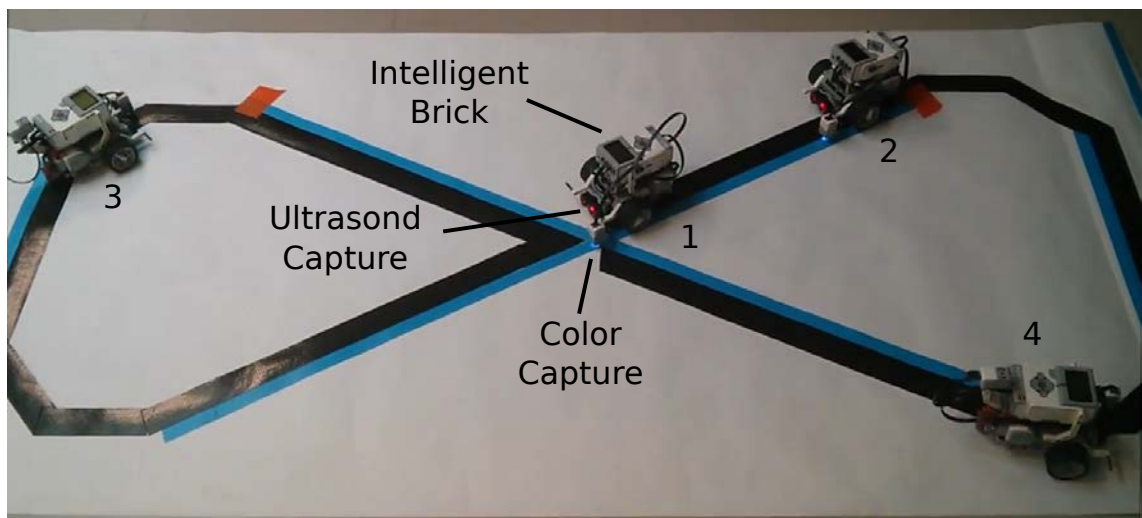


Figure 3.32: Simulation of proposed method in the scenario shown in Figure 3.12



### 3.9/ CONCLUSION

Some of the reasons of vehicle accidents that occur at an intersection could be summarized and then be abstracted to the time interval between the two reactions of ego-vehicle to the actions of previous vehicle. The proposed Reaction-Time based Cooperative Velocity Control (RT-CVC) is developed based on importing the reaction time interval. Comparing with the Intelligent Drive Model (IDM), it helps in avoiding collision with its previous vehicle even if the vehicle brakes with a huge deceleration.

After, the term, obstacle, is introduced for importing the factors belongs the intersection management. By importing the obstacles, the stop line and the virtual previous vehicle that is running on other lane but listed in the *sequence*, the RT-CVC was extend to the Reaction-Time based Cooperative Adaptive Cruise Control (RT-CACC). In order to increase the usage efficiency of the storage zone, the Smoothness Strategy was introduced too. And consequently, the RT-CACC method is extended as Reaction-Time based Cooperative Adaptive Cruise Control with Smoothness strategy (RT-CACCS). The experiments show that the vehicles equipped with the proposed method could traverse the intersection safely if there is an abrupt brake of leader vehicle. The RT-CACCS method does not perform better than the RT-CACC method on increasing the efficiency of an intersection. But it works better than RT-CACC on improving the traffic flow of the whole transportation network.

# FRENET BASED CONTROL

## 4.1/ INTRODUCTION

As one of major functions of the Advanced Driver Assistance System, the lateral control of autonomous vehicle has been studied extensively over the past two decades. Some are already implemented on business vehicles. With the recent boom of self-driving vehicle business, it's obvious that the researches on lateral control of vehicle will continue attracting attention.

The lateral control is carried out by controlling the steering angle. This chapter is focused on developing an Automatic Steering (AS) control method for tracking a given path. In standard AS device operation, the driver could switch the AS device on or off at any time. In this chapter, only the situation that the AC device is activated will be considered. In other words, the automatic steering device tries to keep the vehicle in a safe position in accordance with the given path. During this process, it does not need any intervention from the driver.

In order to carry out the lateral control of a vehicle, the steering control method needs more and detailed information of the vehicle's outside environment: the model of the tracking path and ego-vehicle's relative position to the path. For the lane-change decision, the steering control method requires the well planned trajectory that is already produced by the trajectory planning step in the second stage shown in Figure 2.10. For the lane-keep decision decided in the second stage, the pre-detected road is necessary. This chapter is focused on the most normal lateral control scenario, tracking a given path. So the mainly required information are the detected road model and the relative position of vehicle to the road.

The turns of vehicle at intersection area, particularly at a complex big intersection (see Figure 3.13b), represents a more critical vehicle motion than the movements in other areas of transportation environment. One of the reasons is the turns of vehicles are parallel, one vehicle's abnormal action will immediately affect the vehicles running on neighbor lanes. This chapter is aimed at developing a suitable automatic steering method for controlling vehicle turns precisely in intersection environment along tracking lane. It helps not only to increase ego-vehicle's safety but also to decrease the influence of ego-vehicle's movement to the vehicles running on neighbor lane, especially these vehicles are being driven by human drivers in a hybrid transportation system. So the main concerns of the steering control method proposed in this chapter are the lateral lane offset and the duration of unstable situation.

Because of the importance of detecting tracking path, the comparison of the technologies of road perception and the in-lane location is firstly carried out. Basing on the comparison, the vision-based detecting technology is chosen to satisfy the needs of the proposed steering control method in this chapter. In the third part, the three major types of steering control methods are compared so as to choose the most proper one for developing the new steering control method. In the fourth part, basing on the curve theory and the chosen type of lateral control modeling method, a curvature-based automatic steering control method is proposed. Some comparisons between the proposed method and other existing methods are conducted in end of this chapter.

## 4.2/ PERCEPTION AND IN-LANE LOCALIZATION

The information about vehicle's relative position to the tracking road is the basis of several applications. In particular, for driver assistance systems, it is fundamental to have accurate and robust in-lane localization to derive the parameters required by a lateral control method, but also to have detailed information about the position and number of adjacent lanes to realize complex driving strategies, such as lane change maneuver. In order to recognize lanes near ego-vehicle in a complex road, using on-board sensors to detect road and lanes has been extensively implemented in driver assistance systems. There are two directions to achieve high accurate lane-level navigation: the pre-built high precise lane-level map with global positioning system or the real-time perception based on on-board sensors. It is obvious that pre-built maps could not reflect the temporal changes of road. The more conventional approach is using sensors installed on vehicle for real time perceiving the environment.

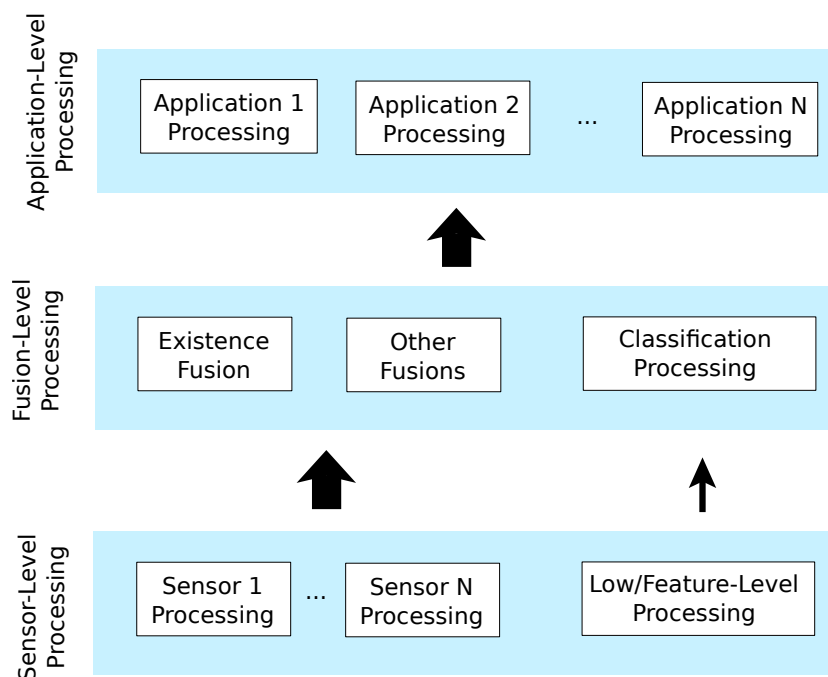


Figure 4.1: System structure for environment perception

Normally, the perception processing is implemented with two steps to gather enough infor-

mation about the environment. The article [164] proposed a three-level fusion architecture for driver assistance system, see Figure 4.1. First, at the sensor-level, the sensor data are analyzed for detecting the existence of objects with some feature-based filter algorithms, for example the Kalman filter tracking algorithms, the Bayes filter [116, 163, 143]. Then, at the fusion-level, the existence probabilities from different sensors are fused to get a higher truthful probability with a sensor-to-global fusion method [176].

Various on-board sensors such as laser scanner, radar, ultrasonic or video camera are employed for perceiving the environment. So it's necessary to compare them so as to choose the proper one for detecting the tracking path and further more to get the vehicle's position relative to the detected path.

#### 4.2.1/ SENSORS

The on-board sensors, for the purpose of perceiving the outside environment of ego-vehicle, are able to detect two types of objects: dynamic objects and static objects [183]. For the steering control, this section only concerns the perception of the tracking lane, one of the static objects.

Various sensors could be used to perform the perception of lane and relative position: LASER radio detection and ranging sensors (RADAR), line sensors, differential GPS (DGPS) sensors, camera and vision sensors and so on.

Before comparing the sensors, a brief survey about the factors that influence the detection of road is helpful for choosing proper sensor. There are two types of factors that affect the detection of road: the constant components that compose the path and the variational outside conditions that influence the detection of path. The road markings and characteristics, as constant factors, may vary not only between areas but also over nearby road, even on the two sides of the same lane. Normally, a lane could be marked by well-defined solid lines, segmented lines, circular reflectors, physical barriers. These markings are the major objects for the perception of road. The road surface could also be comprised of many types of other constant objects: light pavement, dark pavement and various of traffic signs. In addition to these constant components of road, the outside environments of road, for example the weather conditions and the illumination at different time of day, could also have great impact on the visibility of the road markings.

Different types of sensors work extremely well in certain conditions. LASER RADAR could be used to detect the boundary of road with solid objects, for example barriers or circular reflectors, but is helpless in distinguishing different lanes in multi-lanes environment [122]. Line sensor performs well in measuring the accurate lateral error of current position from center line of lane, but is not suitable for computing the distance to lane crossing (DLC) which is based on a look-ahead distance and is used for trajectory forecasting [103]. The DGPS combined with an inertial navigation system (INS) could give a precise global position of vehicle, but it must be related to a high-precision digital map to obtain the lateral errors [50]. The map might be outdated and could not reflect the temporary change of road information, for example road upkeep or traffic road accident. Without the help of digital map, the DGPS could only provide discrete points on the path. Basing on these discrete points, it is not able to construct high-precision road model for the steering control method.

Different from the sensors mentioned above, camera and vision sensor could be able

to provide accurate and actual vehicle position information related to the tracking path [205, 210, 104]. It could be used to detect various road markings without relying on external infrastructures or previously collected road map data. The key strategy of installing vision sensors is making sure that there is no dead zone. In most cases, the important areas are observed by at least two types of sensors with different measuring principles, especially the front and rear of vehicle, for improving the system robustness. From the vision sensor data, the features for locating ego-vehicle could be extracted, such as edge of lane, pavement, road texture and motion vector. For dealing with the outside conditions mentioned before that influence the analytic result, the vision data could be fused with other data from additional sensors in order to get better estimates. These advantages show that the vision sensors are suitable to detect the road environment.

So the hypothetical road model that is used in the steering control method proposed in later of this chapter is based on the vision sensor data. The detections by sensors are the first stage in Figure 4.1. These detected information will be processed in the second stage to obtain more detailed data that are needed by the applications.

#### 4.2.2/ IN-LANE LOCALIZATION

For the lateral control, the most needed information is the road model. There are already many techniques have been developed in order to estimate the tracking path. These techniques deal with the extracted features, such as enhancing, attenuating or culling some of the features, to remove the outliers and finally to obtain an accurate driving road model.

The road features extracted from vision sensing information are used, in combination with predefined simple road models, such as straight lines, clothoid or spline [52, 85], to estimate the road model.

The foreseen application environment and the type of driver assistance system help to choose proper road model. For highway environment, its simple structure may only require a simple road model with very small curvature. The steering control methods, that need a look-ahead, choose the road model basing on the distance of look-ahead to calculate the time to line crossing (TLC). For a small look-ahead, a simple linear road model may satisfy the needs [51]. In the situation of high speed, a spline-based road model may be a better choice for calculating an accurate curvature in forecasting the vehicle's trajectory. In [85], the authors detect the boundaries and mid-line of the driving lane by using the B-Snake.

Basing on the obtained road model, any position and direction, that could be detected in the area of camera, could be considered as accurate reflection of the real road. It is more precise than the position derived from the approximated road model basing on the discrete GPS positions. In [77, 92], the authors estimate vehicle's in-lane position, for example the lateral lane offset (LLO), the heading error between ego-vehicle and the driving path.

#### 4.2.3/ SUMMARY

Comparing with the pre-built high precise digital road map, the on-board sensors are able to detect actual and accurate outside environment information of ego-vehicle and so

as to achieve higher performance of control system. Among the on-board sensors, the vision sensors are the most suitable choice for detecting the road information nearby ego-vehicle so as to estimate the most proper road model. The detected driving road boundaries could be used to construct the center line of lane with some assumptions, for example the two boundaries are parallel. The constructed line is the target path in the following proposed path tracking algorithms. Basing on these information, it is able to calculate the actual position of vehicle in relative to the lane, such as lateral lane offset, heading error. Some concerned positions, for example a target position on tracking path with a look-ahead distance from ego-vehicle, could also be obtained with the road model.

### 4.3/ MODELING METHOD

In my view, the fundamental function of lateral control is driving the vehicle along a given path which could be called as path tracking. The two major applications of path tracking in lateral control domain are lane keeping and lane change. The path tracking support systems have produced notable research results. These systems mainly differ in the employed controller or in the control input variables. The low-control systems normally consider either steering angle as control input, which is called *Steering Angle Control* or steering torque as control input, which is named as *Steering Torque Control*. Many path tracking systems produce the steering torque to control the vehicle's motion [69, 106, 82]. Meanwhile, many research works also have great interest on steering angle control. This chapter is focused on the steering angle control. In order to obtain proper steering angle, it is necessary to build a proper model.

The vehicle could be modeled as realistically as possible, a six-degree-of-freedom (6-DOF) nonlinear model (longitudinal, lateral, vertical, roll, pitch and yaw) or be simplified by linearizing the 6-DOF model with retaining the lateral and yaw motion dynamics, 2-DOF model. The article [19] has implemented an open-loop simulation about the two types of models and shown that both models remain close to each other with abrupt steering input under typical operating conditions. In [134], the authors have compared the two and four wheel steering (WS) dynamic model of CarSim and concluded that the 4-WS system resulted in lower rear path deviation and slid slip angle (at constant radius) than the 2-WS system. The article [34] has also concluded that the front wheel steering model provides the most of performances of 4-WS system. Normally, it is common practice to use relatively simple and sometimes naive control strategies and/or system models for vehicle control. This dissertation would like to focus this section on the front wheel steering vehicle control and do not take into account the deformation of tire and the lateral slip.

The most common model for the lateral dynamics of vehicle is a single track model for the vehicle known as *Bicycle Model*. In the bicycle model, the left and right front/rear wheels are represented by a single wheel. There mainly are three types of interesting vehicle models have been developed: *Geometric Vehicle Model*, *Kinematic Vehicle Model* and *Dynamic Vehicle Model*. So it is necessary to compare the three types of models so as to choose a proper modeling method for the steering control in the intersection area.

### 4.3.1/ KINEMATIC MODEL

Simplifying the vehicle to a kinematic model is a common approximation used for robot motion planning, simple vehicle analysis and deriving intuitive control laws.

Many types of vehicles, such as vehicle for transporting cargo containers in harbor area, are implemented as four-wheel-steering vehicles. When the vehicle is rotating, the center lines of axle of all wheels intersect at an unique point called rotation center of the vehicle [28].

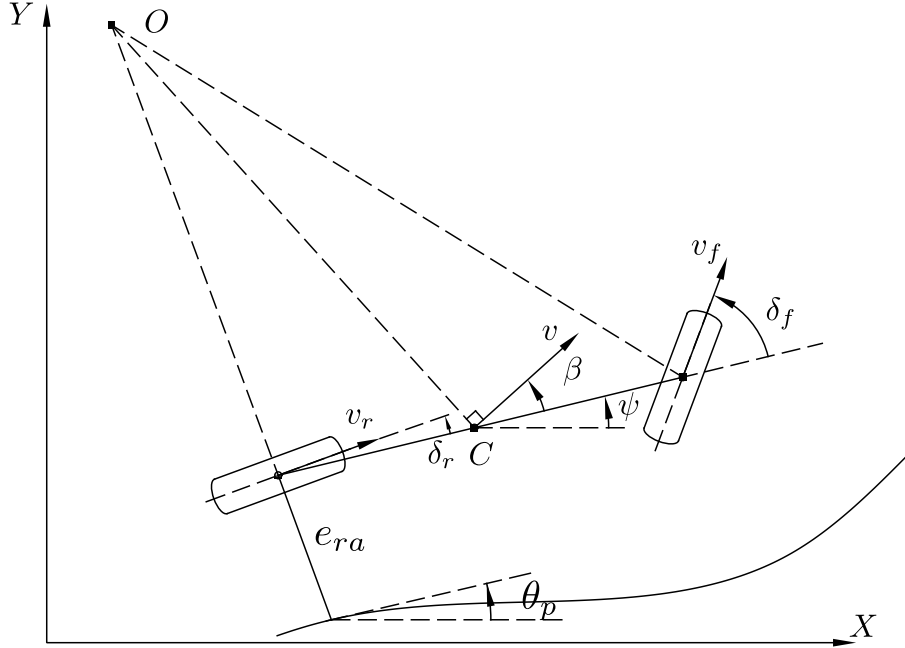


Figure 4.2: Kinematic model

Figure 4.2 shows a kinematic model.  $O$  is the instant rotating center,  $C$  is the reference point of vehicle located at the center of gravity of the vehicle body.  $v_f$ ,  $v_r$  and  $v$  are respective the velocity of front wheel, rear wheel and reference point  $C$ . Their directions are all respectively normal to the directions from their locations to  $O$ .  $\delta_f$ ,  $\delta_r$  are respectively steering angle of front wheel and rear wheel.  $\beta$  is the slip-angle from longitudinal axis of vehicle body to the direction of velocity  $v$ .  $\psi$  is yaw angle, the orientation angle of vehicle with respect to the global X axis.

In [182], basing on the assumption that there is no slip between the wheels and the road, the kinematic relationship is described by following equation:

$$\begin{bmatrix} \dot{X} \\ \dot{Y} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} V \cos(\psi + \beta) \\ V \sin(\psi + \beta) \\ \frac{V \cos(\beta)}{l_f + l_r} (\tan(\delta_f) - \tan(\delta_r)) \end{bmatrix} \quad (4.1)$$

where

$$\beta = \tan^{-1} \left( \frac{l_f \tan(\delta_r) + l_r \tan(\delta_f)}{l_f + l_r} \right)$$

The slip could occurs at both the longitudinal and the lateral directions of vehicle. Increasing speed with the deformation of steering-wheels leads to a significant slip along

the longitudinal direction. Meanwhile, high speed and small turning radius also generate lateral slip. So the assumption indicates that the kinematic vehicle model is reasonable for low speed scenario.

The Equation 4.1 just describes the model of the vehicle itself. In order to track one path, the model needs to be expressed with respect to the tracking path. The article [43] shows a steering control method derived from the kinematic model. In order to connect the path and vehicle, a desired position on the tracking path is chosen. The connection line between the point and the center of rear wheel is perpendicular to the direction of vehicle. And then, it takes into account the length of the connection line  $e_{ra}$  and the global tangent direction  $\theta_p$  of path at the selected position.

#### 4.3.2/ DYNAMIC MODEL

When running at a high speed or there is a sharp steering angle input, the vehicle may significantly deviate from the planned trajectory, because of the centrifugal force. Consequently, lateral slip between wheels and road occurs with respect to the increasing of vehicle's lateral velocity. At high lateral velocity, the slip becomes large enough to impact the stability of system. This would lead to skids and collisions. So it is necessary to create high fidelity model for studying vehicle motion by taking into account the lateral velocity.

Figure 4.3 shows the dynamic model by placing the kinematic vehicle model (Figure 4.2) in the road environment with vehicle's mass and the tire forces. Basing on considering different state variables of vehicle, there are two common types of dynamic vehicle models for tracking path [182]: **dynamic model in terms of error** with respect to path, **dynamic model in terms of yaw rate and slip angle**.

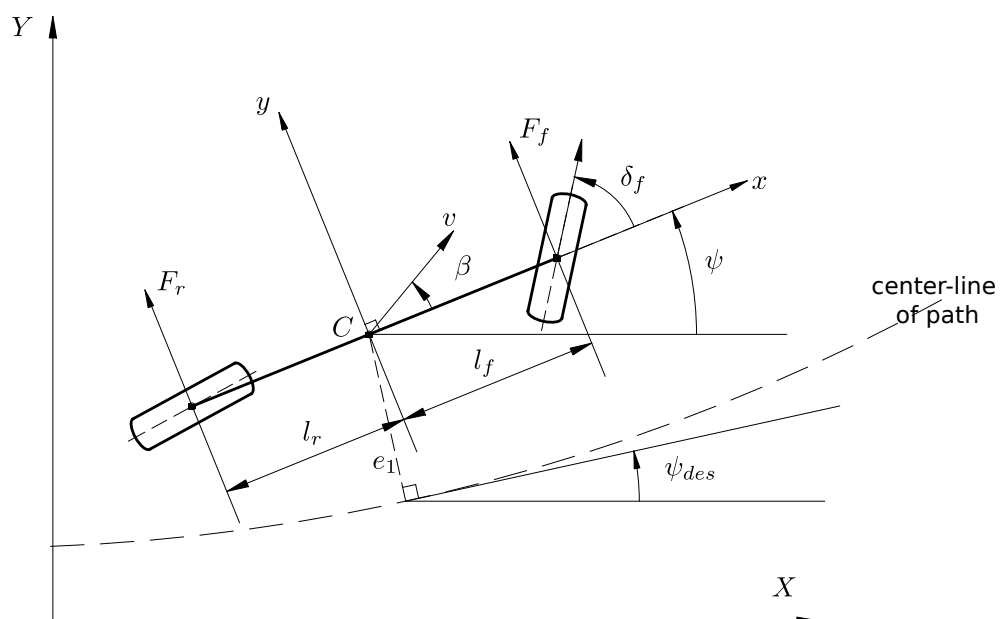


Figure 4.3: Dynamic model of vehicle

$[X, Y]$  is inertial coordinate,  $[x, y]$  is body-fixed coordinate located at center of gravity of vehicle.



#### 4.3.2.1/ DYNAMIC MODEL IN TERMS OF YAW RATE AND SLIP ANGLE

The dynamic model in terms of yaw rate and slip angle considers the slip angle  $\beta$  and yaw rate  $r = \dot{\psi}$  as state variables. The dynamic model is expressed as following equations:

$$mv_x \left( \frac{d\beta}{dt} + r \right) = F_f + F_r + F_{bank}$$

$$I_z \ddot{\psi} = F_f l_f - F_r l_r$$

where,  $m$  is the vehicle's mass,  $v_x$  is the vehicle's longitudinal velocity,  $F_f$ ,  $F_r$  are respectively the forces at front and rear tires,  $F_{bank}$  is the force with respect to the road bank angle at position  $C$ ,  $I_z$  is the yaw moment of inertial,  $l_f$ ,  $l_r$  are respectively the distance of front and rear axle from the center of gravity  $C$ .

#### 4.3.2.2/ DYNAMIC MODEL IN TERMS OF ERROR

The dynamic model in terms of error with respect to the tracking path are described with state variables in terms of position and heading error of vehicle respect to the center line of given path [32]. So the kinematic model, Figure 4.2, could be re-defined in terms of variables:

- $e_1$ , the distance of  $C$  from center-line of given lane. As shown in Figure 4.2, the steering angle has a direction, so the signs of the value of distance are different in accordance with the position of vehicle with respect to the center-line of given path.
- $e_2$ , the heading error of vehicle with respect to the center-line of tracking path  $e_2 = \psi - \psi_{des}$ , as shown in Figure 4.3.

Referencing to Figure 4.3, the dynamic model could be expressed as followings:

$$\dot{\psi}_{des} = \frac{V_x}{R} \quad (4.2)$$

$$\ddot{e}_1 = (\ddot{y} + V_x \dot{\psi}) - \frac{V_x^2}{R} \quad (4.3)$$

$$e_2 = \psi - \psi_{des} \quad (4.4)$$

where, Equation 4.2 is based on an assumption that the vehicle moves at constant longitudinal velocity  $V_x$  along the center-line of path whose instant radius is  $R$ . Another assumption of Equation 4.2 is the small angle assumption theory. Equation 4.3 is the centripetal acceleration of vehicle [32].

The dissertation [140] showed a detail process of rewriting this model, with assumption that the steering angle of rear wheel  $\delta_r = 0$ , as an optimal control model with feed forward term (Linear Quadratic Regulator with Feed Forward, LQRwFF):

$$\dot{x} = (A - B_1 K)x + B_1 \delta_{ff} + B_2 \dot{r}_{des} \quad (4.5)$$

where,

$$x = (e_1, \dot{e}_1, e_2, \dot{e}_2)^T,$$

$\dot{r}_{des}$  is the desired yaw rate calculated with the current path curvature and the vehicle speed.

The steering angle input of front wheel  $\delta_f$ , rewritten as  $\delta$ , is:

$$\delta = -Kx + \delta_{ff} \quad (4.6)$$

### 4.3.3/ GEOMETRIC MODEL

As one of the popular classes of path tracking models, the geometric models consider the geometric relationships between the vehicle and the tracking path to obtain control law solutions for the path tracking problem [25, 109]. One obvious feature of this type of model is the considered target position located on the tracking path. This position is used to measure the heading error of vehicle and the distance from that position. The kinematic vehicle model in Figure 4.2 could be simplified to the geometric model basing on two limitations, vehicle only moves on a plane and the rear wheels are fixed. Figure 4.4 shows the illustration of geometric model.

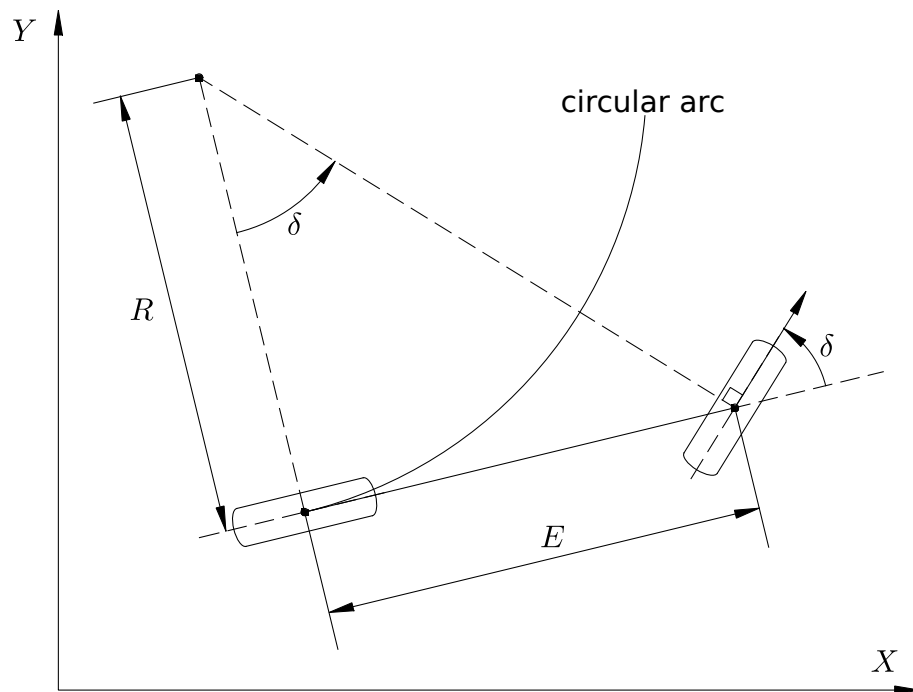


Figure 4.4: Geometric vehicle model in [140]

In accordance with Figure 4.4, the fundamental relationship between the front wheel steering angle and the radius of curve that the vehicle will follow during its movement could be expressed as following:

$$\tan(\delta) = \frac{E}{R} \quad (4.7)$$

where  $\delta$  is the steering angle input,  $E$  is the wheelbase,  $R$  is the radius of the circle that the concerned point on vehicle, such as the gravity center or center point of rear or front axle, will travel along with given constant steering angle  $\delta$ . In Figure 4.4, the concerned point is the center of rear axle. From above figure, it is obvious that this type of model does not consider the slip between vehicle and road and the deformation of tires. Similar to kinematic model, it approximates the motion of vehicle well at low velocity and moderate

steering angle. At high speed or big steering angle, partly because of the deformation of tire and slipping of wheels, the motion of rear wheel is not a circle.

Equation 4.7 indicates that the processing of its implementation in path tracking problem is how to get the value of  $R$ , further more is how to get the value  $E/R$ . Different ways of determining the mentioned value generate various methods, for example **Pure Pursuit Algorithm** [25] and **Stanley Method** [109].

#### 4.3.3.1/ PURE PURSUIT ALGORITHM

The difference among pursuit algorithms is how to deal with the target point located on the tracking path [53, 25].

In order to obtain the  $R$  in Equation 4.7, as shown in Figure 4.5, the pure pursuit algorithm locates the concern point on the center of rear axle. The rear wheels are not steerable. The circular arc cross the concerned point  $(x_v, y_v)$  and the target point  $(x_t, y_t)$  on tracking

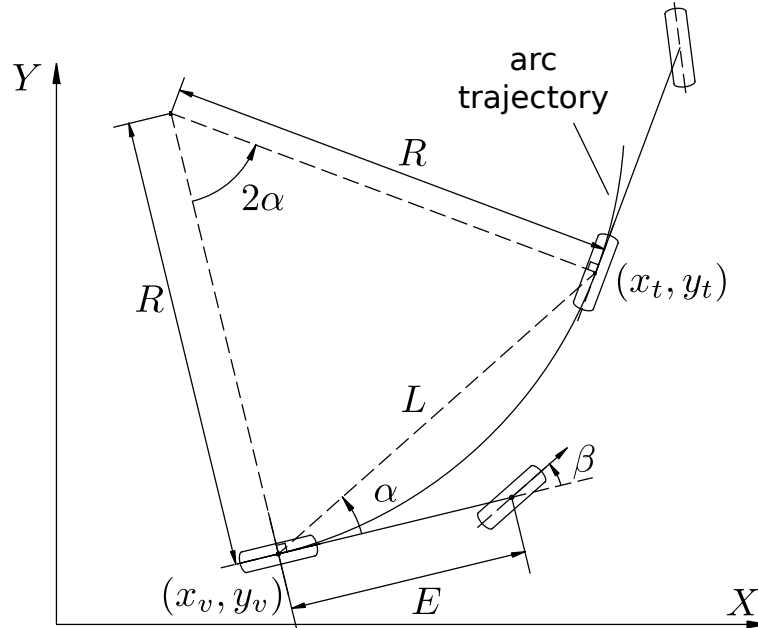


Figure 4.5: Pure pursuit algorithm

path. The extension of center line of rear axle passes the center of the assumed arc. The relationship between variables shown in Figure 4.5 could be expressed as following:

$$\frac{2L}{\sin(2\alpha)} = \frac{R}{\sin(\frac{\pi}{2} - \alpha)} \quad (4.8)$$

Substituting  $R$  with Equation 4.7, the desired steering angle obtained from the pure pursuit algorithm is:

$$\delta(t) = \arctan\left(\frac{2E \sin \alpha(t)}{L}\right) \quad (4.9)$$

where  $L = \sqrt{(x_t - x_v)^2 + (y_t - y_v)^2}$  is the distance between current position of vehicle and the target position.

The pure pursuit algorithm commands the vehicle to follow the circular arc that brings the vehicle close to the line between the vehicle's current position and the target position. The tracking path, for example detected in section 4.2, is no longer necessary. The trajectory of vehicle is computed only through the selected target point. The key point of the algorithm is choosing a proper target position on the tracking path. The correctly chosen target point could cause minimal lateral lane deviation (LLO). This consequently decreases the risk of collision. On the other hand, because of the characteristic of circular arc, the pursuit of small LLO would prolong convergence of LLO to zero.

#### 4.3.3.2/ STANLEY METHOD

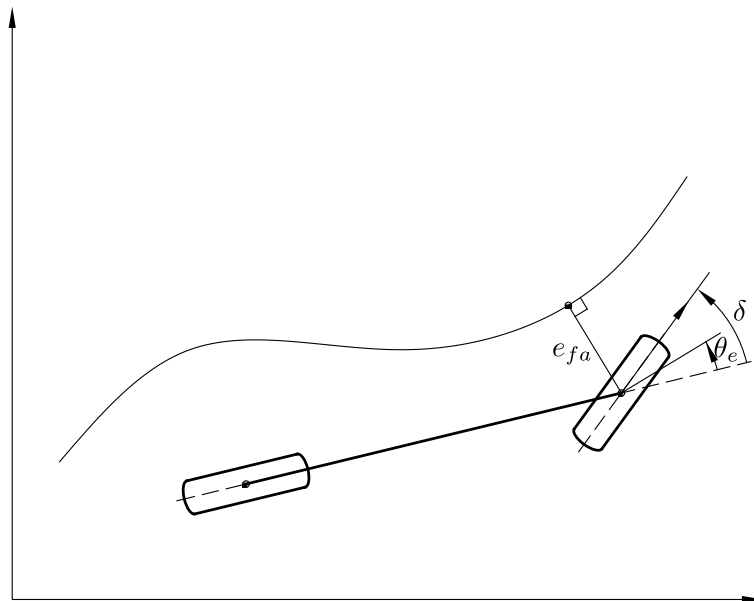


Figure 4.6: Stanley method

As the steering control law of autonomous vehicle that won the DARPA Grand Challenge, the Stanley method attracts many attentions in the lateral control domain. Basing the simple kinematic model, shown in Figure 4.6, the basic Stanley method is given by:

$$\delta(t) = \psi(t) + \arctan\left(\frac{kx(t)}{u(t)}\right) \quad (4.10)$$

Its key error metric is the cross-track error  $x(t)$  measured from the center of steerable front axle to the nearest point  $(x_p, y_p)$  on tracking path. The term  $\psi(t)$ , orientation of path at the nearest point and is measured with respect to the vehicle's own orientation, makes the front wheel parallel to the tracking path at the nearest point, in the absence of lateral lane offset  $x(t)$ . The second term shows that the degree of steering response toward the tracking path depends both on the cross-track error  $x(t)$  and the speed  $u(t)$  at the orientation of front wheel.

#### 4.3.3.3/ COMPARISON AND CONCLUSION

Each type of above mentioned vehicle control methods has respective characteristics. These features determine respective proper application scenario.

As discussed in previous section, the basic assumption of kinematic model, no slip between wheels and road, decides that it should only be applied in low-speed scenario. The friction coefficient between wheel and ground as well as the tire properties limit the maximal lateral velocity for stability. As opposed to the low-speed limitation of kinematic model, the dynamic models are suitable for applying in high-speed and/or high turning curvature scenario.

In article [150], a steady-state cornering test about the kinematic vehicle model and the dynamic vehicle model in terms of yaw rate and slip angle, was implemented with different constant velocity. The test result showed that the kinematic model is suitable for low-slip scenario while the dynamic model should be applied in high-slip environment.

Based on more comprehensive simulations of the three types of vehicle models, the article [140] gave more detailed description of application scenarios of these vehicle models. The dynamic model breaks down in very-high speed scenario. The dynamic properties of tire and suspension of vehicle influence the performance too. The detailed comparison of computation time made in the article [107] shows that the dynamic model costs much computation time than the kinematic model. This is also a limitation of application of dynamic models.

The geometric methods achieve the majority of path tracking performance, even if they are simple to understand and implement. The methods need few quantity of inputs comparing with the two other types of models. The path model and in-lane position of vehicle that detected through vision sensors are normally enough to the geometric methods. Meanwhile the simple equations of geometric methods imply the lower computational cost.

The characteristics of geometric methods indicate that it requires few on-board sensors and few computational resources. These mean that the methods are easy to implement on vehicle and consequently suitable for commercial vehicles. So the proposed steering control method in remainder of this chapter is partly derived from the simple geometric model shown in Figure 4.4.

## 4.4/ FRENET BASED CONTROL

At the beginning, it is helpful to have a brief recognition of the target application environment. In modern city, most part of roads compose of straight segment and regular curvature, especially in the area of intersection. In modern differential geometry theory, a "small range" of any curve could be considered as a simple curve. So the curvature segment of road could be simply approximated as circular arc(s). Particularly, the lane of vehicle turns at intersection could be simplified as ellipse arc [147]. So the proposed steering control method here is partly derived from the geometric model (see Figure 4.4).

Before proposing the new lateral control method of vehicle, it's necessary, at first, to describe the studying vehicle's motion model. Then the proposed method is divided into two terms for different purposes: fitting the curve and forcing the vehicle to approach

the center-line of tracking path. The fitting curve term is derived from the fundamental theory of curve to fitting vehicle's trajectory in with the tracking path. The term of forcing convergence is derived from the Pure pursuit method.

From previously discussed path tracking methods in section 4.3, the target of steering control method is to minimize the lateral lane offset and heading error between vehicle and the tracking path. In this section, all the discussions are based on following assumptions. The accurate and actual road model is already detected in the perception step, see the section 4.2. And the two parameters, the lateral lane offset which will be renamed as the deviation for simplicity and the heading error, are already obtained. The motion plane of ego-vehicle is same to that of the tracking path. All positions, for example positions of ego-vehicle, target positions concerned by the proposed methods, are located on the same plane. In other words, all informations about the tracking path are accurate.

#### 4.4.1/ STUDIED VEHICLE MODEL

There are already many models about vehicle's motion. As shown in Figure 4.4 and Figure 4.5, the geometric algorithms, such as Pure Pursuit method, take into account the motion trajectory of rear wheel and the steering angle of front wheel. So, in this chapter, we adopt the following vehicle bicycle model (see Figure 4.7) for simulating the vehicle's movement. The model does not consider the deformation of tire. And there is no lateral slipping in the model.

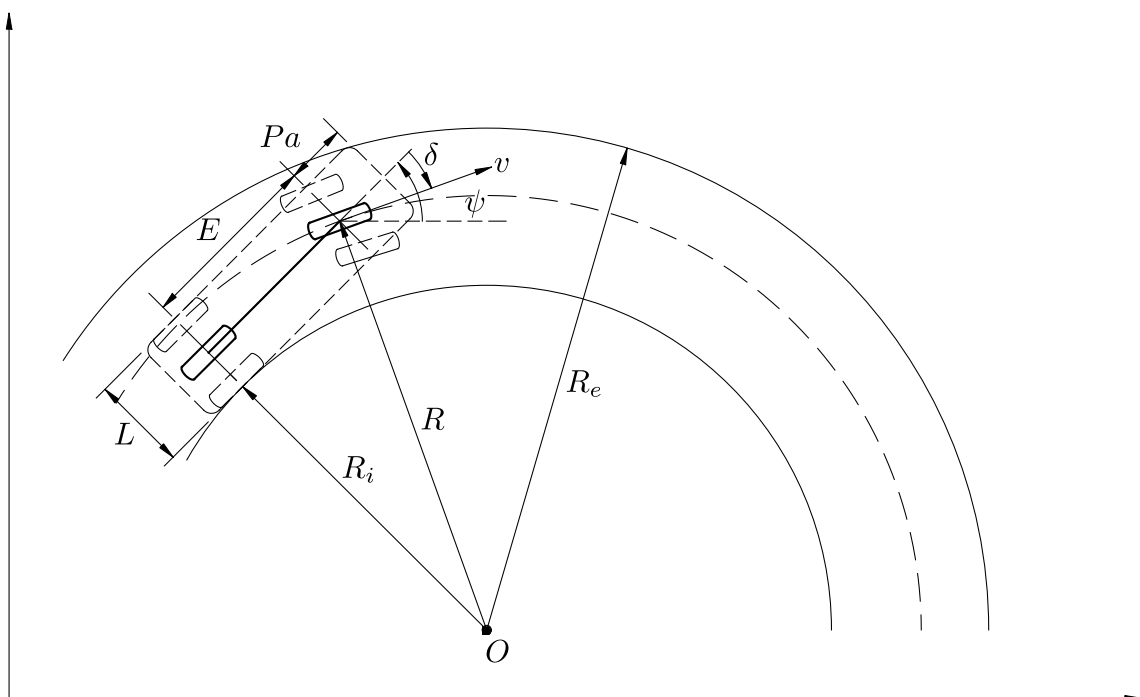


Figure 4.7: Vehicle model for estimating trajectory boundary

The velocity direction of front wheel  $v$  is just the direction of front wheel.  $\psi$  and  $\delta$  are respectively the direction of vehicle and the steering angle of front wheel. They are signed. Basing on before assumptions, the rigid body moves, with a constant steering angle input, along a circular arc. The reference point  $C$  is defined at the intersection of mid-plane of the virtual front wheel and the front wheel axle.  $Pa$ ,  $E$  and  $L$  are respectively the front

overhang, the wheelbase and the width of vehicle body.  $R_e$  and  $R_i$  are respectively the outside radius and the inside radius of vehicle's turning trajectory. The center point  $O$  locates on the extensions of the center line of rear axle. This is a character of the geometric model theory, see Figure 4.5.  $R$  is the turning radius of front wheel of the bicycle model with respect to the turning center  $O$ .

This model will be used in the proposed steering control method for calculating the steering angle. It is also employed by the simulation platform that is developed during this thesis to calculate the boundary of the vehicle's trajectory. The boundary information could be used in many aspects. For example, it could be used in detecting collision between other vehicles or infrastructures, such as the stop line that be concerned in the longitudinal control method proposed in section 3.5.2. The model is also used to forecast the vehicle's trajectory with constant steering angle input for avoiding collision with boundary of driving lane.

Referencing to Figure 4.7, the turning radius can be expressed as followings:

$$R = \frac{E}{\sin \delta} \quad (4.11)$$

$$R_e = \sqrt{\left(\sqrt{R^2 - E^2} + \frac{L}{2}\right)^2 + (E + P_a)^2} \quad (4.12)$$

$$R_i = \sqrt{R^2 - E^2} - \frac{L}{2} \quad (4.13)$$

In the simulation platform of this dissertation, the Equation 4.11 is used to calculate the instant turning center  $O$ . And the turning radius of rear wheel of the bicycle model in Figure 4.4 is  $R_i + \frac{L}{2} = \sqrt{R^2 - E^2}$ .

#### 4.4.2/ CURVATURE TERM

The most common driving scenario is tracking a path which has a very small curvature especially the straight path. The movement of vehicle is regarded as a safe situation when the orientation of vehicle is same with the direction of tracking path, even if there is a lateral lane offset which does not cause collision between ego-vehicle and the ones running on neighbor lanes. In other words, the heading error between vehicle and tracking path plays a key role to the stability of steering control method. In [140], the experiments of Stanley method, Equation 4.10, conducted on the Figure Eight Course could partly show the effect of heading error on stability. Basing on the modern differential geometry of curves theory [99], the curvature term focuses on fitting the trajectory of vehicle in with the tracking path.

Let  $\mathbf{r}(s)$  is the curve's function that be parametrized by curve length  $s$ . If the first and second derivative of  $\mathbf{r}(s)$  (see Figure 4.8) exist and continuous, the curvature of curve at point  $P$  could be defined as following:

$$k(s) = \lim_{\Delta s \rightarrow 0} \left| \frac{\Delta \varphi}{\Delta s} \right|$$

where,  $\Delta s$  is the curve length from point  $P = \mathbf{r}(s)$  to another point  $P_1 = \mathbf{r}(s + \Delta s)$  which is on same curve and near to point  $P$ .  $\Delta \varphi$  is the angle difference between the tangent vectors  $T$  and  $T_1$  of curve respectively at the points  $P$  and  $P_1$ . The radius of osculating

circle (the dashed circle in Figure 4.8) of curve  $R(s)$  is the reciprocal of the curvature of curve at same point and could be expressed as following,

$$k(s) = \frac{1}{R(s)}.$$

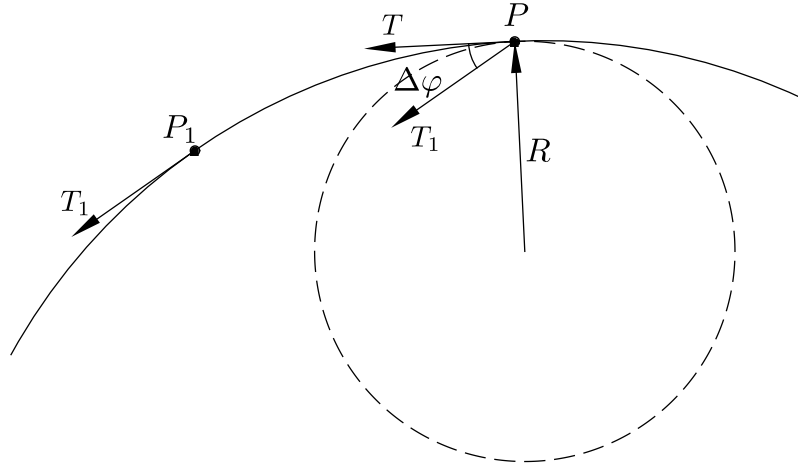


Figure 4.8: Curvature of curve

In curves theory, a small range of curve could be considered as a simplest regular curve, such as straight line or circular arc. The proposed method assumes that the tracking path could be segmented into straight line and circular arc segments. For straight line, its curvature is  $R \equiv 0$ . The circular arc's curvature is constant

$$\frac{1}{R} = k(s) = \left| \frac{\Delta\varphi}{\Delta s} \right|. \quad (4.14)$$

If the path segment between  $P$  and  $P_1$  is not straight line, the circular arc with radius  $R$  could be considered as the most osculating arc of the path segment.

In [99], the theorem

**Theorem 1: Fundamental Theorem of Plane Curves, Uniqueness**

Let  $\alpha$  and  $\gamma$  be unit-speed regular curves in  $\mathbb{R}^2$  defined on the same interval  $(a, b)$ , and having the same signed curvature. Then there is an orientation-preserving Euclidean motion  $F$  of  $\mathbb{R}^2$  mapping  $\alpha$  into  $\gamma$ .

has proved that there exists a unique circular arc connects two given points at which the arc's positive curvatures are same. So the curvature term is constructed basing on the assumption that the curvature of turning circle of vehicle with constant steering angle input  $\delta$  (Equation 4.11) is same to the curvature of tracking path at target point  $(x_{ts}, y_{ts})$  (Equation 4.14)

$$\begin{cases} R &= \frac{E}{\sin \delta} \\ \frac{1}{R} &= \left| \frac{\Delta\varphi}{\Delta s} \right|. \end{cases}$$

In other words, the direction of vehicle at the end point of next sample interval is parallel to the vector of tracking path at  $(x_{ts}, y_{ts})$ . It is obvious that the position of vehicle at the end of next sample interval is not the target point.



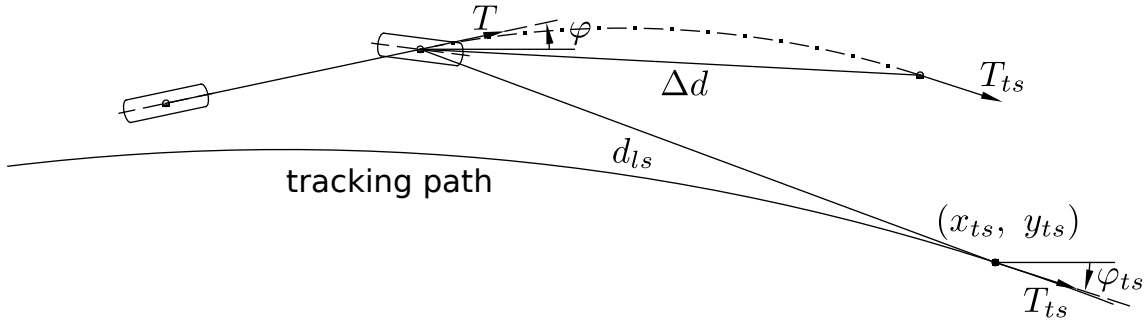


Figure 4.9: Curvature term

Figure 4.9 illustrates the curvature term.  $(x_{ts}, y_{ts})$  is the target point located on the tracking path that is already perceived and modeled in the perception stage. The look-ahead distance between vehicle's front wheel and target point is  $d_{ls}$ .  $T$  and  $T_{ts}$  are respectively the direction vector of vehicle and the tangent vector of path at the target point.  $\varphi$  and  $\varphi_{ts}$  are respectively the angles of  $T$  and  $T_{ts}$ .

Replacing the curve length  $\Delta_s$  with the direct distance between the two points on curve, the curvature term of desired steering angle could be expressed as following:

$$\delta_s = \arcsin\left(\frac{E\Delta\varphi}{\Delta s}\right) = \arcsin\left(\frac{E(\varphi_{ts} - \varphi)}{\Delta d}\right) \quad (4.15)$$

where  $\Delta d$  is the projected length of  $d_{ls}$  on direction of vehicle  $T$ .  $d_{ls} = k_s v$  is the look-ahead distance in which the  $k_s$  and  $v$  are respectively a factor and the vehicle's longitudinal speed. The dashed dot line is the expected circular arc trajectory of vehicle with constant steering angle input  $\delta_s$ . The tangent vector of end point of the trajectory is parallel to the tangent vector of tracking path at the target point.

Some methods just consider the direction of tracking path which is near to the concerned point on vehicle, for example the minimal distance as shown in Figure 4.3 and Figure 4.6. This type of selections could only reflect the current orientation relationship between ego-vehicle and the tracking path. It could not give any information about the trend of tracking path. In my view, the current information is useless for controlling the later movement of vehicle. Different from the methods mentioned above, basing on the road model and the in-lane location of vehicle detected by the vision sensors, see section 4.2, the curvature term selects the target point  $(x_{ts}, y_{ts})$  with a look-ahead distance  $d_{ls}$  to partly reflect the direction trend of tracking path. Looking ahead is also part of the behavior of human driver in tracking path operation. If there is no change of curvature, the look-ahead direction trend helps to control the vehicle to get an almost steady deviation state in short time interval. The behavior of curvature term has a little difference in tracking different types of curves.

Tracking straight path is the simplest scenario. Because the direction of straight path is constant, the curvature term could control the vehicle to get a parallel movement with the tracking path in a short time interval.

A more complex scenario is the circular arc path with constant curvature. When running on straight segment and approaching circular arc segment, once the target point is selected on the arc, the controller immediately gets a non-zero heading error and consequently turns ego-vehicle to approach the path's direction at the selected point. Once the

vehicle runs on the arc segment, there will be an almost constant heading error between the vehicle and the target point. Because we replace the arc length with projected length of the chord lend on the direction of vehicle, the trajectory's curvature of vehicle is greater than that of the tracking path. And because the difference between the two lengths is small, the convergence of difference between the directions of vehicle and tracking path to 0 is a slow process. When approaching a straight path from a circular arc path, once the target point is located on the straight path, this term reacts to the change of curvature immediately and leads the vehicle cross the center-line of tracking path and finally get a steady deviation on the other side of the center-line.

*Basing on these discussions, a final and obvious characteristic is that the curvature term continuously decrease the heading error between vehicle and tracking path until 0. The final steady deviation of ego-vehicle from the center-line of tracking path generally is not 0. The speed of converging to steady state is very small.*

The equation 4.15 indicates that the change of curvature leads to the change of deviation of ego-vehicle from path. Increasing value of  $|\Delta\varphi|$  leads to the increase of deviation. The final steady deviation and this possible increasing of deviation requires another method to make sure that the vehicle approaches the center-line of tracking path.

Normally, there is a time delay when turning the steering wheel from current position to desired position. This delay will consequently delay the vehicle's reaction. The result of the delay of turning steering wheel is similar to the scenario that the there is no delay but a shorter look-ahead distance between ego-vehicle and the target point.

As mentioned before, the curvature term is built basing the assumptions that the tracking-path model has already been obtained and that the curvature between the projection of  $T$  on the tracking path and  $T_{ts}$  is constant, see Figure 4.9. But in real tracking scenarios, there generally are many factors that cause errors of modeling the tracking path. And at some time, the curvature between the projection of  $T$  on the tracking path and  $T_{ts}$  may not be constant. For example, the there might be a curvature change of the tracking path between the two position, but the curvatures at the two positions are same. If set the value of  $d_{ts}$  is set too big, above case would appear too. In order to weaken even eliminate the influences of this error, the correction term is proposed.

#### 4.4.3/ CORRECTION TERM

As discussed in previous section, under the control of curvature term, the convergence of vehicle's deviation is a very slow process. And normally, the final steady deviation is not 0. These characteristics require another term of the steering control method to *pull* the vehicle back to the center-line of tracking path. The *pull* term's convergence process should be short so as to face the possibility of frequent change of curvature of tracking path.

From the discussions in the section 4.3, the kinematic model and dynamic model spends too much computation time. It is not proper for high speed of calculations on the controller installed on vehicle. Meanwhile, the geometric is simple and easy to understand, even if there are some assumptions, for example, no lateral slipping. More important, it does not need to occupy too much computing resources. So in this section, the correction term of proposed steering control method is derived from the geometric model as shown in Figure 4.4.

The main idea of geometric model is that, with a given target position, the method gives a steering angle to control the vehicle to arrive at the target geometrically. With different strategy of selecting the target point, there are different types of methods. The Pure Pursuit and its extensions [53, 25, 35] select the target point on the path basing on a look-ahead distance between the target and ego-vehicle. They take into account the trend of tracking path but does not consider the deviation from tracking path. So they could not help to converge the deviation in an visible and controllable way. The Stanley method (see Figure 4.6) considers the point on tracking path which is the nearest one to ego-vehicle. Comparing the experiments [140] that are conducted on different road geometric conditions (*Lane Change Course, Road Course and Figure Eight Course*), Stanley method performs better than the Pure Pursuit approach when the curvature of tracking path changes. This dissertation considers that the deviation factor in Stanley method plays a part. Actually, taking only into account the LLO, some PID steering control methods had been studied.

Taking into account the current deviation of vehicle from center-line of tracking path and the target position in front of ego-vehicle, the correction term of proposed steering control method could be illustrated as Figure 4.10. The deviation  $d_p$  is calculated between the rear position of vehicle and a selected position  $P_p$  on tracking path. The line that passes the two positions is perpendicular to the tangent vector of tracking path at  $P_p$ . The target position  $P_{tp} = (x_{tp}, y_{tp})$  is located on the direction of tangent vector at  $P_p$ . It's obvious that the target position is not absolutely on the tracking path. The distance between  $P_{tp}$  and rear position of ego-vehicle is the look-ahead distance  $d_{lp}$ . In accordance with the Figure 4.5, the correction term generates a constant steering angle  $\delta_p$  to control the vehicle's rear wheel passes the position  $P_{tp}$ . The dashed dot line is the circular arc trajectory of ego-vehicle.

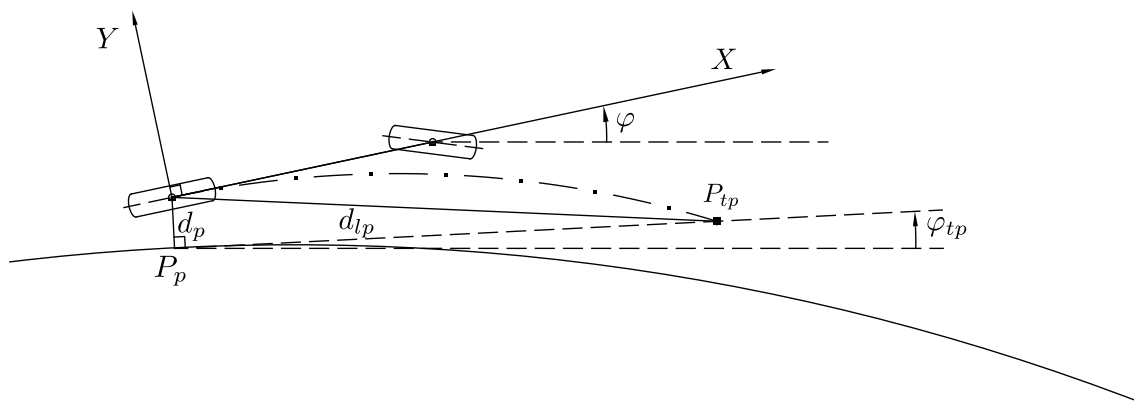


Figure 4.10: Pull term

The coordinate of target position relative to the body coordinate of ego-vehicle is

$$\begin{cases} x_{tp} = \sqrt{d_{lp}^2 - d_p^2} \cos(\varphi_{tp} - \varphi) - d_p \sin(\varphi_{tp} - \varphi) \\ y_{tp} = -d_p \cos(\varphi_{tp} - \varphi) + \sqrt{d_{lp}^2 - d_p^2} \sin(\varphi_{tp} - \varphi) \end{cases}$$

Basing on relation between  $R$  and the relative position of  $(x_t, y_t)$  to vehicle's position  $(x_v, y_v)$  as shown in Figure 4.5, the turning radius of circular arc trajectory of ego-vehicle's

rear wheel is

$$R_{pr} = \frac{d_{lp}^2}{2y_{lp}}$$

In accordance with the Figure 4.7 and Equation 4.13, we have

$$R_{pr} = \sqrt{R^2 - E^2}$$

Substituting above  $R$  into the Equation 4.11, the expected steering angle of correction term is

$$\delta_p = \arcsin\left(\frac{E}{\sqrt{E^2 + \left(\frac{d_{lp}^2}{2(-d_p \cos(\varphi_{lp} - \varphi) + \sqrt{d_{lp}^2 - d_p^2} \sin(\varphi_{lp} - \varphi))}\right)^2}}\right) \quad (4.16)$$

where,  $\varphi$  and  $\varphi_{lp}$  are respectively the directions of ego-vehicle and the tangent vector of tracking path at selected position  $P_p$ .  $d_p$  is the deviation of ego-vehicle's rear wheel from  $P_p$ .  $d_{lp}$  is the look-ahead distance for creating the target position  $P_{lp}$ . The longitudinal velocity  $v$  affects the arc length of trajectory. Taking into account  $v$ , the look-ahead distance is  $d_{lp} = k_p v$ .  $k_p$  is the factor of correction term.

#### 4.4.4/ FULL METHOD

The curvature term and correction term have their own factors to adjust their performances. The final desired steering angle combines the steering angles calculated through curvature term ( $\delta_s$ ) and correction term ( $\delta_p$ ) as following

$$\delta = \delta_s + \delta_p \quad (4.17)$$

In order to show the characteristics of proposed lateral control method and to compare with different existing methods, this dissertation designed two scenarios in which the tracking path is closed.

## 4.5/ EXPERIMENTS

As a turning point of the development of autonomous automobile, the DARPA Grand Challenge has re-aroused hug enthusiasm on self-driving car. In the competition, the automatic steering control methods that derive respectively from the three types of vehicle models (see section 4.3) are all presented. This section only compares the proposed method with the Stanley method and the Optimal Control with Feed Forward Term (Linear Quadratic Regulator with Feed Forward) which are respectively derived from the geometric vehicle model (see section 4.3.3) and dynamic vehicle model (see section 4.3.2).

### 4.5.1/ SCENARIO DESIGN

The proposed steering control method is developed basing on some assumptions. One of them is that the tracking path is composed of the simplest geometric segments: straight line segments and circular arc segments. In order to illustrate the steady state characteristics of the proposed steering control method while ego-vehicle travels along nonzero

curvature path or straight path, we designed two closed infinite courses called Figure Infinite Courses, see Figure 4.11. It helps to provide valuable insight into the handling of a vehicle as well as some important characteristics of a controller. The method's response to this discontinuity provides insight into its robustness.

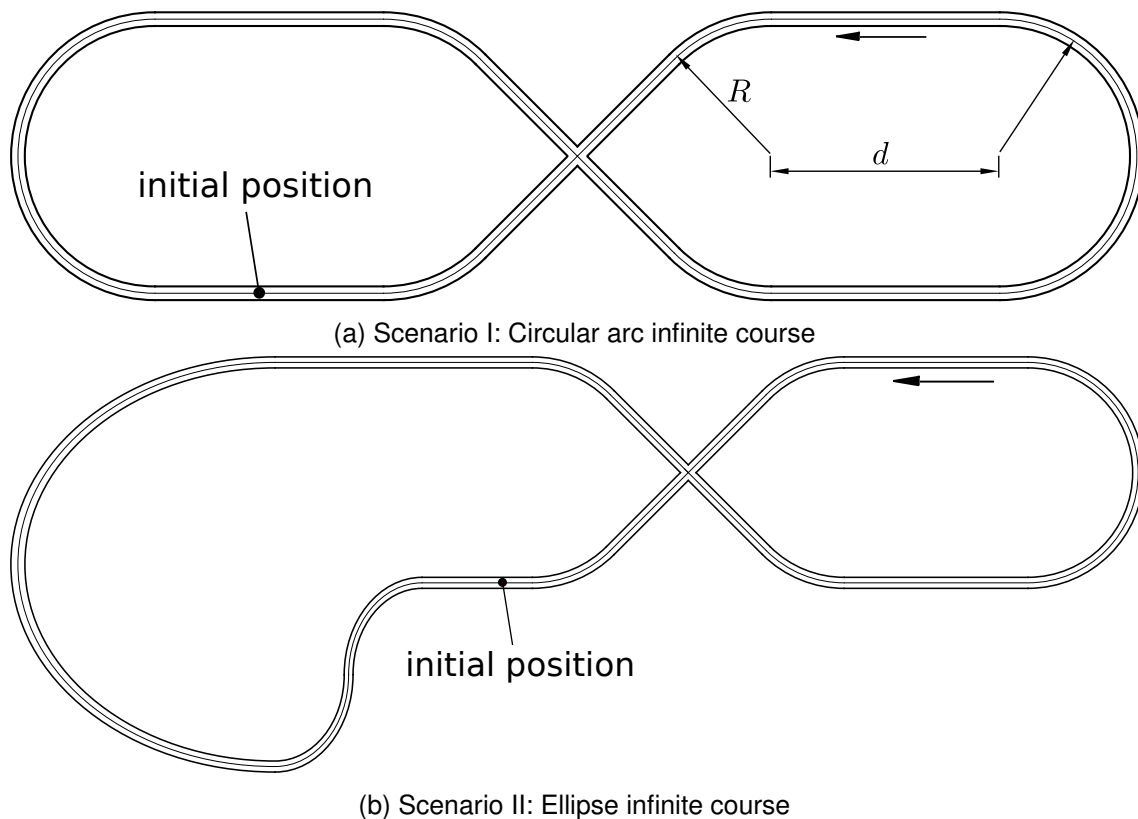


Figure 4.11: Figure Infinite Courses

As discussed at the beginning of this chapter, the non-straight paths particularly the turns in intersection area could be approximately described as circular arc. The simple course is composed of straight segments and circular arc segments as shown in Figure 4.11a. The arc segments have the same radius. The path near the connection between arc segment and straight segment could give a transition of curvature and could help to show the influence of curvature change on the steering control method. This closed infinite course is named as Scenario I. In the rest of this chapter, without special declaration, the course is perfectly symmetrical. The radius of circular arc path segment are all  $R = 30$  m. The distance  $d$  between the two centers of arc segment at each side of the course is  $d = 50$  m.

For comparing the lateral action of the proposed control method, we also designed a more complex course as shown in Figure 4.11b. It comprises straight segments, circular arc segments and ellipse segments. The curvature changes among straight segment, ellipse segment and arc segment could be used to test the reaction of the control method to complex situations. Particularly, the connection between arc segment and the small ellipse segment helps to represent the characteristic with the most abrupt curvature changes. Similar to Scenario I, this course is named as Scenario II. The right part of the courses is same to same part of Scenario I. The radius of all circular arc segments are same. The big ellipse arc is half of ellipse whose major radius is 70 m and whose minor radius is 55

m. The two smaller ellipse arcs have the same size. They are quarter of ellipse whose major radius is 25 m and whose minor radius is 20 m. The horizontal distance between center of big ellipse arc and the center of circular arc is 70 m.

In the two scenarios, every two successive path segments are different. The two neighbor segments are tangent at the connection point. There is no management at the intersection. In other words, the vehicle consider the conflict zone as normal part of path. The direction of traffic flow is direction of the arrow in each figure. The default initial direction of vehicle is parallel to the tracking path. When studying the steering control method, the speed of turning steering wheel affects the final performance of control method. In rest of this chapter, the statement that the speed of steering wheel is 0 indicates that the steering wheel could be set to desired steering angle at the beginning of each sampling interval, whatever its current angle. Meanwhile, the range of reachable steering angle is  $[-\frac{\pi}{6}, +\frac{\pi}{6}]$ . In order to weaken the influence of sampling time on the lateral control method, if there is no explicit declaration, the following experiments are conducted with the sampling time 0.01 s. The unit of the factors for the curvature term and the correction term is second.

#### 4.5.2/ CURVATURE TERM

The experiments in this section are carried out for observing the influences of factor  $k_s$  and the speed of turning steering wheel on the performance of curvature term. The controller in this section is just the curvature term.

##### 4.5.2.1/ CLOSED CIRCULAR PATH

The curvature term mainly focuses on fitting with curve path. It is developed based on one of basic assumptions of differential geometry theory that any small range of curve could be considered as simplest regular curve. Figure 4.12 compares the performances of curvature term of fitting a circular path with different factor  $k_s$ .

The radius of center line of the circular path is 30 m. Initial deviation of ego-vehicle from the center line is 0.5 m. At the beginning, ego-vehicle is parallel to the path at the nearest position on path. The experiment result shows that smaller  $k_s$  leads to slower convergence to steady deviation state. Bigger  $k_s$  causes bigger deviation of ego-vehicle from center-line of the tracking path. Ego-vehicle runs at constant velocity 10 m/s. Speed of turning steering wheel is 0. Comparing the scenarios that the radius of tracking path are 50 m and 30 m, smaller constant curvature of tracking path leads to slower convergence to steady state. Comparing the scenarios that the constant longitudinal velocities of vehicle are different, higher speed leads to quicker convergence to steady state.

From above discussions, with given tracking path, the performance of curvature term mainly depends on the factor  $k_s$ , the reaction time of steering wheel and ego-vehicle's speed. In the rest of this section, curvature term will be experimented at the two scenarios to observe the relations between factor  $k_s$ , the reaction time of steering wheel and the vehicle's velocity. Because the speed of turning steering wheel depends not only on the mechanical structure, the following experiments just consider two situations: at constant speed and no delay of turning steering wheel.

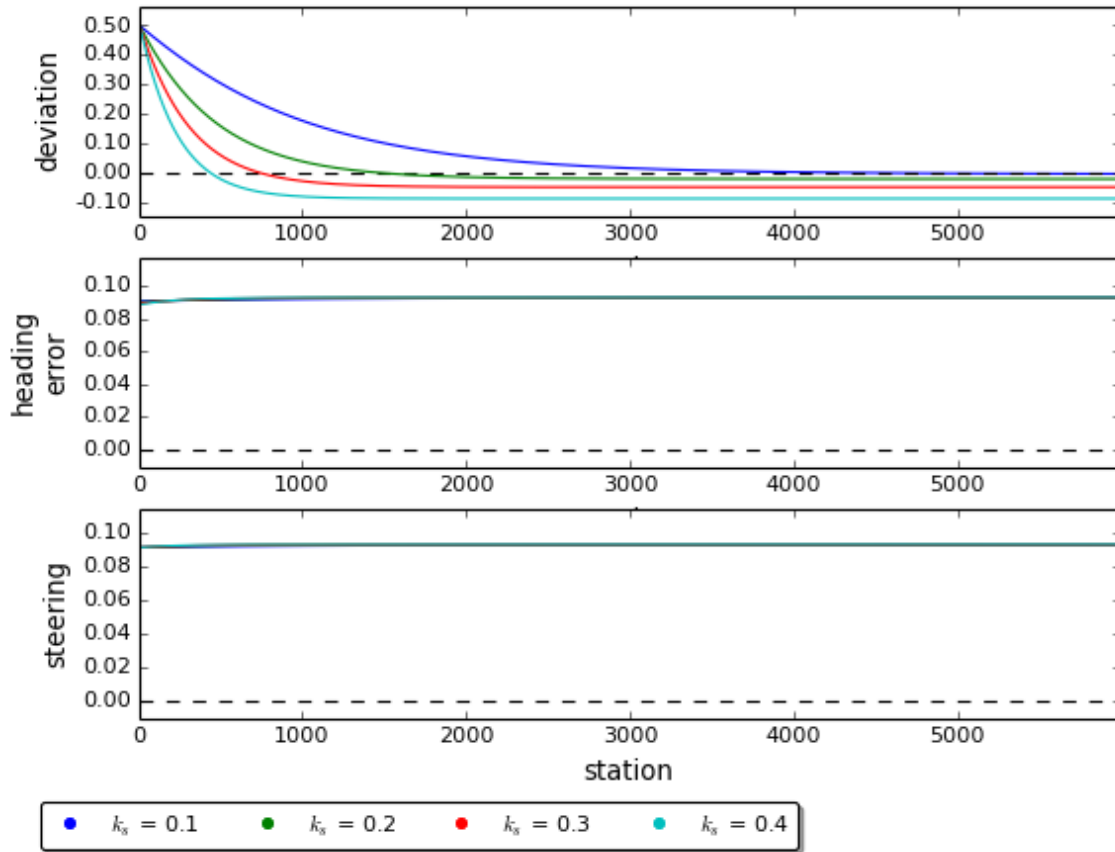


Figure 4.12: Curvature term: closed circular path

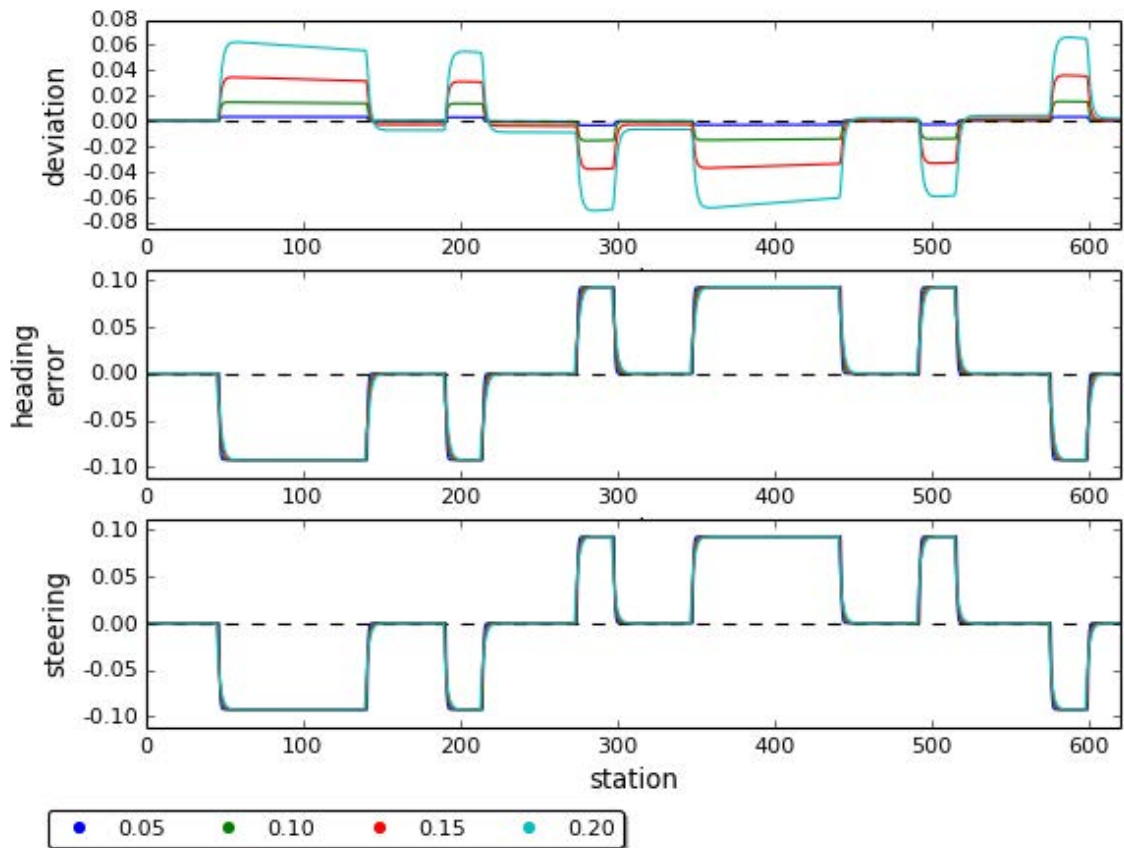
#### 4.5.2.2/ SCENARIO I

Among the three factors that influence the performance of curvature term, only the factor  $k_s$  is controllable. At constant ego-vehicle's speed, this section firstly compares the performances with different value of  $k_s$  and different speed of turning steering wheel. From the comparison, a proper  $k_s$  is selected. Then, taking the chosen constant factor  $k_s$ , this section compares the performance with different speed of vehicle and different speed of turning steering wheel. From the results, it's able to observe the effective working range of the curvature term under the selected factor  $k_s$ .

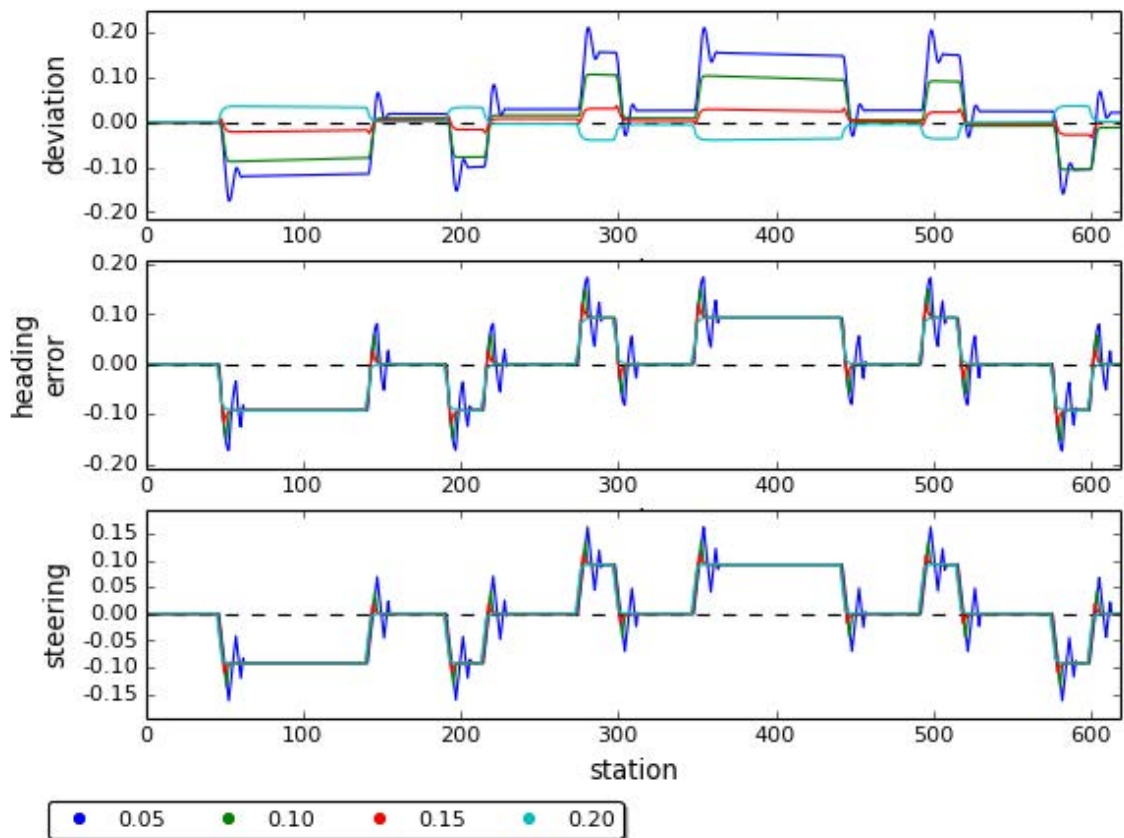
Figure 4.13 shows the experiment of curvature term in scenario I in which the vehicle runs at constant speed 10 m/s.

In the experiment of Figure 4.13a, there is no delay of turning steering wheel. From the plot *deviation*, smaller factor  $k_s$  leads to smaller deviation from center-line of tracking path. The stable *heading errors* between vehicle's direction and respective tangent direction of tracking path and the stable *steering* angle inputs of different value of factor  $k_s$  are similar.

In the experiment of Figure 4.13b, the maximal speed of turning steering wheel is  $\frac{\pi}{12}$  rad/s. The plots *heading error* and *steering* show that with the factors that less than  $k_s = 0.2$ , each time the curvature changes, the control method causes waves before the heading error or steering achieve almost steady state. From the plot *deviation*, only the method with  $k_s = 0.2$  controls the vehicle have a similar deviation to that in Figure 4.13a.



(a) Curvature term: Scenario I without delay of turning steering wheel



(b) Curvature term: Scenario I with speed of turning steering wheel  $\frac{\pi}{12}$

Figure 4.13: Experiment of curvature term in scenario I and at constant speed 10 m/s



And because of the exist of speed of turning steering wheel, the steady deviation of in Figure 4.13b is less than that in Figure 4.13a.

Basing on the comparison of Figure 4.13b and Figure 4.13a, in the rest of this chapter, the default value of factor  $k_s$  is 0.2.

Figure 4.14 shows the experiments of curvature term in scenario I in which the vehicle runs at different speed. Comparing the *deviation* plots of Figure 4.14a and Figure 4.14b, the delay of turning steering wheel leads to a smaller stable deviation. It's similar to the result of previous experiment. It also shows that bigger speed causes bigger stable deviation. From the plots *heading error* of two sub figures, when the vehicle is running at high longitudinal speed, for example 15 m/s or 20 m/s, there is an abrupt change of heading error at each time the curvature changes.

The four experiments represent that the turning speed of steering wheel and speed of vehicle have significant influence on the performance of curvature term. This scenario helps to observe the reaction of curvature term on path which has a constant curvature. It is also necessary to test the algorithm on path with variational curvature.

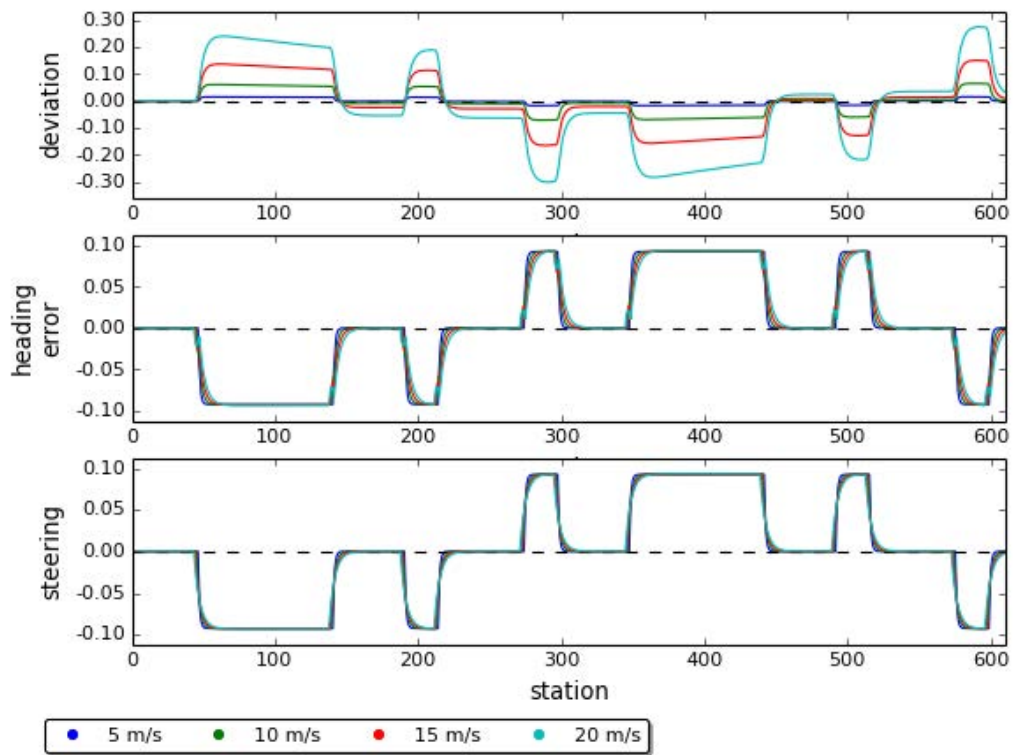
#### 4.5.2.3/ SCENARIO II

As shown in Figure 4.8 and Figure 4.9, the fundamental assumption of curvature term is that any smallest trajectory of vehicle is circular arc. And curvature term also assumes that there is no lateral slipping and the direction of speed of front wheel is direction of front wheel. But in real traveling scenario, because of the force of friction between wheel and ground as well as deformation of tire, the real direction of velocity of front wheel is not same to the direction of wheel. The trajectory of vehicle is not circular arc.

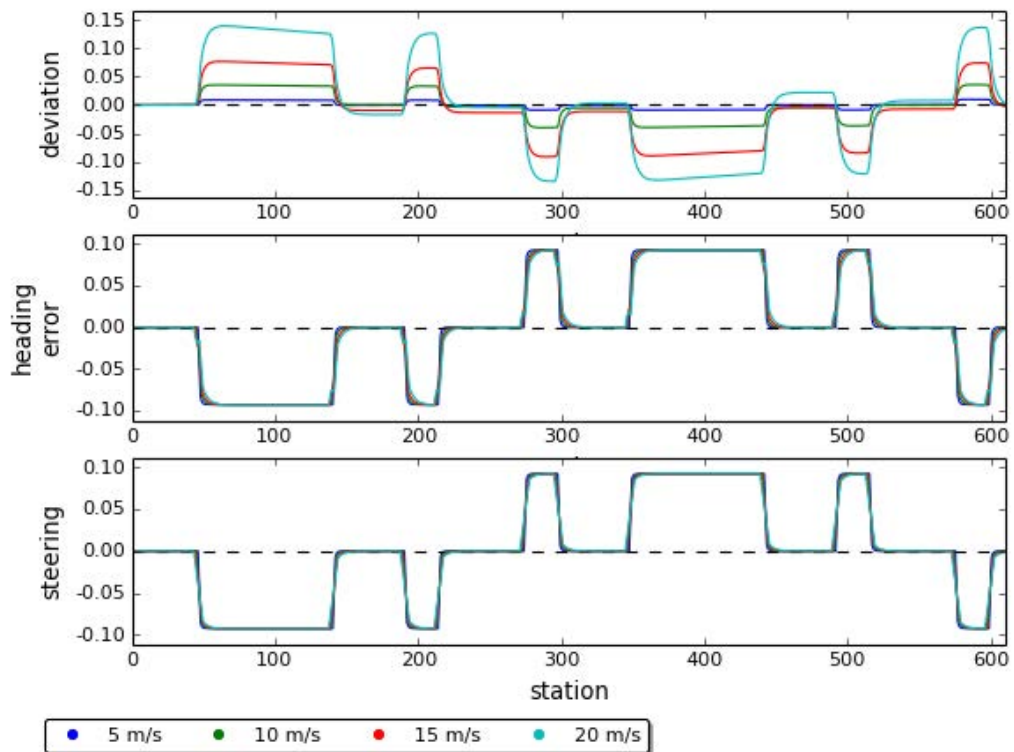
Meanwhile, the curvature term (Equation 4.15 and Figure 4.9) assumes that the vehicle's trajectory has same curvature to that of the selected target position  $(x_{ts}, y_{ts})$  on center-line of tracking path. When there is a deviation from center-line, the trajectory of vehicle does not coincide with the circular arc pass the target position  $(x_{ts}, y_{ts})$ . After several steps of movement, the final trajectory of vehicle is not circular arc. This is one of the reasons that why the vehicle converges to the center-line of path in the experiment of section 4.5.2.1. Because of same reason, the vehicle's trajectory is not circular arc too when tracking a straight path. In other words, the curvature of trajectory of vehicle that controlled by curvature term is not constant.

From above discussions, it's necessary to observe the performance of curvature term on path that has non-constant curvature. The ellipse arcs in Scenario II (see Figure 4.11b) is simple to be implemented in the simulation platform and provides a non-constant curvature. The first two small quarter ellipses arc provide a curve whose absolute curvature changes from big value to small value and then back to small value at the end of the second ellipse arc. The curvature's signs of the two ellipse arcs are different. The value of curvature of the bigger half ellipse arc grows at first and then becomes smaller. Meanwhile, the sign of curvature remains same. Figure 4.15 shows the experiment of curvature term in Scenario II.

Figure 4.15a plots the experiment of curvature term in the scenario II with factor  $k_s = 0.2$ . In the experiments with bigger factor  $k_s$ , for example  $k_s = 0.3, 0.4$  or  $0.5$ , the deviation increase. Meanwhile, abrupt wave of head error appears (comparing the *heading error* plots of Figure 4.15a and Figure 4.15b).

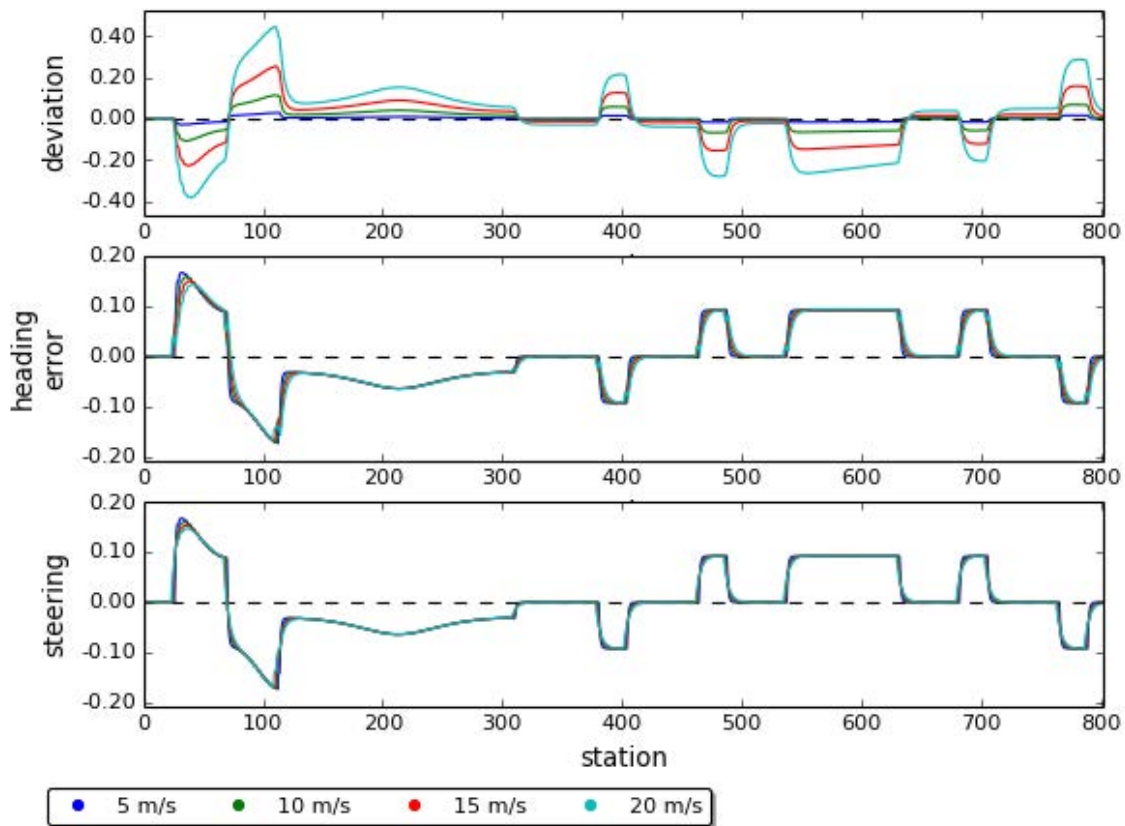


(a) Curvature term: Scenario I without delay of turning steering wheel

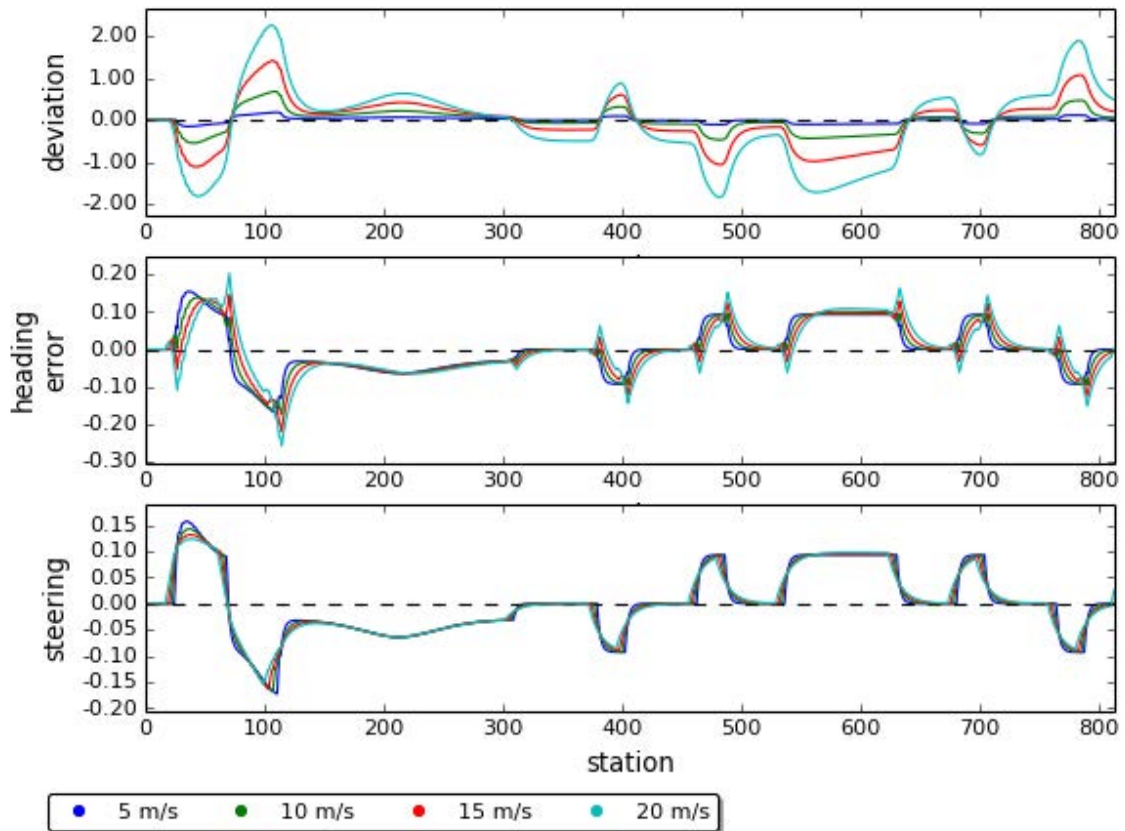


(b) Curvature term: Scenario I with speed of turning steering wheel  $\frac{\pi}{12}$

Figure 4.14: Experiment of curvature term in scenario I and with constant factor  $k_s = 0.2$



(a) Curvature term: Scenario II without delay of turning steering wheel



(b) Curvature term: Scenario II with speed of turning steering wheel  $\frac{\pi}{12}$

Figure 4.15: Experiment of curvature term in scenario II

Figure 4.15b shows the experiment of curvature term with factor  $k_s = 0.5$ . In the experiments with smaller factor  $k_s$ , for  $k_s = 0.2$  or  $0.4$ , the deviation increase. In other words, the delay of turning steering wheel causes the control method could not react to the changed of curvature in time, especially in case that vehicle has a higher speed.

The smaller ellipse has bigger curvatures than bigger ellipse. The *deviation* plot shows that, at the end of second small ellipse arc, the vehicle could not converge back to center line of tracking path. But the deviation converges to 0 at the end of the bigger ellipse arc, even if at the beginning the deviation is not 0. So the range of curvature of tracking path should be taken into account in the process of deciding the factor  $k_s$ .

Comparing the plots *deviation* in Figure 4.15a and Figure 4.15b, when the curvature is not constant, the delay of turning steering wheel makes less influence on the deviation of vehicle under the control of curvature term .

The *heading error* plots shows that bigger speed leads to unstable of heading error between vehicle and tracking path. The moderate velocity  $v = 10$  m/s is acceptable.

#### 4.5.3/ CORRECTION TERM

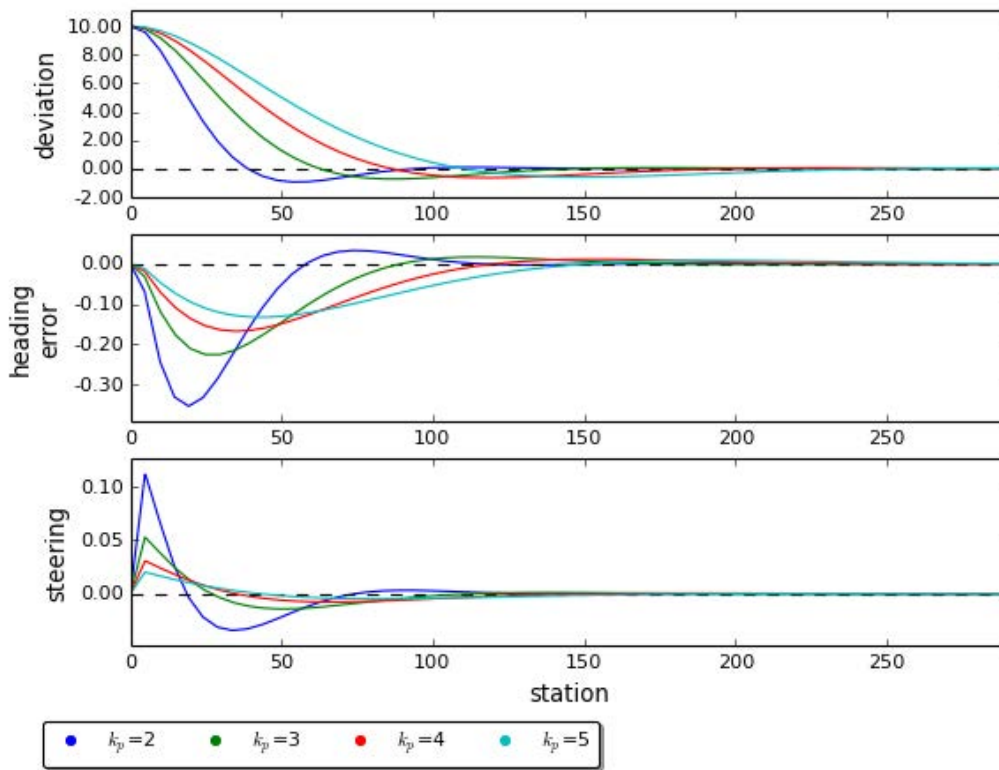
As the curvature term is helpless on controlling vehicle converge to center-line of tracking path in short time, the correction term is proposed to *pull* the vehicle back to the tracking path quickly. So the straight path is helpful on representing the characteristic of correction term. Figure 4.16 shows the experiments of correction term on tracking straight path at a constant speed 10 m/s.

In the experiments, the initial deviation of vehicle from center-line of tracking straight path and the initial heading error are respectively 10 m and 0 rad. In accordance with the Figure 4.10 and the definition of look-ahead distance  $d_{lp}$ , when factor  $k_p = 1$ , the look-ahead distance  $d_{lp}$  equals to the initial deviation 10 m. This causes the vehicle aims at its projection on the straight path. So the smallest value of  $k_p$  depends on the value of speed and possible maximal deviation from path.

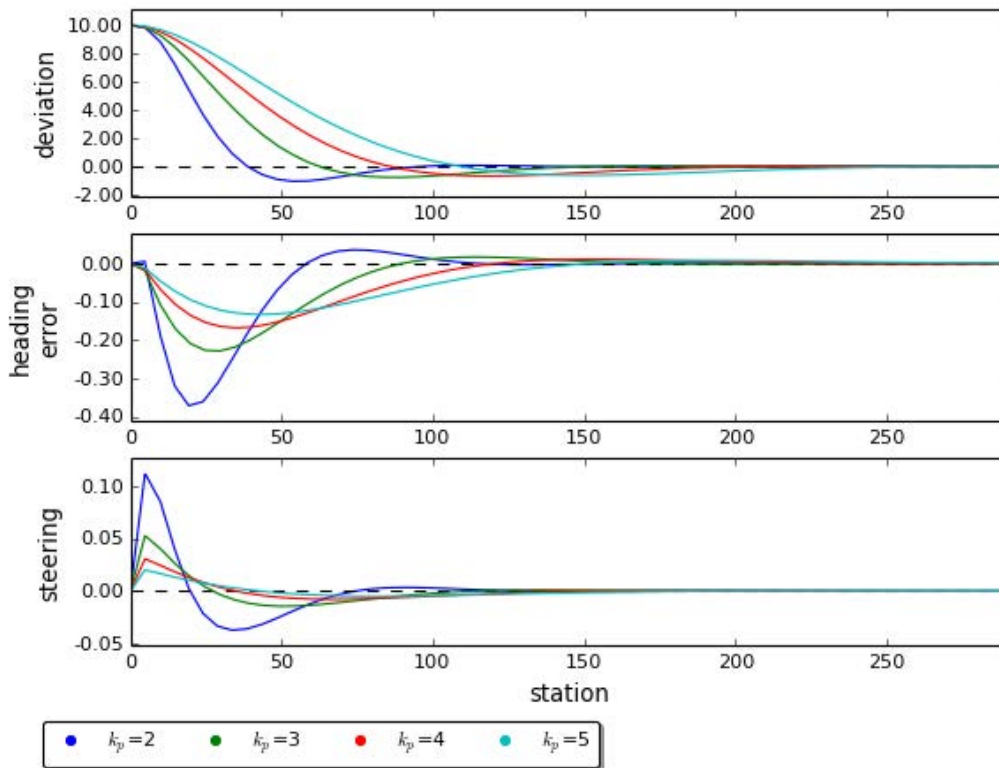
Comparing results of different value of  $k_p$ , bigger factor leads to quicker convergence but bigger amplitude. Smaller factor has opposite effect. Comparing the *deviation* plots in Figure 4.16a and Figure 4.16b, the delay of turning steering wheel does not cause huge difference. In case that the initial deviation is small, for example 0.5 m, the influence of delay of turning steering wheel is obvious and similar to that on curvature term.

#### 4.5.4/ FRENET BASE CONTROL

Comparing the experiments of curvature term without delay of turning steering wheel (see Figures 4.13a, 4.14a and 4.15a) and the ones with speed of turning steering wheel (see Figures 4.13b, 4.14b and 4.15b), the delay of turning steering wheel has a positive influence on decreasing amplitude of deviation of vehicle from tracking path. It's similar to the effect of smaller factor  $k_s$ . Meanwhile, there is a delay of reaction of steering wheel mechanical system. Low traveling speed also causes a delay of turning steering wheel. So the experiment of the full method will only consider the scenario that there is a speed of turning steering wheel  $\frac{\pi}{12}$ . There is no initial deviation of vehicle from path. The vehicle is parallel to the tracking path.



(a) Pull term: straight path without delay of turning steering wheel



(b) Pull term: straight path with speed of turning steering wheel  $\frac{\pi}{12}$

Figure 4.16: Experiment of correction term in tracking straight path

## 4.5.4.1/ SCENARIO I

Figure 4.17 shows the experiment result of full method (Equation 4.17) in scenario I with factors  $k_s = 0.2$  and  $k_p = 0.4$ . Comparing with the plot *deviation* in Figure 4.14b, the correction term effects significantly not only on the convergence of deviation but also on the amplitude of deviation. The correction term causes a bigger decrease of amplitude of deviation at bigger speed. Bigger speed weakens the effect of correction term on the speed of convergence of deviation.

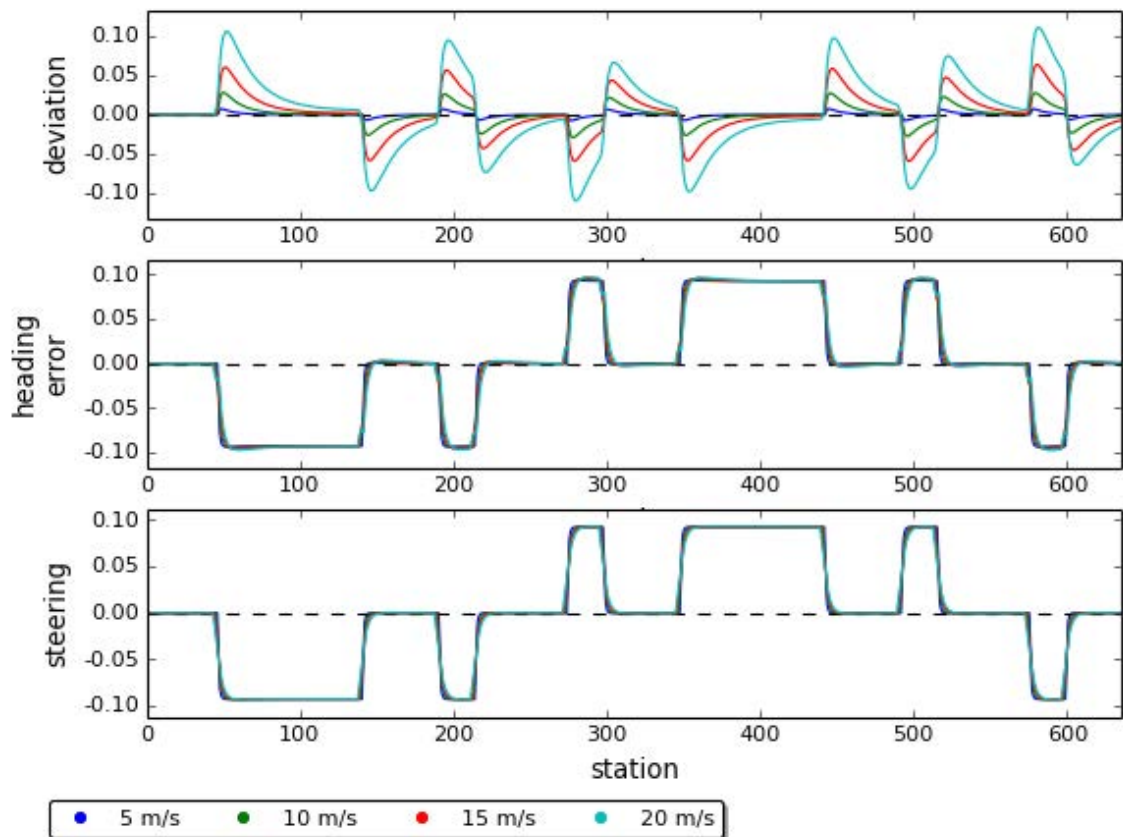


Figure 4.17: Full method: Scenario I with speed of turning steering wheel

## 4.5.4.2/ SCENARIO II

In scenario I, except the small neighbor range of connection between two different types of segments, the curvature is constant. The value of  $k_s$  mainly causes the change of amplitude of deviation. Different from scenario I, the curvature of ellipse arc segments of scenario II is different between any two neighbor positions. In this case, too small value of  $k_s$  leads to unstable reaction of the controller method. The experiments with factor  $k_s = 0.2$  or  $0.3$  show that the difference of deviation between the two small ellipse segments is big. In the experiments that the factor  $k_s$  is greater than  $0.4$ , the deviation becomes big. So the factor  $k_s = 0.4$  is chosen for the scenario II. Figure 4.18 is the experiment result of full method in scenario II with  $k_s = 0.4$  and  $k_p = 0.4$ .

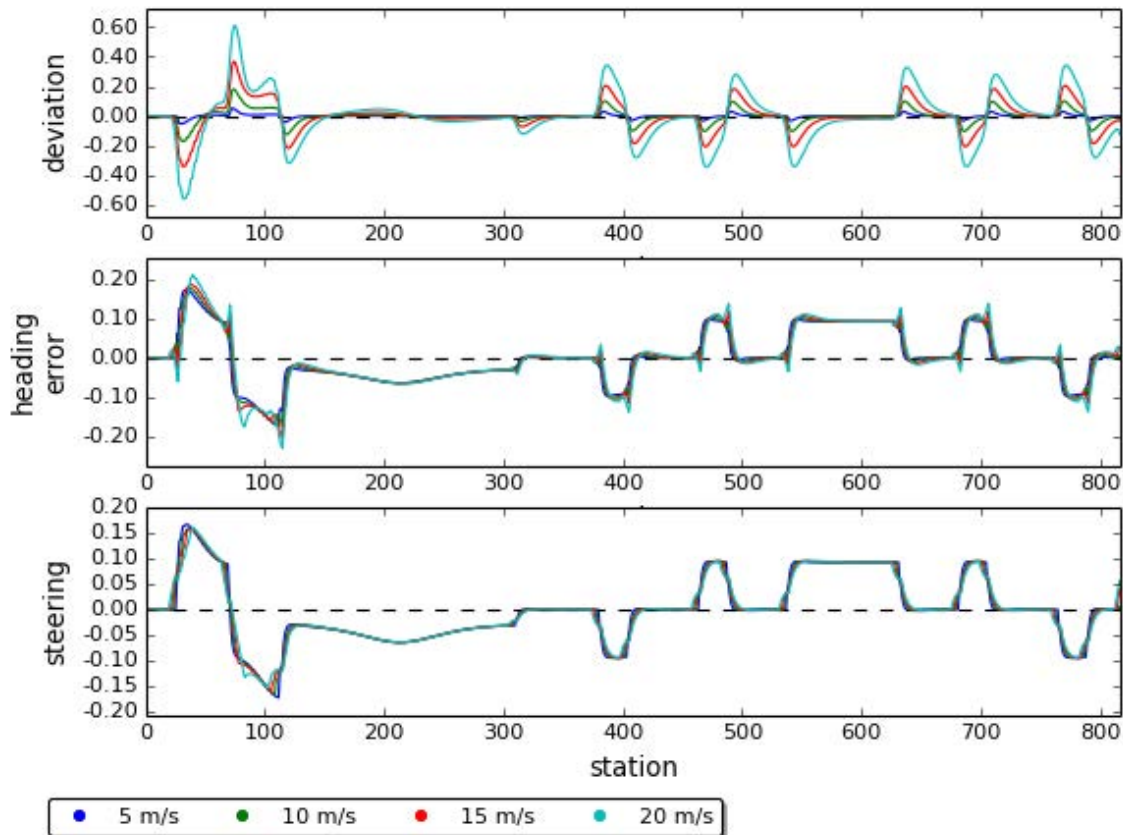


Figure 4.18: Full method: Scenario II with speed of turning steering wheel

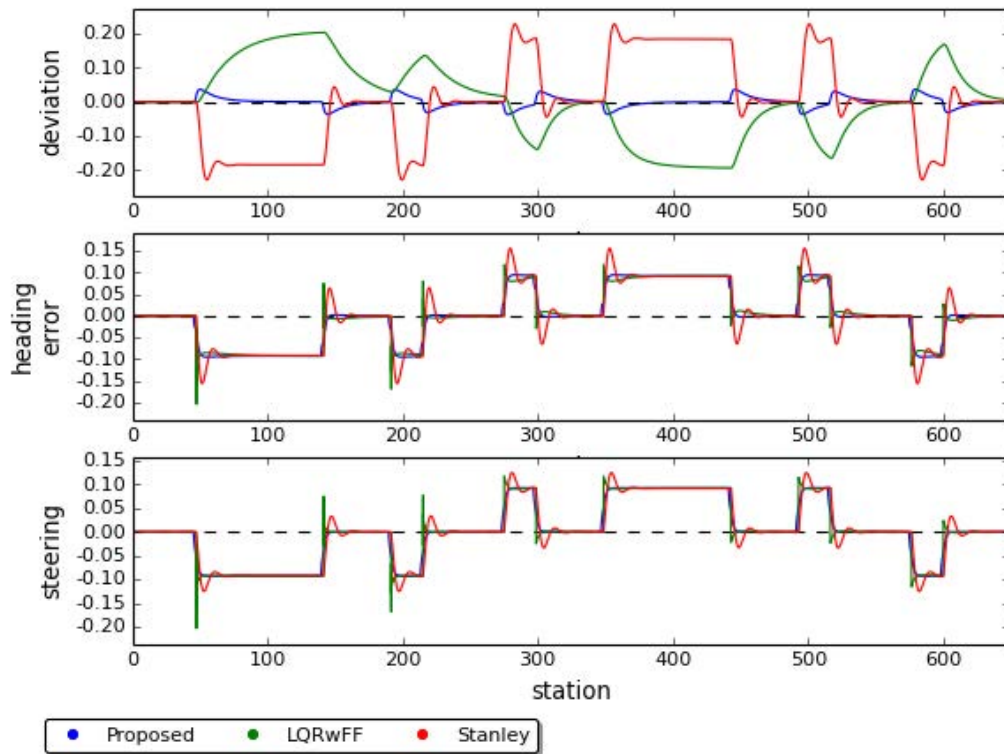
#### 4.5.5/ COMPARISON

In this section, the proposed steering control method is compared with two existing automatic steering methods: *LQRwFF* (see Equation 4.5) and *Stanley* (see Equation 4.10). The proposed Frenet base Control method is shown as *Proposed* in the figures about the experiment results. They will be experimented on the two scenarios at constant traveling speed 10 m/s. The parameters of proposed method are same with that in the section 4.5.4. The factor  $k$  for Stanley is set as 5.

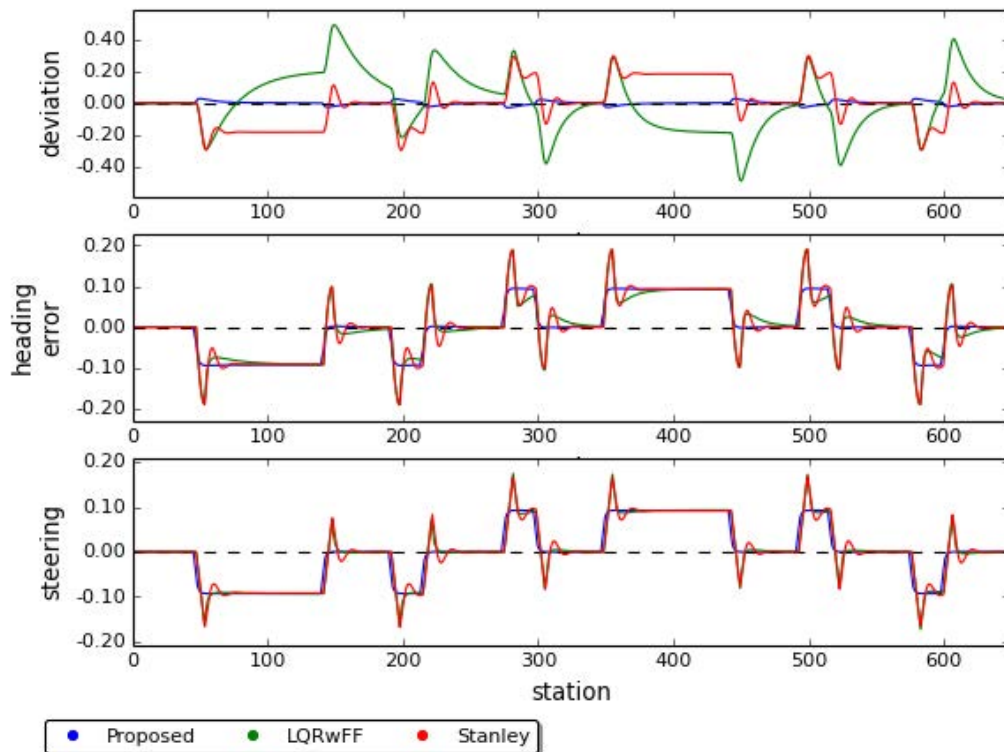
##### 4.5.5.1/ SCENARIO I

This simplest regular path architecture helps to observe the characteristics of the compared steering control methods when they are tracking regular path. Figure 4.19 shows the experiment results.

As shown in the plot *deviation* of Figure 4.19a, the first situation change occurs near the connection from straight path to circular arc path. The *LQRwFF* method takes long time to approach a steady state. During the turns process it keeps an increasing deviation on right side of center line. The *Stanley* method reacts quickly to the curvature change. After a short wave, it rests on a steady deviation state at the left side of mid line of tracking path. The *Proposed* method reacts to the curvature change quickly than the *Stanley* method with a smaller amplitude. After the smaller duration of adaptation wave,



(a) Comparison: Scenario I without speed of turning steering wheel



(b) Comparison: Scenario I with speed of turning steering wheel  $\frac{\pi}{12}$

Figure 4.19: Comparison: Scenario I



it controls the vehicle back to the mid line of tracking lane quickly. During the turning process, comparing with the other methods, the vehicle keeps a very small and steady lateral lane offset at the right side of center line of tracking path.

The plot *heading error* of Figure 4.19a shows orientation difference in the turning process. The *LQRwFF* method causes an instant huge direction change at the first curvature change but also a quick convergence to steady heading error. In the following curvature change cases, it causes to decreasing wave amplitudes when reacting to the curvature changes between straight path and circular arc path. The *Stanley* method reacts to the curvature change with a smaller amplitude of wave and then keeps a steady heading error. Among the three methods, the *Proposed* method presents the smoothest adaptation from one steady heading state to another steady state. The three methods spend similar time to achieve the same steady heading error state. But, among the three methods, the *Proposed* method gives the smallest and smoothest operation during the adaptation.

Comparing with the Figure 4.19a, Figure 4.19b shows more obvious differences between the three methods which are caused by the speed of steering speed. As discussed in previous experiments, the speed of steering speed causes a more smooth reaction of *Proposed* method. Because of the speed of steering wheel, the *Stanley* method reacts to the curvature change with a bigger wave amplitude as shown in plot *heading error* than the that without speed of steering wheel. The speed of steering wheel has the biggest influence over the method *LQRwFF*. Different from the scenario without speed of steering wheel, the *LQRwFF* reacts to the curvature change softly. The adaptation is similar to the *Stanley* at the beginning of adaptation process. This soft reaction leads to an intersection of the center-line of tracking path and vehicle's trajectory, see plot *deviation* in Figure 4.19b. Because of soft reaction, the vehicle firstly deviates from the path to its left side after a while, it passes over the center-line to the other side.

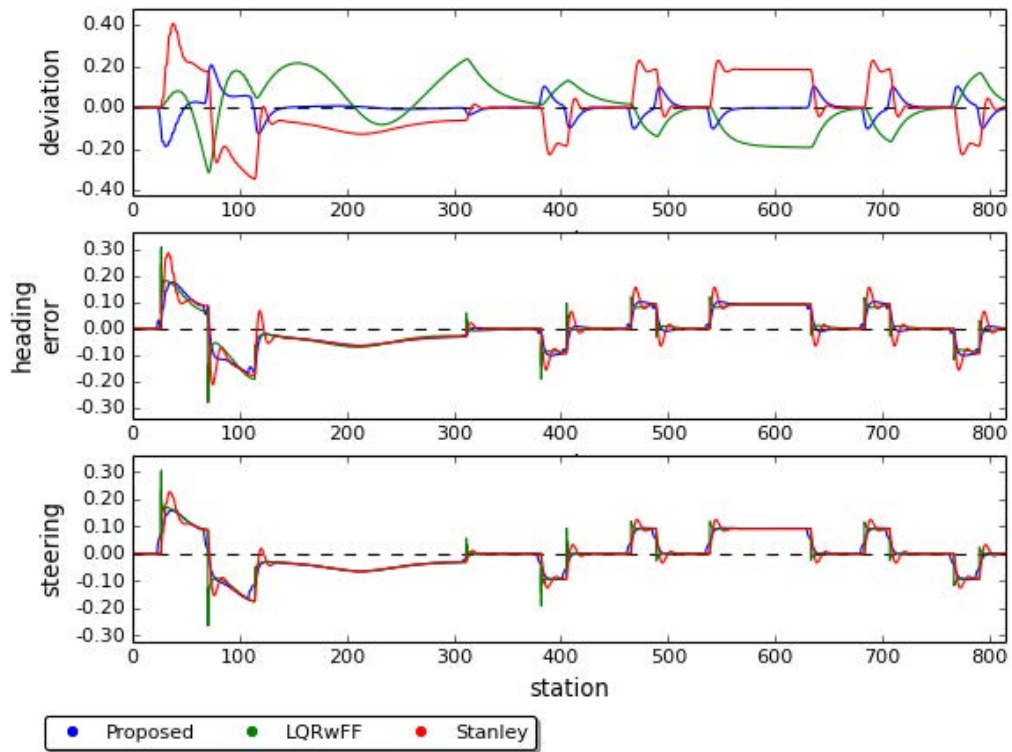
Figure 4.19 shows that the proposed method performs better than the two compared methods in two cases. When there is an abrupt change of curvature, for example the curvature changes because the tracking path transforms from straight line to constant curvature curve or on the contrary, the proposed method reacts quicker, smoother and with a smaller deviation wave from the tracking path. When the tracking path has a constant non-zero curvature, the deviation of vehicle that is under control of the proposed method could converge to 0. The *Stanley* method could only keeps a constant deviation. The *LQRwFF* even leads to an increasing deviation if the tracking path with constant non-zero curvature is not too long.

#### 4.5.5.2/ SCENARIO II

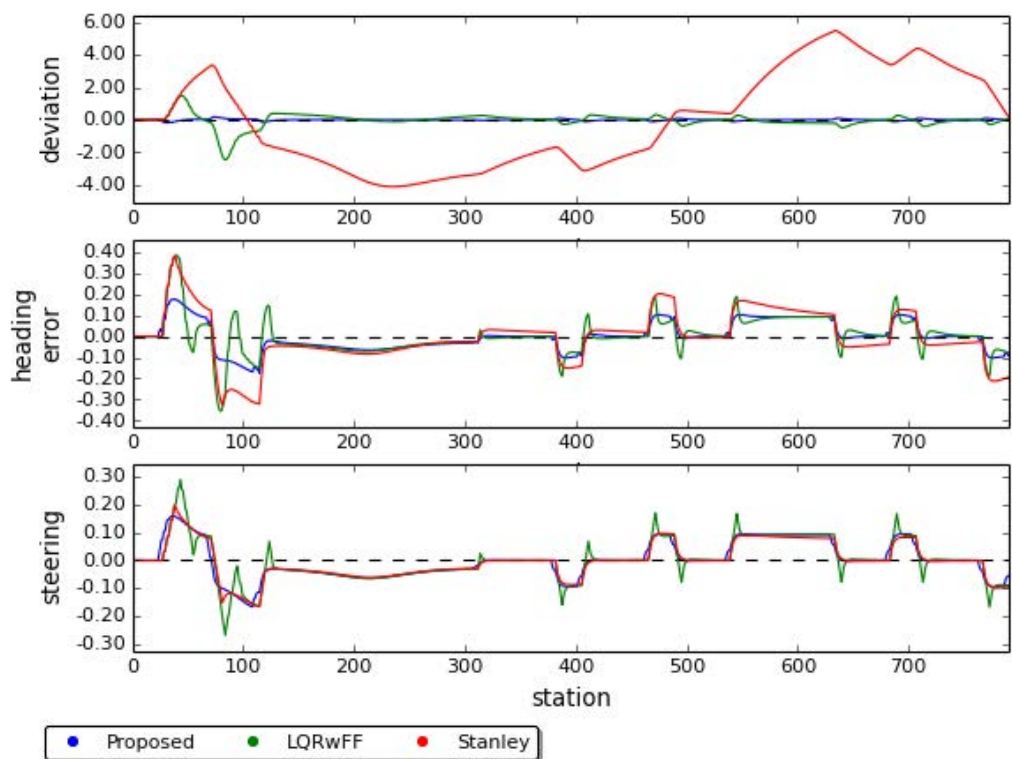
The FIGURE.1 in article [147] modeled the center-lines of turn segments in the intersection as ellipse arcs. The scenario II helps to check the performance of the three methods during the turns in the conflict zone of an intersection.

Figure 4.20 shows the experiment results of the three methods whose parameters are same to that in section 4.5.5.1 except the smooth factor  $k_s$  of the proposed method. In this comparison, the smooth factor is set as  $k_s = 0.4$  which is same to the value in section 4.5.4.2.

The plot *deviation* of Figure 4.20a shows the most obvious differences between the compared methods. Firstly, because of the inconstant curvature value of the ellipse segment,



(a) Comparison: Scenario II without speed of turning steering wheel



(b) Comparison: Scenario II with speed of turning steering wheel  $\frac{\pi}{12}$

Figure 4.20: Comparison: Scenario II

the three methods all react with a larger lateral lane offset (LLO). The *Stanley* method results the largest LLO among the methods on the two small ellipse segments and then a smaller LLO on the big half-ellipse than *LQRwFF*. The *LQRwFF* have the least ability in tracking the ellipse arc segment. It could not keep the vehicle stay on one side of the center line during one ellipse arc segment and results two times of crossing the center line on the bigger ellipse arc path. The *Proposed* method could not also keep the vehicle on one side of mid line of lane but the deviation is the smallest among the three. Comparing with the *LQRwFF*, it decreases the amplitude of deviation on larger ellipse arc.

The plot *heading error* in Figure 4.20a shows a similar change of heading error of the three methods, especially on the two small ellipse arc segments. The *LQRwFF* makes the most quick but also the sharpest adaptation when approaching the steady state of damping of heading error. The *Stanley* spends the longest time and much the same amplitude with *LQRwFF* before the steady state. The smallest amplitude is presented by *Proposed*. But, if the curvature changes too fast, for example the curvature at the beginning of the first small ellipse and the beginning of the big ellipse segment, it causes a very frequent and small heading error wave.

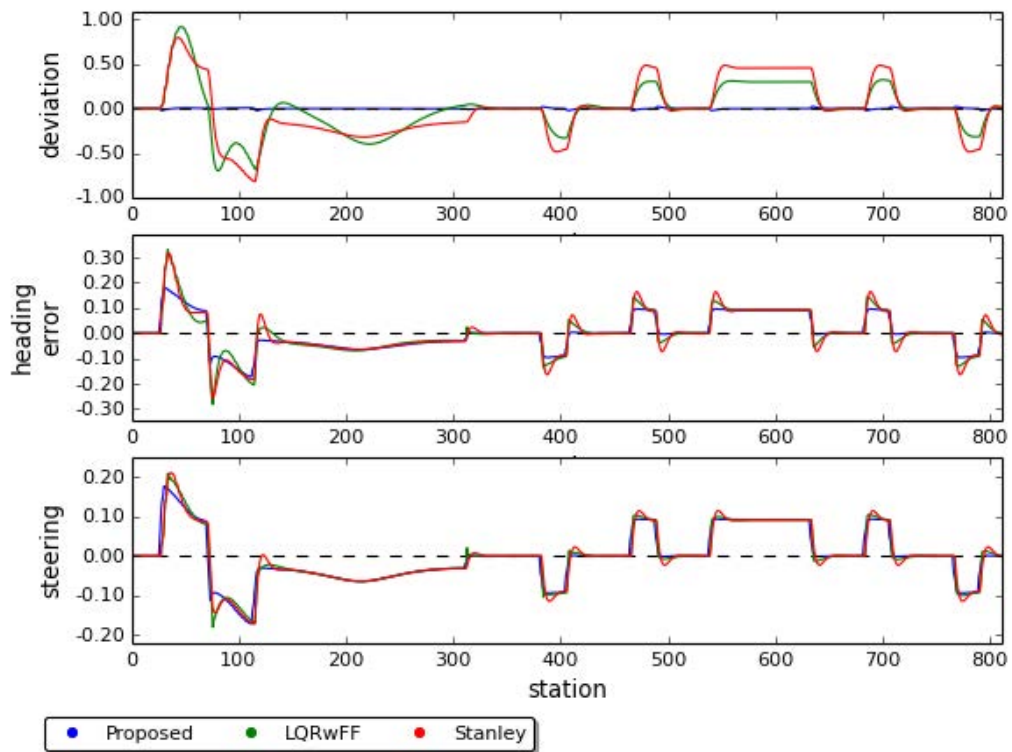
Figure 4.20b shows the influence of speed of steering wheel on the experiments on scenario II. Similar to its influence on scenario I, the speed of steering wheel also leads to smoother reactions of the methods. But the soft reactions of the method *LQRwFF* and *Stanley* consequently cause the increases of deviation. Among them, the speed of steering wheel has the most big influence on the *Stanley* method.

Figure 4.20 shows a complex tracking scenario which is more general than the course shown in Figure 4.19, for example the turns at intersection described in [147]. The proposed method performs better than the two other methods on dealing with the continuous change of the curvature of tracking path. When tracking the path that has smaller curvatures, for example the bigger ellipse segment, the proposed method causes the smallest deviation among the three compared methods. When tracking the path that has bigger curvatures, for example the two smaller ellipse segments, even if the maximal deviation is bigger than that the proposed method causes on the bigger ellipse segment, the deviation could also converges to a smaller and steady state in comparison with the other two methods.

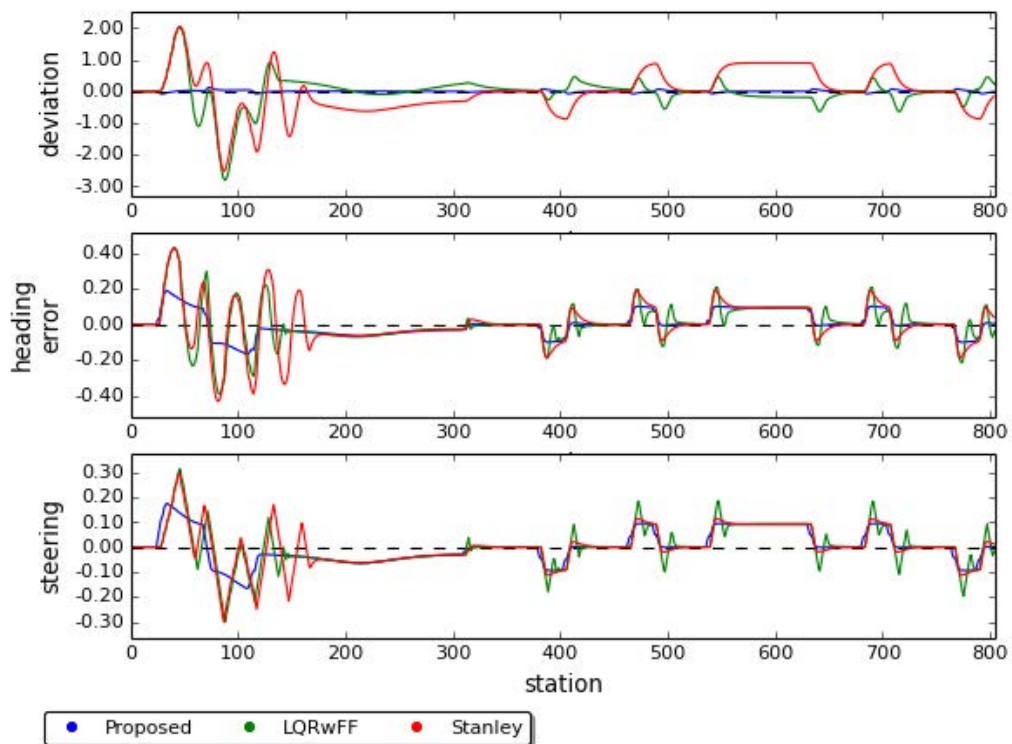
#### 4.5.6/ COMPARISON AT DIFFERENT REACTION TIME

In previous sections, we choose a small sampling time (0.01 s) to focus on observing the performance of the lateral control methods at different speed. In addition to the influence of vehicle speed, sampling time is another factor that affects the performance of lateral control method.

When vehicle runs at low speed and very small sampling time of perceiving environment, each existing lateral control method works very well. But, for most of vehicles, the compute capability of on-board devices is limited. In other words, the process of perceiving environment, especially by vision sensors, generally costs much time. One of the solutions of dealing with big perceiving time is to enlarge the look-ahead distance and estimating, between each two successive perception results from on-board sensors, the relative position between vehicle and tracking path with the outdated tracking path model. On one hand, the enlargement of look-ahead distance leads to less precision of modeling the tracking path. Meanwhile, the estimating process indicates the errors. On the other



(a) Comparison: Scenario II, speed 5 m/s



(b) Comparison: Scenario II, speed 10 m/s

Figure 4.21: Comparison: Scenario II, reaction time 0.1 s

hand, the enlargement of look-ahead works on tracking path which has small curvature. But it is useless on modeling the turns at intersection. So it is necessary to compare the performance of lateral control methods with different sampling time.

Figure 4.21 shows the comparison of the three methods at different velocity in the scenario II. The reaction time of the lateral control method is 100 ms. In the experiment, the values of the two factors  $k_s$  and  $k_p$  are same,  $k_p = k_s = 0.4$ . The experiment result shows that, the proposed method performs better than *Stanley* and *LQRwFF* at different speed. The performance of *Stanley* and *LQRwFF* is acceptable when the speed is 5 m/s. At the speed 10 m/s, they cause too large deviation from tracking path. So, in our opinion, the proposed method performs is more suitable to be used on the control of turns at intersection.

Comparing the two major features of all steering method concerns with some automatic steering control methods, for example the Stanley method and the optimal control method (Linear Quadratic Regulator with Feed Forward), the proposed method presents a better performance on curvature path, especially on the path that has an inconstant curvature. This could help to control vehicles to move along the given path precisely and so as to increase the safety of movement on the turns of an intersection, not only the ego-vehicle's but also the vehicles running on neighbor paths.

## 4.6/ CONCLUSION

As foundation of automatic steering control methods, various types of technologies of perceiving ego-vehicle's outside environment are already developed. In this chapter, based on the comparison of these techniques, the vision-based environment perception method was chosen as most actual and usable method to model ego-vehicle's tracking path. The development of the steering control method proposed in this chapter was based on the precisely detected path model.

After the comparison of the three major types of automatic steering control methods, the geometric method was chosen as the foundation of modeling the correction term of proposed control method. Its simpleness indicates the control method would not occupy too much computing resource. It's important characteristic of control method for implementing on on-board computer and for being computed in a high frequency application scenario. The curvature term, the rest part of the control method, was developed basing on modern differential geometry theory. The final equation is simple too.

The comparisons between proposed steering control method and other methods show that the proposed method have more effects on tracking curve path than other methods. The smaller amplitude and quick convergence of ego-vehicle's deviation from center-line of tracking path, which is caused by the change of curvature of tracking path, provide more safety, especially in turns at a complex and huge intersection.

## CONCLUSION AND FUTURE WORK

### 5.1/ CONCLUSION

The cooperative intersection management normally concerns the longitudinal movement control of vehicle. This thesis firstly is focused on the longitudinal control. But, because of the complexity of the lateral movement control at complex intersection, especially in case of hybrid traffic environment, the lateral control also plays an important role in the cooperative intersection management. So, after the part about longitudinal control, this thesis proposed a new lateral control approach.

For cooperative intersection management, the longitudinal safety of individual vehicle is important to any management strategy. The safety issue could be caused by unexpected abrupt brake of preceding vehicle or wireless communication constraints. We firstly proposed the *Reaction Time based Cooperative Velocity Control (RT-CVC)* by importing the reaction time into the control approach for these reasons. It takes into account the assumption that previous vehicle will brake immediately with its maximal deceleration capability until the vehicle has stopped. The simulation shows that the RT-CVC helps to improve the longitudinal safety of vehicle at intersection.

The centralized architecture and the sequence based protocol were chosen for intersection management. Each vehicle that is approaching the intersection has two situations, obtained the right of way from intersection manager or not yet. If the vehicle has got the authorization of traversing the intersection, it only needs to consider its previous vehicle listed in the sequence. If the vehicle is denied to cross the intersection, it considers the stop line to slow down even stop. By considering these objects as different obstacles, we proposed the *Reaction-Time based Cooperative Adaptive Cruise Control (RT-CACC)* to implement the cooperative intersection management with the *First Come First Served (FCFS)* policy. The simulations of safety show that the following vehicles could safely adapt their motion before they obtain the authorization, even if there is an unexpected stop of a vehicle at the intersection.

The two existing strategies of synchronizing the traffic flow could not balance the usage of lane space before intersection, the occupancy of intersection and the density of traffic flow after intersection. We proposed the *Reaction-Time based Cooperative Adaptive Cruise Control with Smoothness strategy (RT-CACCS)* to balance the three targets. It spreads out the adaptation of velocity during the whole movement in the storage zone. For increasing the usage the space of lane before intersection, if the vehicle needs to brake or even stop, RT-CACCS controls vehicle to achieve its lowest speed at the middle of the storage zone. This avoid the less usage of storage zone that is caused by the strat-

egy of adapting at the beginning of storage zone. And then RT-CACCS adapts vehicle's velocity to a desired speed before the vehicle arrives at the intersection. This avoid the speeding up that is caused by the strategy of adapting in the end of storage zone. And it consequently decreases the time of occupying the intersection. Meanwhile, the adaptation under control of RT-CACCS is smooth so as to avoid sharp adaptation and to improve the passenger's experience. The density of the traffic flow after intersection under control of RT-CACCS is close to that of the better one of the two existing strategies.

For the lateral control, we compared the on-board sensors and finally chose the vision sensors to obtain actual and accurate turning path at intersection. Because the turning curve at intersection is sharp, we considered the existing modeling approaches and chose the geometric approach. The frenet curvature is imported into the geometric modeling approach and then the *Frenet based Control* (FBC) is proposed. Comparing FBC with *Stanley* and *LQRwFF*, the proposed method has better performances in two aspects: the minimal deviation of vehicle from tracking path and the most quick convergence of deviation to 0. Most of turning path at intersection is not circular arc but ellipse arc which has a non-constant curvature. So the simulations of tracking ellipse arc path were also conducted to show the performance of our approach. The proposed lateral control method performs better and is suitable for controlling the lateral movement of vehicle at intersection.

## 5.2/ FUTURE WORK

The experiments of longitudinal control are just conducted on simple scenario and the road course could not represent the real transportation environment. So a complex road course that includes a more real intersection will be created in the simulation platform to verify the smoothness effect on traffic flow. Then a transportation system that consists of many intersections will be designed to observe the smoothness.

The proposed methods in this dissertation are about the control of an isolated intersection which just consider the vehicles that are approaching ego-intersection. But the output of one intersection might lead to congestion at downstream intersections, even if the management of ego-intersection performs well. So the management of ego-intersection that involves the longitudinal motion of vehicles and the situation of downstream intersections is an interesting direction.

The output of each intersection affects not only its downstream intersection but also the whole transportation system. Actually, some researches that concerns the tricolor signal system are already carried out basing on this point of view. Basing on the previous works, the intersection management that considers the situation of the intersection network to balance the traffic flow of the whole transportation system deserves to be studied.

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# PUBLICATIONS

1. *V2I-based Velocity Synchronization at Intersection*  
Xuguang Hao, Abdeljalil Abbas-turki, Florent Perronnet and Rachid Bouyekhf  
Proc. Mathematical Methods & Computational Techniques in Science & Engineering, Athens, Greece, 2014.
2. *Intersection management based on V2I Velocity Synchronization*  
Xuguang Hao, Abdeljalil Abbas-turki, Florent Perronnet, Rachid Bouyekhf and Abdellah El-Moudni  
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3. *V2x for vehicle speed synchronization at intersections*  
Alexandre Lombard, Xuguang Hao, Florent Perronnet, Abdeljalil Abbas-Turki, Abdellah El-Moudni and Rachid Bouyekhf  
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4. *V2x for vehicle speed synchronization at intersections*  
Alexandre Lombard, Xuguang Hao, Florent Perronnet, Abdeljalil Abbas-Turki, Abdellah El-Moudni and Rachid Bouyekhf  
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## Abstract:

The intersection management has received a particular attention during more than a half of century for improving the urban traffic throughput. In order to fully benefit from the cooperative intersection management, the longitudinal control and lateral control of vehicles are considered.

In this thesis, two issues of cooperative longitudinal are treated. The first one is raised by the communication problems and kinetic constraints. The adopted longitudinal control is a non-linear function in which a maximum communication time that should be respected at the worse case and a deceleration constraint are considered. If the constraints are not respected, the function triggers the stop of vehicle. The thesis addresses also the problem of traffic efficiency. There are two approaches for the speed synchronization but because the synchronization point is determined, each of both raises either the problem of empty lanes or the problem of slow clearing of the potential zones of collision. The thesis proposes an approach that spreads out the synchronization during all the travel of vehicle.

For the lateral control of vehicle at intersection, there are two problems. The first is the limit of the field of vision due to sharp curves. The second is the delay of the processing by cameras. Thus the thesis proposes a control based on the calculation of Frenet curvature coupled with correction of deviation from tracking path. Both the curve tracking and the correction are deduced from the circular motion induced by the steering wheel angle. The advantages of this approach compared to traditional approaches (the Linear Quadratic Regulator with Feed Forward and the Stanley) are to be not greedy in terms of the necessary field of view and to have more flexible real-time constraints. The comparison with current approaches shows that the proposed approach under urban traffic conditions is able to resist against a longer sampling time in contrary to the other two traditional approaches.

**Keywords:** cooperative intersection management, longitudinal control, lateral control

## Résumé :

L'amélioration de la fluidité du trafic aux intersections a reçu une attention particulière depuis près d'un siècle. Dans la thèse nous nous intéressons à la régulation coopérative des intersections par la synchronisation des vitesses. La synchronisation des vitesses grâce à la communication sans-fil a plusieurs avantages mais pour les exploiter pleinement, il est nécessaire d'aborder les problématiques des commandes longitudinale et latérale des véhicules.

En ce qui concerne la commande longitudinale, la thèse s'intéresse à deux problématiques. Pour des raisons évidentes de sécurité, les délais de communication sans-fil avec les véhicules des autres voies, à savoir hors de la portée des capteurs, doivent être pris en compte. Pour ce faire, la commande longitudinale adoptée est une fonction non linéaire qui considère un temps maximal de communication et une borne de décélération. Si les contraintes de ne sont pas respectées, la fonction déclenche l'arrêt du véhicule. Les résultats de simulations étant concluants dans des cas extrêmes, la thèse aborde la problématique de fluidité du trafic. En effet, le comportement du trafic dépend du choix du lieu où commence la synchronisation des vitesses. La thèse discute les deux approches classiques et propose une solution de lissage.

En ce qui concerne la commande latérale, l'intersection pose deux problèmes. Le premier est la limite du champ de vision à cause des courbures serrées des mouvements tournant et la deuxième est le délai de traitement par les caméras. Ainsi, la thèse propose une commande basée sur le calcul de la courbure de Frenet couplé à la correction des écarts. Le suivi des courbures et la correction sont tous les deux déduit à partir du mouvement circulaire induit par l'angle du volant. Les avantages de cette approche par rapport aux approches classiques (Linear Quadratic Regulator with Feed Forward et Stanley) est d'une part, de ne pas être gourmande en termes de champs de vision nécessaire et d'avoir des contraintes temps-réels plus souples.

**Mots-clés :** régulation coopérative des intersections, commande longitudinale, commande latérale

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