Multiagent-based Virtual Reality Intelligent Vehicles Simulation Platform

Yue Yu

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ÉCOLE CENTRALE DE LILLE

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Spécialité : Automatique, génie informatique, traitement du signal et des images

par

YU Yue

Master of Engineering of Beijing University of Aeronautics and Astronautics (BUAA)

Doctorat délivré par l'École Centrale de Lille

Conception et Développement d'une Plateforme Multi-Agent en Réalité Virtuelle de Pilotage de Véhicules Intelligents

Soutenue le 9 septembre 2013 devant le jury :

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Thèse préparée au Laboratoire d'Automatique, Génie Informatique et Signal
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École Doctorale Sciences pour l'ingénieur - 072
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In the end, I convey special acknowledgement to my family for supporting me to pursue this degree and to accept my absence for three years of living abroad.

Yue YU

Villeneuve d'Ascq, France
June, 2013

To my parents,
to all my family,
to my professors,
and to all my friends.

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Acronyms

AHS - Automated Highway System

DCOM - Distributed Component Object Model

GIS - Geographic Information System

HLA - High Level Architecture

ITS - Intelligent Transportation Systems

MAS - Multi-Agent System

SNE - Synthetic Natural Environment

VR - Virtual Reality

VR-ISSV - Virtual Reality Intelligent Simulation System of Vehicles

General Introduction

General introduction of the thesis

This thesis is the fruit of a three years work (2010-2013) spent in "Laboratoire d'Automatique, Génie Informatique et Signal (LAGIS)" in Ecole Centrale de Lille, under the supervision of Prof. Abdelkader EL KAMEL (in France) and Prof. Guanghong GONG (in China). With the research background of Prof. Abdelkader EL KAMEL in intelligent vehicle control and the research background of Prof. Guanghong GONG in advanced simulation technology, the research presented in this thesis contributes to multi-agent based modeling and simulation of microscopic traffic in virtual reality system. The intent of this research is to provide a new approach to effectively ensure traffic safety.

In the developed countries worldwide, road accidents are causing more injuries and casualties than any other man-made or natural hazard. In the European Union, more than 40,000 people die and over one million are injured every year because of road accidents. Major challenges that roadway transportation faces are increasing traffic congestion, accidents, transportation delays, and vehicle emissions. To solve these problems, US Department of Transportation has taken an approach called Intelligent Transportation Systems (ITS), and Automated Highway System (AHS) is a major element of ITS development. Both ITS and AHS are comprehensive programs, including technological advances in computers, communications, and sensor technology to transform road transportation into an effectively managed, well-integrated, universally available, and affordable system.

Transportation research and development are no longer a field dominated by civil, mechanical, operation research, and other traditional engineering and management disciplines, but it is an interdisciplinary field. ITS and AHS are complex systems, in which various factors such as human, vehicle and environment interact with each other, and abundant information is multi-sourced, heterogeneous and unstructured. Implementation of these systems require the intelligent vehicles. The development of ITS and AHS requires extensive testing, verification and evaluation of new traffic concepts. Therefore, many traditional technologies are severely limited so as to be disabled in this area. Modeling and simulation (M & S) have been identified as important steps in realizing the transportation initiatives. It is widely used in the design and test of intelligent vehicles, to complement experimental results as well as to analyze different control algorithms in different traffic situations and environment, where realistic experimental tests with real vehicles would be hard to accomplish due to hardware and vehicle availability problems.

Traffic simulation provides a flexible, effective and safe way to research innovative concepts and applications. Virtual Reality (VR) technology and Multi-Agent System (MAS) are increasingly being used in transportation system, especially for traffic simulation. Thus this thesis combines the traditional ITS with VR and MAS to research on the microscopic traffic simulation system, including systematically investigating the modeling method of vehicle simulation, integrating intelligence into vehicle simulation framework, and researching on the interactions among the vehicles, the traffic situations and the environment.

Main contributions

- Oriented traffic safety, a modular application software, Virtual Reality Intelligent Simulation System of Vehicles (VR-ISSV) is designed. VR-ISSV researches on the interactions among the vehicles, the traffic situations and the environment information, especially intelligence is integrated into vehicle simulation framework based on multi-agent. Multi-agent technology sufficiently reflects the thought of the artificial intelligence and is a more suitable method for constructing VR-ISSV. Based on multi-agent technology, the study focuses on the modeling methodology of VR-ISSV and its some key aspects. The goal is to build up the systematical modeling methodology for VR-ISSV as well as to improve its intelligence and scalability. Multi-agent based VR-ISSV has the characters of reusability, scalability and flexibility, which could realize the rapid construction of VR-ISSV with model reconfigurability and code reusability.

- An intelligent vehicle agent in virtual reality simulation system is proposed. It is a comprehensive model of 3D virtual vehicle combining with perception module, motion module, cognition and behavior module, and internal properties. Intelligent vehicle agent is well suited to incorporate and simulate driver's cognitive processes and personalities' mechanism in the complex traffic situation.

- The car following behavior and the overtaking behavior based on the intelligent vehicle agent are realized in straight lane, which is better understanding of the human factors to analyze car following behavior and the traffic situation to analyze overtaking behavior in traffic.

- Most existed researches on traffic simulation with virtual reality have done little work to profit the VR system to provide realistic environment information for simulation. Combining Geographic Information System (GIS) and VR to realize the terrain visualization could enhance the authenticity. Environment agent is constructed based on the conception of Synthetic Natural Environment (SNE), which is the representation of the natural environment in the system established by the modeling and simulation methods, taking into account the interaction between the simulation entities and natural environment simulation system. GIS is used to establish environment agent, which makes the simulation system much more real. Environment agent is dynamic and its characteristic could be changed, and it also could affect entity agents through the environmental parameters stored in the model database.

- Microscopic traffic behavior model based on the intelligent vehicle agent involving environment are studied. To ensure the safety in microscopic traffic maneuver, the intelligent vehicle controllers adapting to complex environment are considered. Fuzzy logic based controllers are designed for sending the appropriate output to the vehicle's actuators - the steering wheel and the throttle/brake pedals. The fuzzy logic controllers are designed to mimic human behavior with the consideration of environment.

Outline of the thesis

This thesis is divided into 5 chapters.

Chapter 1 reviews the related fields of ITS, M & S, VR and MAS, and some previous research about VR and MAS applications in transportation system. The concept and development of ITS is introduced. The development of M & S is briefly described. VR and VR system are presented. Agent, MAS and ABMS are surveyed. This chapter gives the application of VR in traffic simulation, traffic visualization and driving simulator, and shows MAS applications in traffic modeling and simulation. Inspired by the previous work, this thesis contributes to an interdisciplinary area of ITS, VR and MAS technologies. This study is interested in two aspects that are important for VR traffic simulation system: intelligent simulation based on multi-agent and realistic dynamic features from VR environment.

Chapter 2 proposes multi-agent based framework modeling for Virtual Reality Intelligent Simulation System of Vehicles (VR-ISSV), analyzes its advantages and studies the behavior of typical agent definitions. VR-ISSV includes entity agents (intelligent vehicle agents and around vehicle agents), service agent and environment agent. Meanwhile, the system implementation is introduced in detail, especially two distributed simulation supporting services are presented. Finally rapid construction of simulation system with AppWizard are illustrated and two simulation scenarios are carried out to show the valid of our method.

Chapter 3 concentrates the intelligent vehicle agent model. As the most important part of VR-ISSV, the intelligent vehicle agent could reflect the microscopic traffic behavior considering environment effects and traffic situation. Car following behavior is shown in detail. Car following behavior of virtual vehicle is realized by the coordination mechanism of agent-based multi-controller, which is determined by predetermined perceptual threshold levels. Besides, overtaking behavior model based on the intelligent vehicle is introduced in detail. First, there is the decision whether to initiate an overtaking behavior, the lane changing feasibility is studied. Then, after deciding that the maneuver is possible and necessary, the lateral controllers and the longitudinal controllers coordinate to realize overtaking.

Chapter 4 presents the modeling and simulation of environment agent. First, SNE agent is established. The terrain visualization is realized by combining GIS with VR. To establish the SNE agent, not only it is necessary to construct realistic environment model and consider those attributes in the environment which will affect the performance of the vehicle, but also we need to consider the data requirements of other simulation subsystem, such as visualization. Then, the vehicle dynamic models considering the road geometry and the wind is introduced in detail. Finally, this chapter analyzes the effects that the road geometry and the wind affecting on vehicle.

Chapter 5 shows the intelligent vehicle control involving the environment effect. Chapter 4 analyzes the effect of environment affecting on vehicle. This chapter is the further research of intelligent vehicle agent, the fuzzy logic based intelligent vehicle controllers adapting to complex environment are designed. The fuzzy logic based steering controllers, throttle/brake controllers with the consideration of road and wind effect, steering fuzzy controller for lane keeping, steering fuzzy controller for lane changing and throttle/brake fuzzy controller are introduced in detail. The autonomous road behavior, the car following behavior and the overtaking behavior with respect to road curvature and wind are realized in VR-ISSV, and some simulation results are given to explain the validity of the designed fuzzy controllers.

Chapter 1

Background

Contents

1.1 Research motivation

Nowadays simulation is commonly used in engineering design for verifying design concepts before physical prototypes are produced. The simulation of complex products such as mechatronics in general involves a synergy of multiple traditional disciplinary areas and entails the collaborative work of a multidisciplinary team (Wang 2012). Simulation techniques are especially useful when real-world architectures are not available for the purpose of experiments (Núnez 2012).

Major challenges that roadway transportation faces are increasing traffic congestion, accidents, transportation delays, and vehicle emissions. To solve these problems, US Department of Transportation has taken an approach called Intelligent Transportation Systems (ITS), and Automated Highway System (AHS) is a major element of ITS development. Both ITS and AHS are comprehensive programs, including technological advances in computers, communications, and sensors to transform road transportation into an effectively managed, well-integrated, universally available, and affordable system (Yu 2012a).

ITS and AHS are complex systems, in which various factors such as human, vehicle and environment interact with each other, and abundant information is multi-sourced, heterogeneous and unstructured. Implementation of these systems require the intelligent vehicles. Therefore, many traditional technologies are severely limited so as to be disabled in this area. Since intelligent vehicles are very expensive, simulation becomes a very important phase of the development process. Modeling and Simulation (M & S) have been identified as important steps in realizing the transportation initiatives. With the technology of M & S, the complex real traffic systems relating to human, vehicle, road and environment could be transferred into the virtual traffic with model database, simulation platform, *et al.*, shown in Fig. 1 (Yu 2013c).

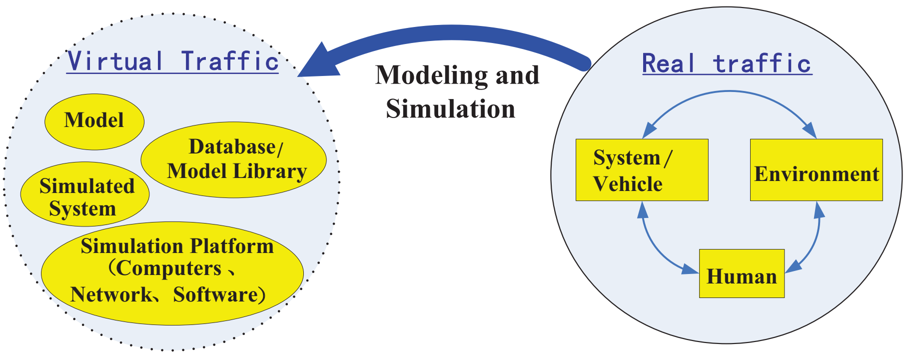


Figure 1.1: Traffic Simulation Demonstration

There are two different approaches used to simulate the traffic in a network. The first one is the macroscopic approach based on an analogy between traffic flow and a real fluid flow. The second one is the microscopic approach simulation dealing with the individual behaviors of each vehicle. However, in recent years, there has been growing interest in driving simulators because they have proved to be highly useful tools for training and instructing drivers, particularly professionals (bus, truck, emergency vehicle drivers, etc.) (Maroto 2006). Furthermore, research complexity in this area is increasing. On one hand, the interaction among vehicles, the knowledge about the traffic situation, the driver behavior and the driver state, the motion of the vehicles, the traffic network dynamics and the communication systems have to be combined into research. On the other hand, traffic problems with the congestion, the safety and the environmental impacts are becoming more important. Therefore, developing the traffic simulation system becomes a difficult work, including the interaction between vehicle and environment, the communication among softwares, the development of different simulation models and the design of all kinds of simulation applications, besides the simulation fidelity needs to be guaranteed, the complicated and dynamic features of real world have to be considered into the traffic simulation system (Yu 2013d).

With the development of computer technology and the increasing complexity of studied objects, different disciplines are involved and system simulation is tending to be more and more complex. The M & S of intelligent system is to apply intelligent theory and methodology to solve intelligent problems and is widely used in Computer Integrated Manufacturing System (CIMS), Computer Generated Forces (CGF), Simulation Based Acquisition (SBA), and so forth. With the development of artificial intelligent, many kinds of intelligent technologies (knowledge engineering, expert system, intelligent optimization algorithm, multi-agent technology, qualitative reasoning, neural network, etc.) have been widely used on the M & S of intelligent systems (Li 2012).

At the same time, several traffic simulation platforms have been developed, recently, such as MOBYSIM (Noort 2010), providing an integrated traffic simulation platform. Meanwhile, some traffic simulation tools have been developed, such as AIMSUN, PARAMICS, VISSIM, MITSIM, *et al.* The AIMSUN microscopic traffic simulator uses car-following models based on the Gipps models. The car-following model in PARAMICS and in VISSIM is based on a variant of psychophysical model. Besides, there are some microscopic models used for simulating traffic on the level of cities and freeway networks. The MITSIM model has been used to evaluate aspects of the traffic control system of the Central Artery/Tunnel project in Boston. AIMSUN2 has been used to simulate the Barcelona Rings Roads (Maroto 2006). Little attention has been paid on system modeling and formal specification of traffic simulation, which results in a gap between the system modeling at the design stage and the implementation at the application stage.

Virtual Reality (VR) technology is increasingly being used in traffic simulation systems (Luo 2012b; Ambrož 2005) and driving simulators (Ambrož 2010; He 2006). Furthermore, with the traffic simulation developing into the large-scale and high speed direction and the increasing number in large extent, traffic simulation system has a comparatively large computation, the distributed interactive simulation technology is used, the function of the whole system has to be distributed in different nodes, and then accomplish the same task collaboratively through the computer network (Yin 2007; Donath 2001). Some distributed vehicle simulation system with virtual reality are proposed in (Yu 2012a; Tong 2009; Raimodi 2007). Meanwhile, Multi-Agent System (MAS) provides a suitable way to model and simulate traffic systems since they offer an intuitive way to describe every autonomous entity on the individual level. MAS has been used in collaborative driving (Hallé 2004; Hallé 2005), agent-based driver behavior modeling (Hidas 2002; Hidas 2005) and multi-agent based microscopic traffic simulation (Doniec 2008; Mandiau 2008).

Inspired by the existing studies mentioned above, this study combines the traditional ITS with VR and MAS to research on the microscopic traffic simulation system, including systematically investigating the modeling method of vehicle simulation, integrating intelligence into vehicle simulation framework, and researching on the interactions among the vehicles, the traffic situations and the environment. With this research, a new approach can be found to effectively ensure traffic safety (Yu 2012b).

This chapter is dedicated to the presentation of the related fields for this study. As mentioned above, M & S is useful in the research of ITS. VR and MAS play important role in M & S and ITS. Thus in the literature reviews, ITS, M & S, VR and MAS will be described. Previous research concerning VR applications in transportation system and MAS applications in transportation system will be introduced in detail.

1.2 Literature review

1.2.1 Intelligent transportation system

ITS has been developed since the beginning of 1970s, which makes human, vehicles, roads united and harmonic, also establishes a wider range, fully efficient, real-time and accurate information manage system (Qi 2008). ITS can be broadly defined as the application of advanced technologies, such as communications, sensors, and computing, to the transportation system, supply the information of real-time used to improve the safety, efficiency, and comforts of transportation systems, and diminish the impact to environment (Perng 2011). The principal of ITS is illustrated in Fig. 1.2 (MLIT).

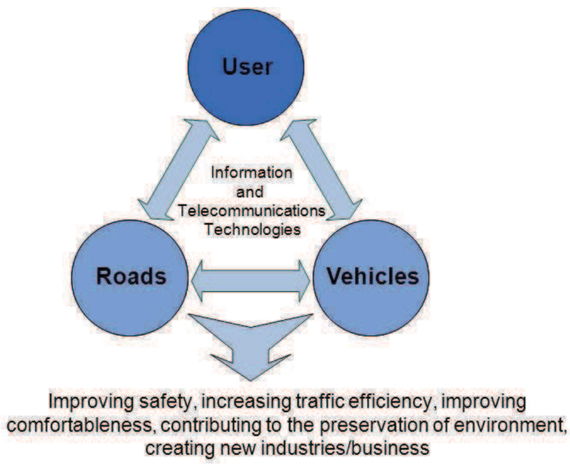


Figure 1.2: Conceptual Image of Intelligent Transportation System

The development of ITS in different countries can be divided into two stages. The typical characteristic of the first stage is mainly on transportation information acquisition and processing intelligentialize. Transportation telematics was probably origin from the beginning of the 1970s in Japan, where several technological programs were conducted to deal with the large number of traffic deaths and injuries as well as the structural ineffective traffic process. In Europe, the first formalized transportation telematics program named Programme for European Traffic with Highest Efficiency and Unprecedented Safety (PROMETHEUS) (Williams 1988) was initiated by European automotive companies in 1986, while in 1988, Dedicated Road Infrastructure and Vehicle Environment (DRIVE) program was set up by the European authorities (Buckley 1990), for the development and test of the communication system, for driving assistance and traffic management (Tomizuka 1997). The USA followed in 1990 by forming Mobility 2000 in 1989 and in 1990 by establishing the Intelligent Vehicle Highway Systems (IVHS) program , that has been renamed into Intelligent Transportation System (ITS) in 1994 (Yan 2012). A key project, Automated Highway System (AHS) was conducted by National Automated Highway System Consortium (NAHSC) formed by the US Department of Transportation, General Motors, University of Californix and other institutions. Under this project various fully automated test vehicles were demonstrated on Califomia highways (Janet 1992).

Intelligent vehicles are important roles in ITS, which are motivated by three desires: improved road safety, relieved traffic congestion and comfort driver experience (Sukthankar 1998). The intelligent vehicle senses the environment around them using sensors (such as radar, lidar or machine vision techniques) and strive to achieve more efficient vehicle operation either by assisting the driver (via advisories or warnings) or by taking complete control of vehicle (Baskar 2011).

Therefore, the technologies for vehicle active safety, collision avoidance and intelligent vehicle were rapidly developed in the second stage of ITS. The NAHSC 1997 Technology Demonstration (DEMO'97) (Ozguner 1997) and Partners for Advanced Transportation Technology (PATH 1986) (Shladover 2007) were most influential project in automated highway system in America. In European Union, the European Road Transport Telematics Implementation Organization (ERTICO) takes advantage of the information and communication to develop the active safety and autonomous driving. The project eSafety (Commission a) was a joint initiative of the European Commission, industry and other stakeholders. The project eSafetySupport gived support to the cooperation of the involved institutions and persons and was one of the pillars of the EU Intelligent Car Initiative" (Commission b). The Technische Universität at Braunschweig is currently working on the project "Stadtpilot" with the objective to drive fully autonomously on multi-lane ring road around Braunschweig's city, shown in Fig. 1.3 (Wille 2010; Nothdurft 2011; Reschka 2012).

With the development of the ITS research, we find that there are many technologies needed to integrate together. (An 2011) integrate those technologies and

Figure 1.3: Proposed Track for Autonomous Driving in Stadtpilot

design an integrated model, shown in Fig. 1.4. If the integrated model system comes true, it is believed that most of current transportation problems can be solved. However, the limitation of any technology could be the limitation of ITS research. Due to the different situations of the fund investment, current technology merit and the various traffic problems for each country, the development level of ITS and research areas are distinct. Therefore, it is difficult to integrate these technology together for different countries. These bring new challenges for ITS research.

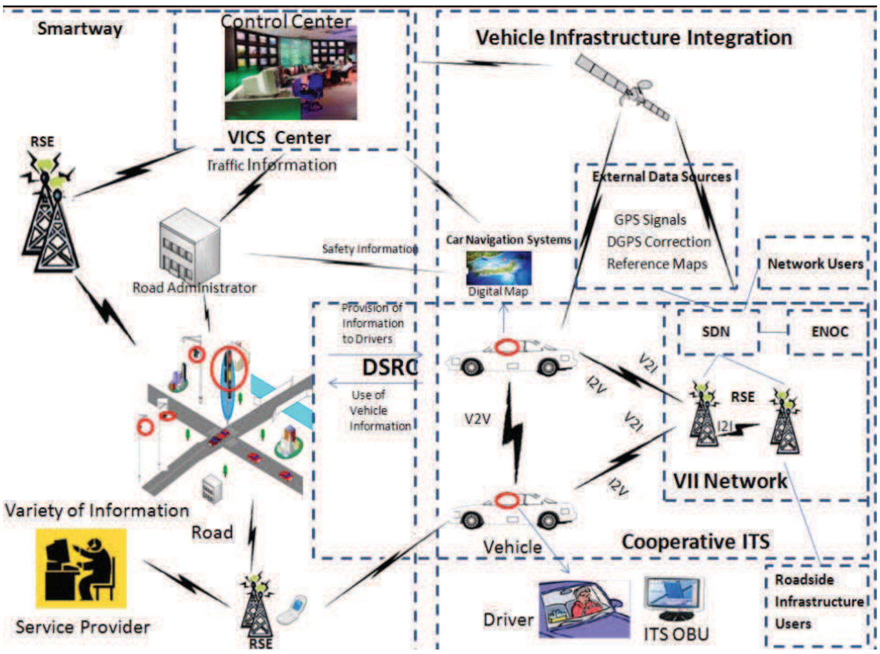


Figure 1.4: An Integrated ITS Model (An 2011)

1.2.2 Modeling and simulation

Since the 1950's, under the pulling of the requirements of various applications and the pushing of the evolution of associated technologies, Modeling and Simulation (M & S) technology has developed to come into being synthesized specialized technology, and rapidly becomes a common and strategic technology. At present, the tendency of modern modeling and simulation technology is developing towards networking, virtualization, intelligence, collaboration, and pervasion. Currently, M & S technology combined with high performance computing is becoming the third important means for recognizing and rebuilding the objective world besides the theory research and experiment research. Some focusing points in recent research and application of M & S including networkitized M & S technology based on modern network techniques, M & S technology on synthetized nature environment, intelligent system modeling and intelligent simulation system, M & S technology of complex system and open, complex, huge system, virtual prototyping engineering technology, high performance computer, pervasive simulation technology, *et al.* (Li 2005).

As introduced above, ITS has been developed into very complicated systems, including the expensive intelligent vehicles, the complex sensors and the different kinds of road structure. More and more tests are needed in the research of ITS. M & S have been applied into all kinds of fields to reduce the cost of tests. With the development of M & S technology, this thesis will propose an intelligent simulation framework for ITS, with the intention to assist the user in preparing the simulation of different traffic situations and designing the control algorithms in different environment.

1.2.3 Virtual reality

1.2.3.1 What is virtual reality?

Virtual Reality (VR) is a computer generated, interactive, three dimensional environments in which a person is immersed. This technology is an advanced man-machine interface of computer. It combines simulation, multimedia, artificial intelligence technology, and network technology together. It can make people immerse in the virtual environment and interact with computer in real time through natural means, such as: gesture, voice, touch, *et al.* VR has been defined as a way for humans to visualize, manipulate, and interact with computer-generated data (Aukstakalnis 1992).

VR is not just stereo graphics and the use of a head-mounted display and a glove. Three specific criteria must be met for an application to be considered as virtual reality. The application must be interactive, immersive, and user-centered (Li 2010).

(1) Interactive: using VR technology, users are able to investigate and explore various design aspects of the virtual environment through visual, aural, and/or

tactile sense. Interactive implies that the user is able to change the virtual environment, in real time, and directly without use of traditional input devices (*i.e.*, keyboard or mouse).

(2) Immersive: immersive environments make the user feel as if he was inside the virtual world and a part of it. This feat is accomplished by providing displays that cover the user's field of vision as much as possible, thereby isolating the user from the physical world.

(3) User-centered: for the virtual world to be user-centered, the computer must know the location and actions of the user. A piece of hardware known as a tracker is used for this purpose. The tracker allows the computer to know the location and orientation of the user when the user is interacting with objects in the virtual environment. With this information, the computer can change the displayed images to match the perspective of the user.

1.2.3.2 Virtual reality system

A VR system is the combination of the hardware and software that enables developers to create VR applications that present a virtual environment to users. The hardware components of a VR system receive input from user-controlled devices and convey multi-sensory output to create the illusion of a virtual world. The software component of a VR system manages the hardware that makes up VR system. This software is not necessarily responsible for actually creating the virtual world. Instead, a separate piece of software (the VR application) creates the virtual world by making use of the VR software system (Bierbaum 2000). There are three characteristics of VR systems: navigation, interaction, and immersion. Users of virtual reality can move about the computer-generated 3D scene and explore their surroundings. In addition to navigating through the environment, users are also able to interact with this virtual environment (Xu 2009).

According to the devices used in interaction, virtual reality system can be divided into four types: desktop system, immersed system, augmented reality, and distributed virtual reality (Li 2010).

(1) Desktop VR system uses PC or station of high quality to compute and display, focuses on mouse, joystick, or space/sensorball-controlled navigation through a 3D environment on a graphics monitor under computer control. This kind of system is cheap and easy to be realized. Application of desktop VR can be found in industrial teacher education (Ausburn 2004) and Virtual Prototyping (VP) to verify assembly and maintenance processes (de Sá 1999).

(2) In immersed VR system, the user is completely immersed in the virtual environment. This environment has been developed to provide a visual, three-dimensional space that the user senses (generally limited to visual and/or aural senses due to their relative importance and current technology). With these VR devices (such as head mounted displays, data glove, stereo glasses and so on), one can actively inhabit an inclusive computer generated environment, shown

in Fig. 1.5 (Mujber 2004). Application of immersed VR system could be find in manufacturing process (Mujber 2004; Bao 2002). The main advantage of immersed VR is that the user or users can have a sense of presence and scale as they observe realistic computer created objects and can interact with them. However, they are too expensive to common people to afford. This weakness really limits the development of immerse virtual reality technology (Li 2010).

Figure 1.5: Fully Immersive VR System (Mujber 2004)

(3) In Augmented reality (AR), 3-D virtual objects are integrated into a 3-D real environment in real time. It works on similar principles as immerse virtual reality system. While immersed, the user cannot see the real world around him. In contrast, AR allows the user to see the real world, with virtual objects superimposed upon or composited with the real world. Therefore, AR supplements reality, rather than completely replacing it(Azuma 1997). General AR system perform four tasks: (a) scene capture; (b) scene identification for selecting the right information for augmenting it; (c) scene processing, enriching scenes captured with augmented information; and (d) visualization of the augmented scene. Fig. 1.6 depicts this process (López 2010). The AR system has been used in industrial construction (Azuma 2001; Shin 2010) (see Fig. 1.7) and telerobotic control (Milgram 1995). The critical problem with present augment reality systems is the lack of real-time speed and accurate tracking. Thus many research deal with the consistency between the coordinate systems of the real and virtual worlds (Wang 2010c; Tian 2010). Most sensor-based tracking systems are not practical for outdoors, and computer-vision methods do not yet produce robust enough tracking for extended experiments outdoors. One method to achieving both control and repeatability is to use Mixed Reality (MR) Simulation (Lee 2013).

(4) Distributed Virtual Reality (DVR) environment belongs to distributed simulation, it is defined as three dimensional, interactive, computer generated

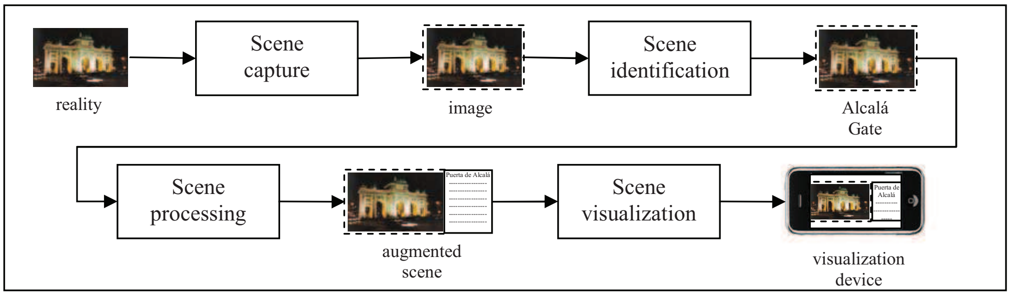


Figure 1.6: Tasks in Augmented Reality (López 2010)

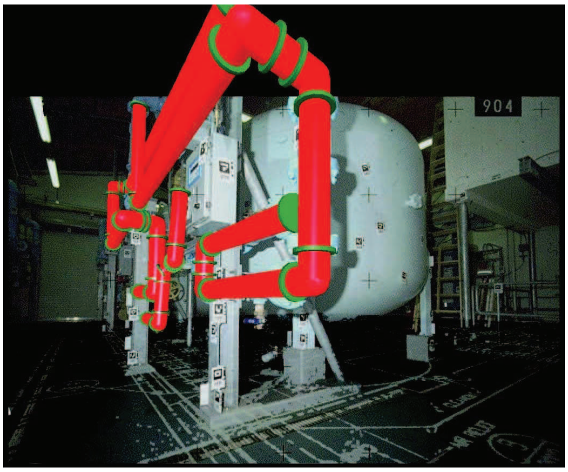


Figure 1.7: Industrial Construction Application of Augmented Reality System (Shin 2010)

environments accessible by several computers (and users) running over the Internet (Sulbaran 2000). DVR environments became more popular during the last decade, which is likely attributable to the wide expansion of high-speed internet access providing the basic support medium for these systems, as well as to the significant advances of both hardware and software (Bouras 2011). DVR environments is useful in the construction industry where a project requires several stages to be completed using a variety of resource by different parties from different places. It acts as a collaborative tool for design and construction of buildings. The standard of DVR has been changed from the Distributed Information System (DIS) interactive simulation of SIMUNET to High Level Architecture (HLA) (Tang 2005). With the development of the Internet, the DVR environment could be realized in Grid-based simulation system (Tang 2005; Zhou 1999) or in Web3D-based simulation system (Yang 2010).

There are some limitation in today's VR research. (1) VR worlds are visually unconvincing because of low resolution, limited field of view and head motion lags. (2) VR worlds are cartoons that lack realism. (3) VR makes people sick because of latency in motion tracking and cue conflicts in visual displays.

VR and VR systems have been presented with their features and broad applications. Nevertheless, most existing research on VR mainly has been concentrated on the visualization in a virtual world, little work has been done to profit the VR system to provide realistic environment information for simulation, which could enhance the simulation authenticity. This study will focus that the VR systems apply in the design and verification in microscopic traffic maneuvers. The visualization system based on VR will be realized. Besides, this thesis will profit the VR system to provide realistic environment information for traffic simulation.

1.2.4 Agent and multi-agent system

1.2.4.1 Agent definition

Although there is no universal agreement on the precise definition of the term "agent", definitions tend to agree on more points than they disagree. The general definition of agent proposed by Wooldridge in (Wooldridge 1997): an gent is an encapsulated computer system that is situated in some environment and that is capable of flexible, autonomous action in that environment in order to meet its design objective. Some modelers consider any type of independent component (software, model, individual, *et al.*) to be an agent (Bonabeau 2002).

Agents are computational entities which are able to interact with the environment in which they are operating in. They have the ability to perceive their environment, to process the information coming from this environment and consequently to perform actions aimed at modifying its status (Mellouli 2007; Mellouli 2009). Agents share the following four characteristics (Jennings 1998): (1) autonomy: an agent is autonomous when it acts without human intervention and controls its actions and its internal states; (2) reactivity: an agent rapidly reacts to what happens in its environment; (3) pro-activity: an agent can take actions by anticipating on what can happen in its environment; (4) social ability: an agent has the ability to interact with other agents when it judges necessary. An agent may also have other characteristics such as rationality, mobility, intelligence and learning abilities (Mellouli 2009). The agent technology can significantly enhance the design and analysis of problem domains under the following three conditions (Adler 2002): (1) The problem domain is geographically distributed; (2) the subsystems exist in a dynamic environment; and (3) the subsystems need to interact with each other more flexibly.

Many researchers believe that the agents represent the most important new paradigm for software development since object-oriented design, and the concept of intelligent agents has already found a diverse range of applications in manufacturing, real-time control systems, electronic commerce, network management, transportation systems, information management, scientific computing, health care, and entertainment (Chen 2010a).

1.2.4.2 Multi-agent system

MAS consists of a set of autonomous agents that interact among them and with their environment. MAS can be defined as the natural platform for studying CAS. Parts of the system are modeled as agents with a set of predefined characteristics (Cil 2010). In MAS, agents communicate with other agents in a system to achieve a global goal.

The characteristic of multi-agent systems is that: (1) each agent has incomplete information or capabilities for solving the problem and thus, has a limited viewpoint; (2) there is no system global control; (3) data are decentralized; and (4) computation is asynchronous (Sycara 1998).

1.2.4.3 Agent based modeling and simulation

Agent based Modeling and Simulation (ABMS) is recognized as many names. Agent Based Modeling (ABM), Agent Based Systems or Simulation (ABS), and Individual Based Modeling (IBM) are all widely used acronyms, but ABMS will be used throughout this discussion. Its origin can be traced back to as early as the 1940s when the first prototypical "cellular automata" was invented simulating grids' interaction with their immediate neighbors by on-off state switches (Von Neumann 1951).

Agent based simulation refers to a model in which the dynamic processes of agent interaction are simulated repeatedly over time, as in systems dynamics, and time-stepped, discrete-event, and other types of conventional simulation. An agent based model, more generally, is a model in which repeatedly agents interact. ABMS has roots in the fields of MAS and robotics from the field of artificial intelligence, as well as artificial life. But ABMS is not only tied to understanding and designing "artificial" agents. Its main roots are in modeling human social and organizational behavior and individual decision-making. With this, comes the need to represent social interaction, collaboration, group behavior and the emergence of higher order social structures (Macal 2008). At the simplest level, an agent based model consists of a system of agents and the relationships between them.

ABMS is a mindset more than a technology. The ABMS mindset consists of describing a system from the perspective of its constituent units (Bonabeau 2002). ABMS is a relatively new approach to modeling systems composed of autonomous, interacting agents. A typical agent structure is illustrated in Fig. 1.8. In an agent based model, everything associated with an agent is either an agent attribute or an agent method that operates on the agent. Agent attributes can be static, not

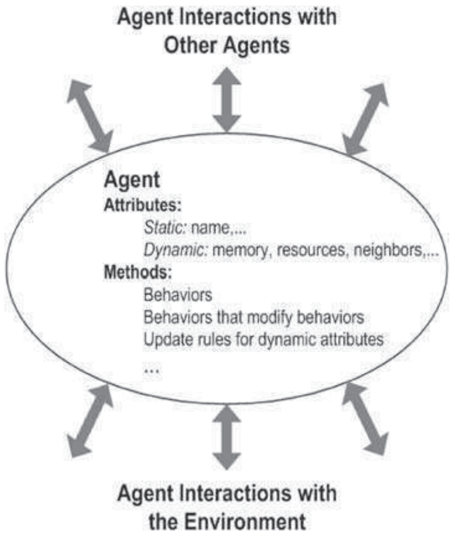


Figure 1.8: A Typical Agent (Bonabeau 2002)

changeable during the simulation, or dynamic, changeable as the simulation progresses. For example, a static attribute is an agent's name; a dynamic attribute is an agent's memory of past interactions. Agent methods include behaviors, such as rules or more abstract representations such as neural networks, which link the agent's situation with its action or set of potential actions. An example is the method that an agent uses to identify its neighbors (Macal 2010). In ABMS, each agent individually assesses its situation and makes decisions on the basis of a set of rules. Agents may execute various behaviors appropriate for the system they represent, for example, producing, consuming, or selling. Even a simple agent based model can exhibit complex behavior patterns and provide valuable information about the dynamics of the real world system that it emulates. In addition, agents may be capable of evolving, allowing unanticipated behaviors to emerge. Sophisticated ABMS sometimes incorporates neural networks, evolutionary algorithms, or other learning techniques to allow realistic learning and adaptation (Bonabeau 2002).

Some ABMS toolkits and development environments have been developed to support modelers by releasing them from the burden of house keeping tasks (Chen 2012b). The first of these to be widely employed was Swarm (Minar), whose design has influenced a series of succeeders including Repast, Mason, *et al.* In parallel, the Logo family has also evolved into a number of software packages for ABMS, such as StarLogo and NetLogo. The most commonly adopted form of these toolkits is libraries of frameworks (Gilbert 2008), which are open source libraries that can be linked to ABMS programs.

Applications of AMBS span a broad range of areas and disciplines. Applications range from modeling agent behavior in the millitary combat (Cil 2010), the urban and architecture field (Chen 2012a), the supply chains (Macal 2004), the social science (Pan 2007), the market mechanisms (Tonmukayakul), the e-government (Mellouli 2009) and many others.

1.2.4.4 Optimization of multi-agent system

The classical optimization concept for solving simulation-based optimization problems is divided into three independent, interconnected parts: the optimization model, the optimization methods and structure simulation. In the context of agent-based optimization concept has extended by an additional four part, *i.e.* the MAS. The MAS represents the Artificial Intelligence Part of the optimization concept linking the technical optimization model (structural optimization model) to the optimization methods applied. In engineering, this concept provides a general solution methodology for simulation-based optimization, regardless of a specific application. Fig. 1.9 summarizes the optimization concept using MAS emphasizing the central role of the MAS as a link between the optimization model and the optimization methods available (Nguyen 2012).

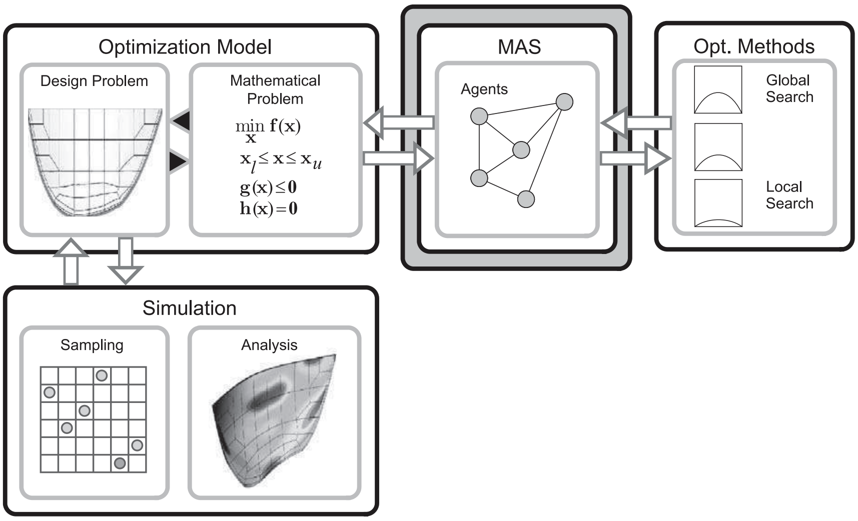


Figure 1.9: Optimization Concept with MAS (Nguyen 2012)

The Optimization Model is responsible for transforming a specific engineering problem to a mathematical optimization problem. The Optimization Methods include different deterministic as well as stochastic approaches, *e.g.* Evolutionary Algorithm (EA) (Michalewicz 1996), Sequential Quadratic Programming

(SQP) (Schittkowski 2007), Differential Evolution (DE) (Storn 1995), Probabilistic Global Search Lausanne (PGSL) (Raphael 2003), *et al.* The Simulation incorporates complex processes or tailor-made physical models using, *e.g.* Finite Element Method (FEM), Multibody System (MBS), *et al.* The MAS represents an agent based strategy network and acts as a link between the optimization model and individual optimization methods. It coordinates and controls on a higher level the connection between the two parts as well as the interaction between various optimization strategies. In addition, it emphasizes the concurrent and cooperative execution of heterogeneous interacting strategies not only for optimization, but also for the adaptation of the strategy network and for the coordination and analysis of the optimization process (Nguyen 2012).

It is necessary to considerate robust optimization in the optimization problems, where the design solution has to be robust with respect to implementation errors, production tolerances, uncertain environmental conditions, *et al.* Furthermore, solving a robust optimization problem needs to take uncertainties into consideration. (Beyer 2007) identify several sources of uncertainties during a design and optimization process of a technical system: (1) changing environmental and operating conditions; (2) production tolerances and implementation errors; (3) uncertainties in the system output; and (4) feasibility uncertainties.

At present, there are some publications which address the optimization of multi-agent system. (Siirola 2003) presented an agent framework that successfully integrates several approaches for single objective optimization. This paper discusses the theory of Collective Intelligence (COIN) using the modified version of Probability Collectives (PC) to achieve the global goal. (Kulkarni 2010) successfully demonstrated this approach by optimizing the Rosenbrock function in which the coupled variables are seen as autonomous agents working collectively to achieve the function optimum, making these agents work in a coordinated way, optimizing their local utilities and contributing the maximum towards optimization of the global objective. Task allocation is a key issue of agent cooperation mechanism in MAS. The main goal of task allocation is maximizing the overall performance of the system and completing the task as soon as possible. (Wang 2013b) proposed the Collection Path Ant Colony Optimization algorithm to achieve global optimization and reduce processing time. In order to design a multi-agent system with required emergent phenomena, evolutionary optimization can be used. (Privosnik 2009) investigated improvements of evolutionary optimization of multi-agent systems when multiple simulations of the system are needed for fitness function evaluation.

According to the previous research, the optimization of MAS could be divided into two aspects: one aspect is agent-based optimization, which uses the MAS to solve the optimization problem; the other aspect is to use some optimization algorithm to improve the performance of MAS. The research in the agent-based optimization is abundant in various fields, especially in distributed and heterogeneous environment, such as electricity market, transport chain, health care, urban environment, *et al.* (Barbati 2012). However, the research of improving MAS features with the optimization methods is not very extensive. This work need to be paid much attention because the global behavior of the strategy system results is more important than the local behavior of agents in MAS.

Agent, MAS, ABMS and optimization of MAS have been introduced in this section. Nevertheless, agent is not an universal solution and there is much room for improvement, such as adapting traditional designs derived from traditional Ordinary Differential Equations methods to Agent-Based models, and to resolve the issues of scalability and universality. The continuous growth in computer capabilities and the extensive research currently being done in the field of agent are expected to provide some of the improvements needed in the near future.

This thesis will research on the intelligent simulation for microscopic traffic system based multi-agent. The concepts of agent and ABMS will be used in the design of simulation framework, including intelligent vehicle agent, environment agent and service agent. Some application of agent technology have been mentioned above. In Section 1.3, the application of MAS in transportation system will be introduced in detail.

1.3 Previous research

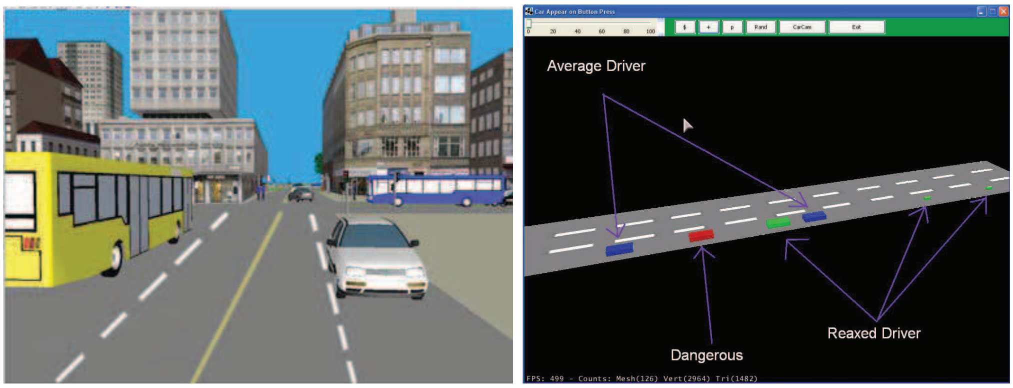
1.3.1 VR applications in transportation system

Application of virtual reality technology to simulate traffic in reality can be used in the field of transport-related personnel in exercises and training. It can save a lot because the real traffic exercises and training take a lot of human material and financial resources. The virtual exercise can avoid human error causing economic loss, but also repeated practice, so that new traffic control staff also have some practical experience to ensure that all emergency situations in a good results. Virtual reality is a new urban transport mode of human-computer interaction. People can communicate with computer like in the everyday environment of the urban traffic. It brings a new approach for mankind to explore the law of things'change and motion in reality (Ye 2010). Trials to diminish several of ITS costs, have indicated that the use of VR technology can provide significant benefits to an ITS industry (Amditis 2004). This section will introduce the applications of VR in traffic simulation, traffic visualization and driving simulator.

1.3.1.1 VR applications in traffic simulation

Traffic simulation describes large numbers of vehicles on a traffic network by taking advantage of the reduced dimensionality typically found on road networks: vehicles follow roads and their motion can be described with few degrees of freedom (Wilkie 2012). Research on techniques for traffic simulation has been carried out since the 1950s; see the survey of (Helbing 2001) for a good overview of the field.

VR in traffic simulation goes into the research of urban traffic planing, road traffic environment, traffic accident analysis, *et al.* (Wang 2008a) discussed the success of using VR technique for urban planning in traffic simulation, and presented a study on traffic flows simulation of the current situation about the regeneration to help decision making, the screenshot of the simulation shown in Fig. 1.10(a). In (Ayres 2009), a virtual reality simulation of a road traffic environment has been achieved through the use of the Java programming language and Java Monkey Engine, realized the analysis of the different scenarios run in the simulation after the simulation had ended, and aided in the discovery of information, shown in Fig. 1.10(b). (Felez 1998) presented an application of virtual reality techniques to traffic accident analysis, and showed the features of the developed software and the characteristics of the corresponding virtual environment: objects, tasks, behaviors, actions, *et al.*



(a) (b)

Figure 1.10: VR Applications in Traffic Simulation

Some traffic simulation platforms with VR have been developed by researchers. A OpenEnergySim platform proposed in (Prendinger 2011) could construct behavioral driver studies based on emerging 3D Internet technology. In OpenEnergySim, multiple drivers could participate simultaneously by simply connecting to the OpenSim virtual world simulator, shown in Fig. 1.11. (Treiber 2010) investigated fundamental issues of traffic dynamics in an open-source microscopic traffic simulator, which is consist of testing theories for the spatiotemporal evolution of traffic jams, comparing and testing different microscopic traffic models, modeling the effects of driving styles and traffic rules on the efficiency and stability of traffic flow, and investigating novel ITS technologies such as adaptive cruise control, inter-vehicle and vehicle-infrastructure communication. The screenshot of the microscopic traffic simulator while simulating the effect of adaptive driving behavior is shown in Fig. 1.12. Recently, in (Gechter 2012), a virtual intelligent vehicle urban simulator supports physics simulation and realistic 3D rendering, which is composed of the following modules and related data structures: physics simulator, artificial intelligence simulator, and 3D rendering engine.

Figure 1.11: Application Scenario in OpenEnergySim (Prendinger 2011)

Figure 1.12: Microscopic Traffic Simulation (Treiber 2010)

1.3.1.2 VR applications in traffic visualization

Transportation systems and infrastructure are being monitored at increasingly unprecedented levels, resulting in tremendously detailed data sets. This data can include geospatial, temporal, and categorical variables. Thus VR gives simple, intuitive, interactive visualization of transportation to monitor the traffic conditions, incident response, weather operations and traveler information. Visualization has increasingly become an important method of real-time transportation operations, incident and emergency management, evacuation planning, and preconstruction realization (Bista 2008).

The 4D visualization system provides a more realistic view of real-time and simulation data on massive transportation networks. The 4D visualization program employs a client and server architecture, shown in Fig. 1.13. The server contains all the data including aerial images, height maps, 3D models, simulation outputs, *et al.* The client simply requests data from the server and displays it in the 4D interactive environment. A 4D, wide-area traffic visualization tool has been developed by The CATT Lab to help incident management personnel, emergency management personnel, and the general public achieve situational awareness in as close to a real-world setting as possible, see Fig. 1.14. The prototype system interacted with real-time traffic databases to show animations of traffic, incident, and weather data (Pack 2010).

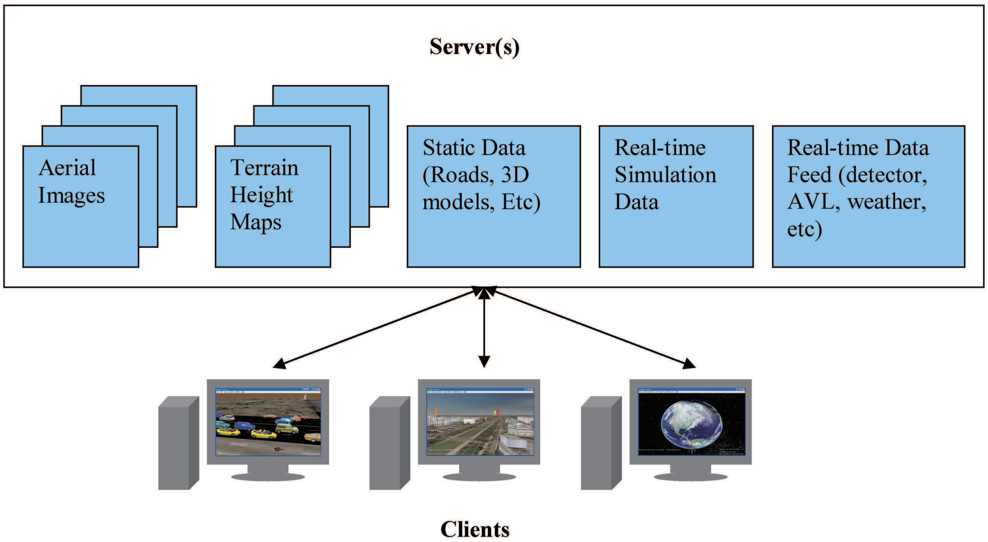


Figure 1.13: General Structure of 4D Visualization System (Bista 2008)

In the transportation sector, design visualization has often taken the form of a simulated representation of a proposed transportation improvement-such as a new bridge, tunnel, overpass, or change in a business district's right of way. These "previsualizations" are often used in the public-participation process to gain project acceptance or to facilitate a discussion around design choice, see Fig. 1.15. Such visualization is often used in the public participation process to gain project acceptance (Pack 2010). As mentioned above, AR system has been developed in recent years. Thus it begins to be used in traffic visualization, especially in traffic design and construction. In (Chen 2012a), a 3D visualized simulation model of construction operations and its modeling method were proposed for simulating transport operations in construction. AR technology was introduced in the system development to combine virtual objects and real field settings, shown in Fig. 1.16.

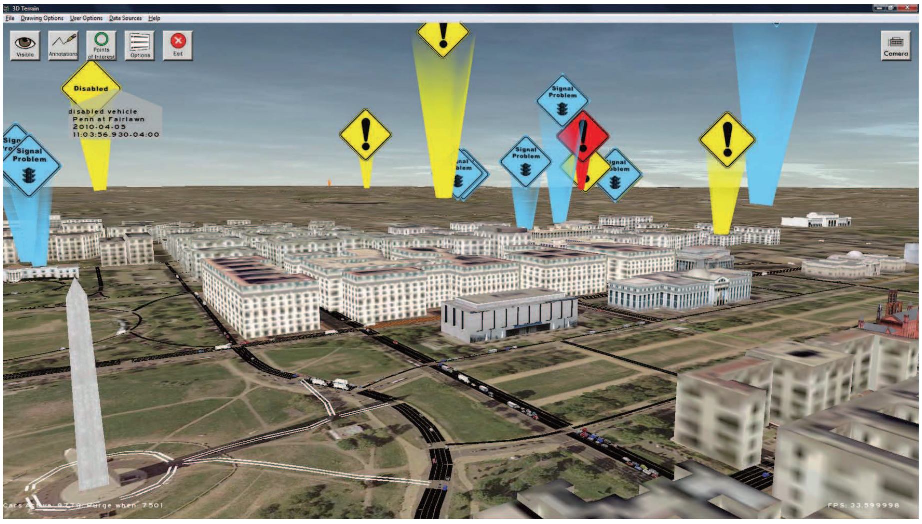


Figure 1.14: A 4D Real-time Visualization System Displaying Traffic Conditions on a Wide Scale (Pack 2010)

Figure 1.15: Typical Previsualizations Traffic Visualization Scene (Pack 2010)

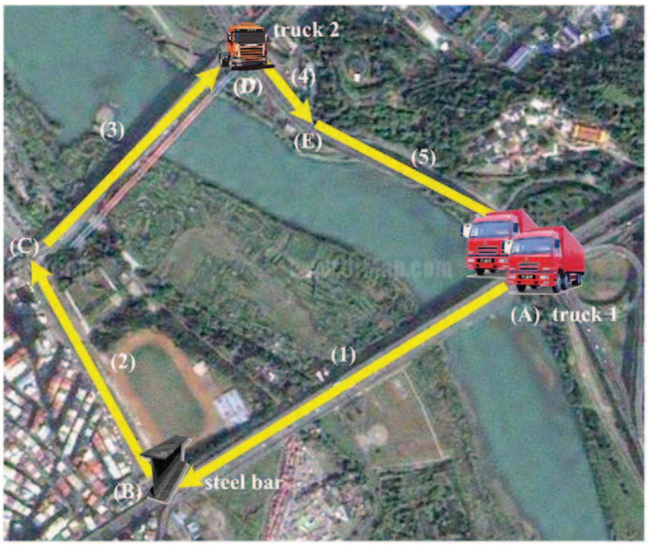


Figure 1.16: AR-based Transport Operations in Construction (Chen 2012a)

1.3.1.3 VR applications in driving simulator

Driving simulator is useful in many areas of human-vehicle-environment system analysis, especially it is very usefully to evaluate and develop ITS such as cooperative systems and advanced driver assistance systems. The driving simulator based on VR requires a combination of some technologies: (1) high-resolution visual, auditory, and haptic feedback; (2) numerically accurate, real-time simulation of complex physical systems; (3) modeling and control of believable agents and scenarios; (4) modeling of large-scale virtual environment databases; (5) a software architecture providing real-time database access and runtime coordination of multiple threads (Cremer 1996).

Driving simulator is composed of six different components, shown in Fig. 1.17. User can control the simulated vehicle using control devices which comprises of steering wheel, acceleration and brake pedal. Visual display can be a projection or big screen monitor depending on the cost and purposes. Driving scenes is represented by visual database and can be seen through visual display. Vehicle dynamic model is applied to create the movement of car. The interaction between car and driver is implemented using motion base system which simulates the car movement inside the vehicle cabin. As data transfer between these components is essential and should be in real-time, relevant communication network system and interfacing system are used in the driving simulator (Siang).

According to the architecture of driving simulator and application areas, different factors should be considered in designing virtual driving environment such as simulation fidelity and realism, construction cost and real-time communication capability (Fouladinejad 2011). Software applications in driving simulator

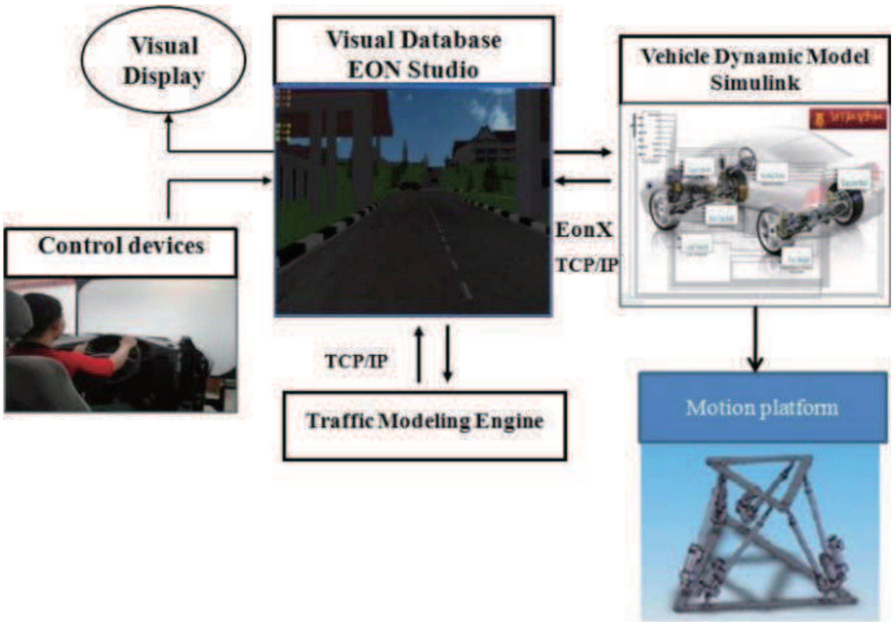


Figure 1.17: Components of Driving Simulator (Fouladinejad 2011)

with VR present different levels of interactivity. These range from navigating the virtual 3D environment without a detailed driving dynamics simulation to full control of a simulated vehicle and all its systems (Ambrož 2010).

Some American automotive companies developed driving simulators using flight simulator technology in the early 1970s. In the following decade, the first advanced models of driving simulation were constructed. General Motors, Daimler-Benz, Renault, Ford and Chrysler were among first companies having activity in development of driving simulation. During 1990s, many universities began to develop driving simulators as well. The Iowa and Virginia State Universities were the early contributors in this field. Although the computer technologies have advanced and become cheaper nowadays, the development of driving simulators is still an expensive business (Kuhl 1995).

With the development of traffic simulation and driving simulator, it is the trend of integrating a driving simulator and traffic simulation. The behavior of individual drivers can properly be analyzed through driving simulators. The simulation of the traffic surrounding the interactive vehicle should be taken into account the driver's behavior in the driving simulator. The integration of a driving simulation and traffic simulation environment may be achieved by implementing a communication structure that can effectively exchange data between the two applications (see Fig. 1.18) (Punzo 2011). The integrated environment has to ensure that, during the driving simulation, the autonomous vehicles are consistently moved by the traffic microscopic simulation model with the movements of the interactive vehicle. In (Jin 2003), a VR-based integrated driving-traffic simulation system was presented to collect data needed to address the travelers behavior under information, different traffic conditions created in the driving simulator, shown in Fig. 1.19.

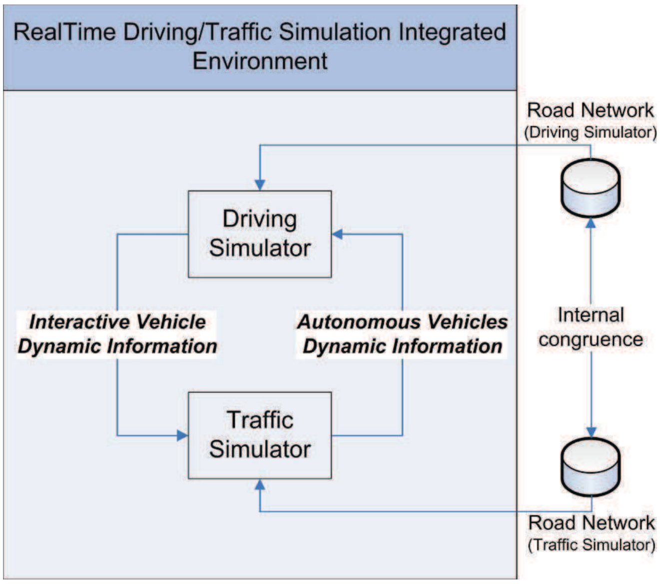
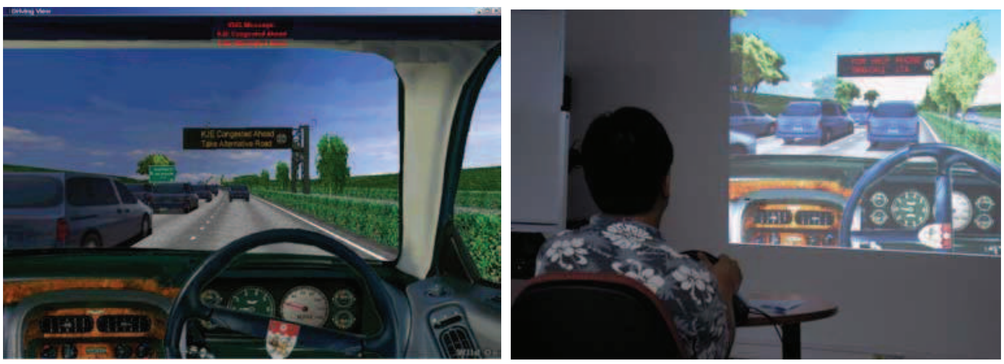


Figure 1.18: Intergration Framework of Driving Simulator and Traffic Simulation (Punzo 2011)



(a) (b)

Figure 1.19: VR-based Integrated Driving-Traffic Simulator (Jin 2003)

Inspired by the work presented above, this thesis will pay attention on the VR applications in microscopic traffic behaviors. The virtual reality traffic simulation system will be established. Not only VR will be used in visualization for the traffic simulation, but also VR will provide realistic environment information to the traffic simulation, which has been ignored in the previous research. The intelligent vehicle in this thesis will be associated with a virtual autonomous vehicle model. The virtual vehicle will combine 3D geometry shape with perception module, motion module, cognition and behavior module, and internal properties. Besides, the vehicle dynamic features and control algorithms will be considered.

1.3.2 MAS applications in transportation system

The domain of traffic and transportation systems is well suited to an agent based approach because of its geographically distributed nature and its alternating busy-idle operating characteristics. Agent based transportation systems allow distributed subsystems collaborating with each other to perform traffic control and management based on real-time traffic conditions (Chen 2010a).

The development of MAS brings a new idea to go deep into recognizing the modeling and simulation of intelligent traffic system. MAS based approach is increasingly important in solving complex problems such as ITS (Liu 2008). In MAS, each intelligent traffic entity is modeled as an agent (Chen 2010a). A simple agent typically needs less computation complexity than traditional control algorithms, and MAS can collaborate to solve complex problems through interaction mechanism among agents (Li 2006). The geographically distributed nature of agents in heterogeneous environments leads to implementation difficulties such as interoperability among agents, which makes demand for a unified software platform and standard implementation protocols (Wang 2006).

For traffic simulation, MAS technology can fully reflect the overall behavior of complex system through the definition of the rules of interaction among the individuals and is well suited to describe traffic simulation. At the same time, developing traffic simulation system is a difficult work because of its inherent complexity, such as the interaction between vehicle and environment, the communication among the softwares, the development of different simulation models and the design of all kinds of simulation applications. Thus it is necessary to structure the complex system into relatively independent module, which can realize making simulation system easy to build and maintain. MAS based simulation system could reach this goal. A model of intelligent transportation systems with multi-agent based Service Oriented Architecture (SOA) has been presented in (Wang 2010a).

Although MAS has been widely used in traffic and transportation system, including traffic control and management, air traffic, roadway transportation, railway transportation and traffic modeling and simulation. The applications in traffic modeling and simulation are listed (show as in Table 1.1) because it is most related with this thesis.

Table 1.1: MAS Apllications in Traffic Modeling and Simulation (Chen 2010a)

Project name	Research group	Application domain	Key features
	Burmeister et al. DaimlerBenz Research Systems Techonology, Gemany	Traffic simulation	The driver-vehicle elements are modeled as agents. The agent architecture consists of five types of modules: Sensors, Effectors, Communication, Motivation, and Cognition.
MARS	Fischer et al. the German Research Center for Artificial Intelligence, Germany	Simulation tool	An agent based simulation tool that provides different cooperation methods based on negotiation, which are required for solving scheduling problems in the transportation domain.
Extension of DRACULA	Rossetti et al. Informatics Institute, PPGC/UFRGS, Brazil	Driver behavior modeling	Using BDI (Beliefs, Desires, and Intentions) agents and agent-based framework to assess drivers'decision making.
	Dia. University of Queensland, Australia	Driver behavior modeling	Modeling dynamic drivers behavioral survey of drivers conducted on a congested real world commuting corridor.
	Wahle et al. Gerhard-Mercator-University, Germany	Driver behavior modeling	Using a two-layered agent architecture to study the impact of dynamic information on traffic systems with the consideration of the drivers'reaction.
CTMRGS	Adler et al. USA	Cooperative traffic management and route guidance	A cooperative traffic management and route guidance system based on the integration of multi-agent systems and principled negotiation.

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Project name	Research group	Application domain	Key features
SAPIENT	SUKTHANKAR et al. Carnegie Mellon University, USA	Tactical driving	Using a set of distributed reasoning agents to independently recommend driving decisions based on their local assessment of the tactical situation.
SITRS	Hidas. University of New South Wales, Australia	Modeling lane changing	Develop a lane-change model based on the autonomous agent concept and implements it in an ARTEMiS traffic simulator.
ITSUMO	Da Silva et al. Brazil	Urban mobility situation	A simulation tool that is capable of performing simulations, such as the driver behavior, traffic light coordination, and traffic-jam prediction.
COTSCS	Li et al. University of New South Wales, Australia	Urban traffic problems	A three-layer cooperative traffic scheduling and controlling system for urban traffic problems.
	Liu et al. Shanghai Jiaotong University, China	Demand bus simulation	The separation of design model and domain model allows domain experts and system users to be involved in the system design.
UDMLA	Salim et al. Monash University, Australia	Model for intersection safety	Integration of intelligent software agents and ubiquitous data stream mining for intersection monitoring, collision warning and avoidance.
PEDELOW	Kukla et al. Napier University, United Kindom	Model of pedestrians	A microscopic model of pedestrians' movement.
ATFMGC	Li et al. University of Brasilia, Brazil	Air traffic flow management	Combining grid computing with multi-agent coordinated to improve air traffic flow management computational efficiency.

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Project name	Research group	Application domain	Key features
PLATFORM	Gambardella et al. Switzerland	Combined rail/road transport planning	A software platform that consists of intermodal transport planner and a simulation system. The agent-based planner organizes transport plans for dispatching intermodal transport units. The simulation system, composed of road simulation, rail simulation, and terminal simulation models, verifies the feasibility of these plans and measures their performance.
	Halle et al. Canada	Collaborative driving	Comparison of centralized and decentralized platoon coordination.
MAS-T2er	Rossetti et al. University of Porto	Artificial traffic control system	A framework consists of a JADE implementation of transportation system, a microscopic traffic simulator, and a control strategy inductor.

The applications of VR has been introduced before, recently, there are some applications integrating VR and agent to solve traffic simulation problems. Agent combining with VR to solve the large scale and realistic traffic simulation could be seen in (Sewall 2011), which simulated individual vehicles in regions of interest using state-of-the-art agent-based models of driver behavior, and used a faster continuum model of traffic flow in the remainder of the road network in virtual world.

Most agent based applications, however, focus on modeling and simulation. Few real-world applications are implemented and deployed. In general, the design, implementation, and application of agent based approaches in the area of traffic and transportation are still immature and need to be further studied (Chen 2010a).

Application projects in multi-agent traffic modeling and simulation show that agent technology is widely useful in traffic and transportation systems, because the traffic and transportation systems consist of many autonomous and intelligent entities. There is the application in which agent combining with VR to solve the large scale and realistic traffic simulation. Therefore, this thesis contributes to an interdisciplinary area of ITS, VR and MAS technologies. This study focuses on the modeling and simulation of microscopic traffic behavior in virtual reality system using multi-agent technology, a hierarchical modular modeling methodology and distributed simulation.

1.4 Conclusions

M & S is a valid method to research on the ITS. This study is actually an interdisciplinary contribution in the areas of ITS, VR and MAS. This chapter has reviewed the related fields and some previous research applications. In the literature review part, the related knowledge of ITS, M & S, VR and MAS has been reviewed. The concept and development of ITS has been introduced. The development of M & S has been briefly described. VR and VR system have been presented, including the features of VR, four types of VR systems and their applications. Agent, MAS and ABMS have been surveyed. The previous research application part has introduced VR and MAS applications in transportation system separately. This chapter has given the application of VR in traffic simulation, traffic visualization and driving simulator. In traffic simulation, VR has been useful in urban traffic planning, road traffic environment, traffic accident analysis and traffic simulation platform. In traffic visualization, the 4D visualization system and design visualization for traffic have been illustrated. VR has been an important part in driving simulator, the integration of driving simulator and traffic simulation has been the development trend. This chapter mainly has shown MAS applications in traffic modeling and simulation. Some research projects have been listed in detail.

To research on the traffic safety, considering the complexity of traffic behaviors and the variabilities of vehicle control algorithms, it is necessary to develop an intelligent simulation system to analyze the traffic safety, with this system, the microscopic traffic simulation could be realized. At the same time, the developers can pay little attention on the programming work, such as the basic communication language, simulation management and scheduling, time management, *et al.*, but the developers could concentrate on building specific traffic applications for different simulation requirements. The intelligent simulation system could realize rapid construction of simulation system according to different configurations in application level. With this intention, MAS is introduced in this research.

In this study, MAS is used in two aspects: one is in the MAS based design for intelligent simulation system; the other one is in the agent-based multi-controller for intelligent vehicle. The intelligent simulation system based MAS uses the design concepts of ABMS, structures the complex system into relatively independent modules (the entity agent, the environment agent and the service agent) to reflect the interaction between vehicles and environment. The agent-based multi-controller for intelligent vehicle realizes a multi-agent controller organization and its implementation. This architecture is open so that controllers can be easily added, removed or changed. The coordination of these controllers could realize different vehicle algorithms for microscopic traffic behavior.

To meet the intent of this study, the related main concepts and modeling ideas include: (1) Agent. Agent model refers to the abstract model of the individuals (entities) model in the complex system. In this study, agent concept is used in the intelligent simulation system and multi-controller of intelligent vehicle. Each independent simulation module is an agent. Each controller is an agent, a pool of controller agents and a coordination object make up a controller agency. (2) Environment. Agent realizes the perception and the action in the environment. The environment is constructed in a virtual world in this study. (3) Perception and action. Agent perceives environment and other agents' information by the internal sensor, act the effect on environment and other agents through actor. There are perception module and motion module in the intelligent vehicle model to realize this work. (4) Events. The microscopic behaviors such as car following or overtaking are the events in the system. (5) Goals. The results of the interaction are to verify the safety of traffic. (6) Rules and attributes. Entity agent (such as intelligent vehicle) defines the rules and the attributes to reflect the entity behaviors. Entity agent changes its rules and behaviors according to the perceived information. (7) Coordination. The coordination of multi-controller could realize different vehicle algorithms. (8) Interaction. The interaction in this simulation system could reflect the interaction between the vehicles and environment. (9) Cooperation. The entity agents (the intelligent vehicles and the around vehicles) need to be cooperated to realize traffic behavior. (10) Code generation. The simulation system required project files, source code files, header files should be added through the configurations.

All the concepts are needed in the design of the simulation system in this study. The existed agent development framework can not provide all the required concepts. Thus, the intelligent simulation system for this study is constructed in Visual Studio C++, with the intelligent vehicle models developed in Matlab/Simulink.

The aim of this thesis is to combine the ITS with VR and MAS to research on the microscopic traffic simulation system. This study will be interested in two aspects that are important for virtual reality traffic simulation system: intelligent simulation and realistic dynamic features. The simulations in a virtual environment need to be modeled as closely as possible to the real situation, with the purpose of avoiding certain dangers, reducing the cost and shortening the development time.

Chapter 2

Multi-Agent Based Modeling And Simulation Framework

Contents

2.1 Introduction

Transportation research and development are no longer a field dominated by civil, mechanical, operation research, and other traditional engineering and management disciplines (Wang 2010b), but it is an interdisciplinary field. The development of Intelligent Transportation System (ITS) and Automated Highway System

(AHS) requires extensive testing, verification and evaluation of new traffic concepts. Intelligent vehicles are important roles in ITS/AHS, which are motivated by three desires: improved road safety, relieved traffic congestion and comfort driver experience. Computer simulation is widely used in the design and test of intelligent vehicles, to complement experimental results as well as to analyze different control algorithms in different traffic situations and environment, where realistic experimental tests with real vehicles would be difficult to accomplish due to hardware, vehicle availability, safety and reproducibility problems (Gechter 2012).

Traffic simulation provides a flexible, effective and safe way to research innovative concepts and applications. As introduced in the Section 1.5, Virtual Reality (VR) technology and Multi-Agent System (MAS) are increasingly being used in the transportation system, especially for traffic simulation.

Most existed research on traffic simulation with virtual reality mainly have been concentrated on the visualization or the real-time traffic simulation in a virtual world (Pack 2010; Wilkie 2012), and little attention has been paid on system modeling and formal specification of traffic simulation, which results in a gap between the system modeling at the design stage and the implementation at the application stage. Besides, the complicated and dynamic features of real world have been ignored in the virtual reality traffic simulation system.

While developing the software, the engineers and programmers often confront the same type of design and implementation problems, which are affected not only by the user requirements, but also by technological advances (Topçu 2013). Developing traffic simulation system is a difficult work because of its inherent complexity, such as the interaction between vehicle and environment, the communication among the softwares, the development of different simulation models and the design of all kinds of simulation applications. Therefore, it is necessary to structure the complex system into relatively independent modules, which can realize making simulation system easy to be built and maintained.

The development of MAS brings a new idea to go deep into recognizing the modeling and simulation of intelligent traffic system. MAS-based approach is increasingly important in solving complex problems such as ITS (Liu 2008). For traffic simulation, MAS technology can fully reflect the overall behavior of complex system through the rules' definitions of interaction among the individuals, which is well suited to describe traffic simulation. The agent technology has been widely used together with computer graphics and virtual reality for the construction of real time simulations with interactive and intelligent virtual entities (Kallmann 2002).

Based on standard supporting platform of advanced simulation technology, the distributed virtual reality traffic simulation system could integrate interoperable and reusable simulation applications among different communities. The simulation of traffic environment could be realized under a distributed network application.

For the purpose of such analysis, a modular application software, Virtual Reality Intelligent Simulation System of Vehicles (VR-ISSV) is designed (Yu 2013c). It assists the user in preparing the simulation of different traffic situations, designing the control algorithms in different environment. The intent of this research is to provide a new approach to effectively ensure the traffic safety.

VR-ISSV is designed by the application of multi-agent and virtual reality technology. VR-ISSV could improve flexibility, reusability, scalability and interoperation abilities of traffic simulation system in the theory, because heterogeneous components and application programs can be seamlessly integrated and interoperated by being encapsulated and provided as agents. VR-ISSV also could realize the model reusability, the code inheritance and the rapid construction of the system in the application level. The goal is to build up the systematical modeling method for VR-ISSV. The main contribution of this chapter is to systematically investigate the modeling method of vehicle simulation, using MAS in the simulation framework. In this way, intelligence could be integrated into simulation framework.

In Chapter 1, the features of multi-agent based modeling and simulation system have been analyzed. This chapter will present the multi-agent based framework modeling for VR-ISSV, analyze its advantages and study the behavior of typical agent definitions. Meanwhile, the system implementation will be introduced in detail, especially two distributed simulation supporting services will be presented. Finally rapid construction of simulation system with AppWizard will be illustrated and two simulation scenarios will be carried out to show the valid of our method.

2.2 Design and analysis of system framework

Higher level simulation application brings the complicated requirement of integrated simulation systems, so it is necessary to meet the simulation needs in different fields and various levels through the relatively simple simulation application. The complex simulation application is flexibly configured and contributed in multiple simulation parts. The structure of traffic simulation system with intelligent vehicles is determined to be as a kind of distributed intelligent simulation system. In addition, the extended demand of traffic simulation requires the structure of simulation system to be open and reusable.

2.2.1 Requirements of system

VR-ISSV could realize different simulation according to simulation tasks and traffic scenarios by the human-machine interface, determine the typical virtual traffic environment factors, form a realistic traffic environment. The microscopic traffic behavior could be analyzed in the VR-ISSV, improving the intelligent vehicle control and the traffic safety. The designed simulation system meets the following standards:

(1) The system could efficiently simulate the control process of intelligent vehicles in the traffic environment, in order to verify the reasonability and correctness of microscopic traffic models and intelligent vehicle control algorithms.

(2) Users can clearly observe the whole process of simulation with 3D visualization. The system provides a simple interface, with convenient human-machine interaction, so that the simulation process and the visualization can be controlled by users.

(3) The system should be with the characters of extension, flexibility, scalability. A decentralized design paradigm is used to realize complex traffic model and simulation. The algorithms could be easily added, removed or changed.

2.2.2 Multi-agent based framework for VR-ISSV

Based on multi-agent technology, VR-ISSV can be modeled as four layers hierarchical framework shown in Fig. 2, which consists of hardware, network and operating system layer; visualization management layer; multi-agent layer; human-machine interface layer (Yu 2013c).

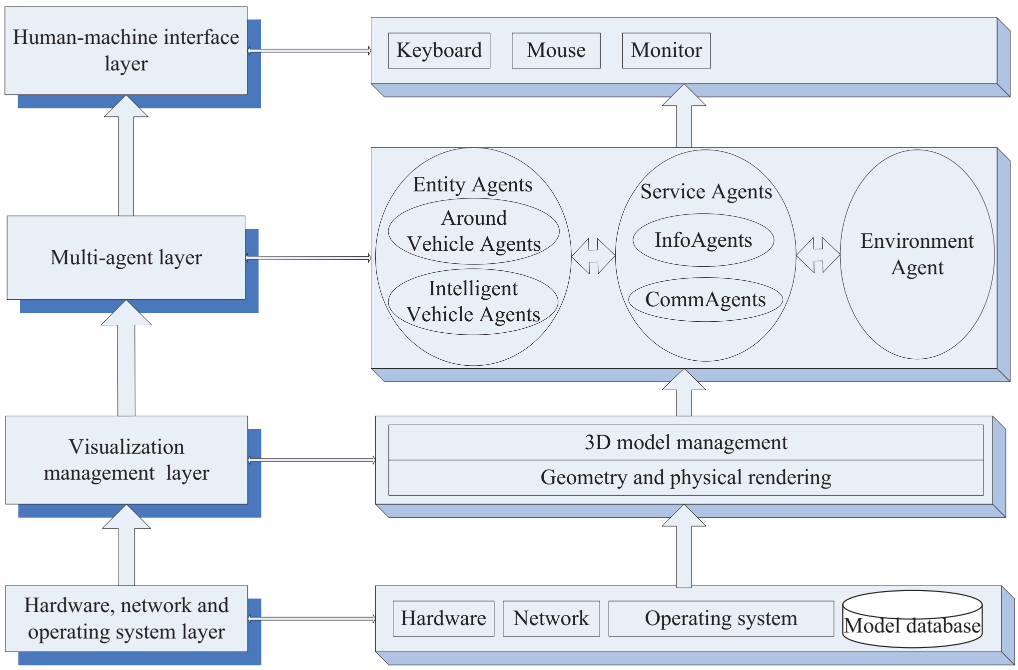


Figure 2.1: Multi-Agent based Framework for VR-ISSV

Hardware, network and operating system layer provides the supporting technology of the system running, which includes the visualization rendering subsystem (*i.e.* the graphics accelerator hardware and the software development library such as OpenGL, DirectX, *et al.*), the vehicle dynamic model and the control model subsystem (Matlab/Simulink), the distributed network communication environment, the operation system and the model database storing Digital Elevation Model (DEM), 3D models, *et al.*

Visualization management layer is responsible for managing the 3D model, organizing the visualization nodes and driving the 3D scenes, and calculating physical properties, such as the collision detection and the scenario-based event management.

Multi-agent layer includes entity agents, environment agent and service agents. This layer reflects the intelligence, the reconfigurability, the reusability and the scalability of VR-ISSV.

Each entity agent corresponds to a 3D entity in the scene and provides the 3D entities with the specific semantics and the rules of behavior as well as the interaction functions. Entity agents are divided into intelligent vehicle agents and around vehicle agents. Intelligent vehicle agents show the behavioral characteristic of driver with the ability of perception, cognition and action. Around vehicle agents interact with the intelligent vehicle through the ability of perception and action. Around vehicle agents could change their own attributes and affect the intelligent vehicle.

Environment agent is constructed based on the conception of Synthetic Natural Environment (SNE), which is the representation of the natural environment in the system established by the modeling and simulation methods, taking into account the interaction between the simulation entities and natural environment simulation system. Geographic Information System (GIS) (Thill 2000a) is used to establish environment agent, which makes the simulation system much more real. The environment agent is dynamic and its characteristic could be changed, and it could also affect entity agents through the environmental parameters stored in the model database.

Service agents have no geometric shapes and their basic functions are to supply system service, which is divided into communication service agent (CommAgent) and information service agent (InfoAgent). CommAgent provides the distributed simulation supporting service. InfoAgent offers the semantic information related to the environment and the necessary knowledge for intelligent behavior, which interacts not only with the entity agents, but also with the visualization management layer. InfoAgent is responsible for translating commands from entity agents into the state changes of specific entities in 3D scenes. The state changes of specific entities could also be translated into meaningful knowledge and transmitted to entity agents for decision making.

Human-machine interface layer is the interface which user interacts directly with intelligent simulation system via the VR devices, such as keyboard, mouse and monitor.

2.2.3 Advantages of multi-agent based VR-ISSV

Multi-agent based hierarchical structure for VR-ISSV has following advantages:

(1) Generality. It provides an hierarchical modular modeling and simulation framework of microscopic traffic that has complicated and dynamic features of the real world. By being encapsulated and provided as agents, distributed, heterogeneous components and application programs can be seamlessly integrated.

(2) Intelligence. Agent is the extension of the concept of the object-oriented paradigm, with the ability of perception, mental status, decision making and communication, *et al.*, so it could describe the complex simulation framework naturally. The multi-agent layer in the architecture reflects the semantic knowledge and application, which could support the reusability and interoperability in the knowledge level.

(3) Scalability. It provides easiness in the design and development of a microscopic traffic simulation system. With the specific interface definition, the simulation application could be realized through the configuration of entity model, environment model and simulation service. Agent-based intelligent simulation system is constructing the system through the bottom to up method. The entities in VR-ISSV are divided into a number of loosely coupled agents. Each agent is relatively independent and self-described, which could communicate with other agents by using standard communication protocols. It is very easy to add, delete and modify some agents without affecting other parts. The behaviors of each agent and the interaction between the agents constitute the behavior of the whole system.

(4) Flexibility and reusability. Comparing to other platforms of traffic simulation, the simulation system in this thesis could work well with the changes of the vehicle model, environment model and simulation supporting service. Other models and softwares could be packaged as agent with the interface specification and be reused in the intelligent simulation system.

(5) Reconfigurability. Multi-agent based VR-ISSV could achieve rapid reconstruction of the application system by modifying the behavior rules of individual agent or by modifying the rules of communication and the interaction among agents.

(6) Authenticity. Using the Geographic Information System (GIS) (Thill 2000a), the traffic simulation could be much more valid in the design and test of vehicle control algorithm and in the analysis of microscopic traffic behavior.

2.2.4 Formal definitions

To explain the general structure, this section gives some more formal definitions to the related concepts and agent properties introduced before. These definitions of agents, rules and interactions reflect the semantic knowledge and application logic of the multi-agent system.

Definition 1: VR-ISSV is defined as Multi-agent based Virtual Reality Intelligent Simulation System for Vehicle ($MVRISSV$), which can be defined as a set of 2-tuples:

$$MVRISSV ::=< Agent, Communication >,$$

$MVRISSV$ is constituted of the agents and the interaction among the agents, where $Agent = \{EnvironmentAgent\} \cup \{ServiceAgents\} \cup \{EntityAgents\}$, $EntityAgents = \{IntelligentVehicleAgents\} \cup \{AroundVehicleAgents\}$, $ServiceAgents = \{CommuAgent\} \cup \{InfoAgent\}$.

Definition 2: $EnvironmentAgent$ can be represented as a 3-tuple:

$$EnvironmenAgent ::=< FeatureName, FeatureType, FeatureValue > .$$

Environment represents a global knowledge space of environment properties including road layout and other natural physical environment such as temperature, air and wind.

$EnvironmentAgent$ provides the semantic knowledge of the simulation environment, where $FeatureName$ is the name of the environment feature,

$FeatureType$ is the value type of the environment feature, $FeatureValue$ is its property value.

Definition 3: $EntityAgent$ can be represented as a 3-tuple:

$$EntityAgent ::=< AgentID, Attribs, BehModel >,$$

where $AgentID$ is the only ID of agent, $Attribs$ is the attribute set, $BehModel$ is the behavior model.

Definition 4: $Attrib$ represents the agent attribute and can be represented as a 4-tuple:

$$Attrib ::=< AttribID, AttribName, AttribType, AttribValue >,$$

where $AttribID$ is the attribute ID, $AttribName$ is attribute name, $AttribType$ is the attribute type, $AttribValue$ is the attribute value.

Definition 5: $Behavior$ can be represented as a 4-tuple:

$$Behavior ::=< AgentID, BehaviorName, BehaviorType, ParameterSet >,$$

where $BehaviorName$ is the name of behavior model, $BehaviorType$ is the type of behavior, which in general includes autonomous behavior ($SelfBehavior$) such as acceleration, deceleration, and interactive behavior ($InteractBehavior$) such as following or overtaking a car.

Namely, $BehaviorType \in \{SelfBehavior, InteractBehavior\}$, $ParameterSet$ is the set of parameters for behavior.

Definition 6: $Communication$ is a set of communication messages among agents in $MVRISSV$. Each communication message includes the entity sending message, the entity receiving message and the message contents. So $Communication$ can be represented as a set:

$$Communication = \{< Sender, Receiver, MsgContent > | \\ (Sender \in Agent) \; and \; (Receiver \in Agent) \; and \\ (MsgContent \in Communication(L))\},$$

where $Sender$ is the agent who sends the messages, $Receiver$ is the agent who receives the messages, so $Sender \in Agent$ and $Receiver \in Agent$.

$MsgContent$ is the communication content according to the protocol of communication language. $Communication(L)$ is protocol of communication language according to $ServiceAgents$. So $MsgContent \in Communication(L)$.

A simulation application example of car following behavior considering road and wind effects is presented to explain the definitions. The car following behavior is a fundamental element of microscopic traffic behavior, which describes how a pair of vehicles interact with each other and adjust the important vehicle behavior characteristics: the distance between two adjacent cars, the relative speed, *et al*. To realize the car following behavior simulation, with the definitions mentioned above, the leading vehicle and the following vehicle are $EntityAgents$, which are defined as following:

$$EntityAgent ::=< 1, Vehicle(1), RF >, \\ EntityAgent ::=< 2, Vehicle(2), CF >,$$

where $Vehicle(1)$ is $Attribs$ of leading vehicle, $Vehicle(2)$ is $Attribs$ of following vehicle. RF is $BehModel$ of road following, CF is $BehModel$ of car following.

The entity attribute sets are:

$$Vehicle(i) ::=< i-1, Longitudinaloffset, double, Value >, \\ Vehicle(i) ::=< i-2, Lateraloffset, double, Value >, \\ Vehicle(i) ::=< i-3, Yaw, float, Value >, \\ Vehicle(i) ::=< i-4, Speed, float, Value >,$$

these equations show the $AttribName$, $AttribType$ and $AttribValue$ of each entity agent.

The behavior models are chosen by the users depending on the driving context:

$$RF ::=< 1, RoadFollowing, SelfBehavior, Vehicle(1) >, \\ CF ::=< 2, CarFollowing, InteractBehavior, Vehicle(2) >,$$

these equations present the $BehaviorName$, $BehaviorType$ and $ParameterSet$ of road following and car following behavior models.

The road and wind effect are considered by the $EnvironmenAgent$, defined as following:

$$\begin{aligned}
&EnvironmenAgent ::=< Interspace, double, Value >,\\
&EnvironmenAgent ::=< Longitudinalwind, double, Value >,\\
&EnvironmenAgent ::=< Lateralwind, double, Value >,\\
&EnvironmenAgent ::=< Slope, double, Value >,\\
&EnvironmenAgent ::=< Curvature, double, Value >,\\
&EnvironmenAgent ::=< Rank, double, Value >,
\end{aligned}$$

these equations give $FeatureName$, $FeatureType$ and $FeatureValue$ of $EnvironmenAgent$.

$EnvironmenAgent$ and $EntityAgent$ realize communication through the $SeviceAgent$ by the $Communication$ between agents, two $Communication$ examples shown as following:

$$\begin{aligned}
&Communication = \{< EnvironmenAgent, ServiceAgent,\\
&STDMETHOD(GetCurvature) >\},\\
&Communication = \{< ServiceAgent, EntityAgent,\\
&STDMETHOD(SetYaw) >\},
\end{aligned}$$

where the first means that $EnvironmentAgent$ sends message to $EntityAgent$, the vehicle entity agent could get the road curvature from the environment agent, the second means that $EntityAgent$ sends message to $EnvironmentAgent$, the vehicle entity agent could send the yaw posture to the environment agent.

2.3 System implementation

Matlab/Simulink software is used to develop the vehicle dynamic model and the agent-based multi-controller model for intelligent vehicle agent. Comparing to the other softwares, this software has the superiorities in the fields of algorithm development, numeric computation, model-based design for dynamic and embedded systems. It also has the speciality of easily modeling, solving and integrating with other softwares. Besides, Simulink is selected for integration as a modern simulation tool because it is an object oriented dynamic system simulation package (Grega 1996).

Visualization is able to realize simulation monitoring in a virtual world, with the ability of constructing, controlling and managing the virtual scenes, and supporting rapid and complex visual simulation, which is achieved through the 3D modeling tools (3D Max, Multigen Creator, *et al.*) and the 3D rendering tools (OGRE, Vega Prime, *et al.*) (MULTIGEN ; Team 2008).

Multi-agent based virtual environment is realized through Visual Studio C++. Visual C++ can be used as an effective agent development language to meet multi-agent system requirements. According to the existed agent development platform, the structure of the platform designed in this study is shown in Fig. 2.2. The application management, the system files, the code generation and the service agent could be realized by the Visual Studio C++. With Visual C++, the visualization and distributed simulation could be integrated in the simulation system.

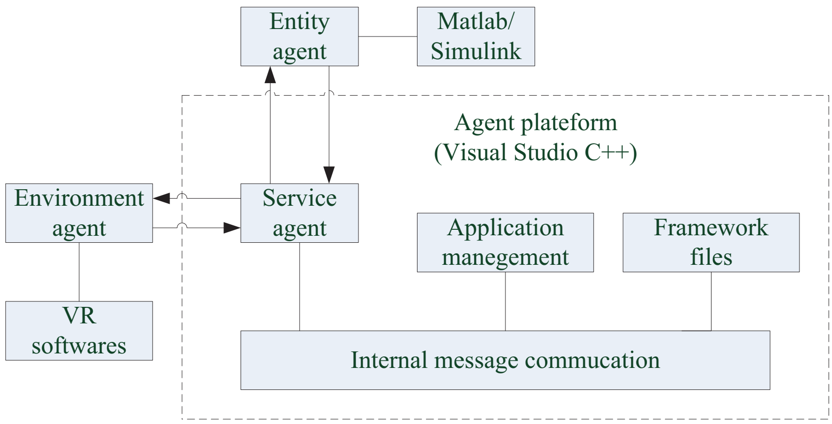


Figure 2.2: Structure of Agent Platform

Distributed Component Object Model (DCOM) and High Level Architecture (HLA) are used to realize the distributed simulation communication, which will be explained in detail next. The Microsoft Component Object Model (COM) technology is used for DCOM, whose source code could be written in any programming languages that support COM, such as C++. Matlab has the features of supporting COM, by integrating COM objects into Matlab/Simulink models through IDispatch interface. HLA/RTI (Run Time Infrastructure) is realized by the simulation federation assistant development tools of HLA/RTI. AST-RTI and AST-OMDT (Object Management Development Tool) are these kind tools, which are developed by Advanced Simulation Technology Laboratory (ASTLab) in Beihang University, and used for research. AST-RTI is a simulation supporting platform, AST-OMDT software helps to define interaction data and Federation Object Model (FOM) and Simulation Object Model (SOM). AST-FEDWIZARD tool software helps to generate a federate application program framework and RTI invoking interface according to FOM and publication/subscription information (Li 2009; Yu 2012a).

According to the multi-agent based framework in Fig. 2, the layered diagram of system implementation is shown in Fig. 2.3.

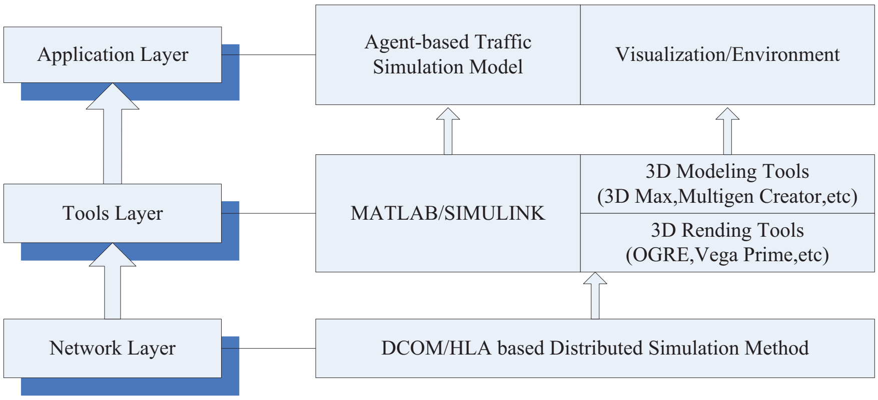


Figure 2.3: Layered Diagram of System Implementation

2.4 Distributed simulation supporting service

Communication service agent provides distributed simulation supporting service. Two methods are proposed to realize the distributed simulation, the Distributed Component Object Model (DCOM) based distributed traffic simulation and the High Level Architecture (HLA) based distributed traffic simulation. The first could realize the capacity of connect-and-play and the second has the capability of plug-and-play. Both of these two method can combine the models in Matlab/Simulation and the 3D models in virtual world.

2.4.1 DCOM-based distributed simulation

2.4.1.1 COM and DCOM

COM technology enables application-specific components produced by different vendors to communicate. It provides a framework for integrating reusable, binary software components into an application. Because components are implemented with compiled code, the source code can be written in any of the many programming languages that support COM. Object-oriented languages, such as C++, provide programming mechanism that simplify the implementation of COM objects (Luo 2011).

COM objects are discrete components, each with a unique identity, which expose interfaces that allow applications and other components to access their features. A COM client is a program that makes use of COM objects. COM objects that expose functionality for use are called COM servers. A COM server could have multi-objects and each object could comprise multi-methods, multi-properties, or multi-events. COM servers can be in process or out of process (Swanke 1996).

DCOM is the Microsoft Distributed Component Object Model technology.

It supports multiple network protocol, the communication between the different components of the computer object and its clients can be achieved in LAN, WAN or the Internet (Thai 1999).

2.4.1.2 Architecture of DCOM-based distributed simulation

Based on DCOM, the Matlab/Simulink as the COM Client and the 3D Visualization as the COM Server could work in the different computer connected through the Internet. The 3D visualization system is available to any user connected to the Internet, which could realize the design and validation of the traffic simulation models. DCOM is a seamless extension of the COM in the field of distributed computing field, based on which the Matlab/Simulink and the 3D visualization system are able to communicate between different computers through LAN, WAN and Internet. DCOM is established in the Remote Procedure Call (RPC) of Distributed Computing Environment (DCE) (Adamopoulos 2002). Comparing to COM using the local procedure call (LPC), DCOM only uses the network protocol to realize the communication between remote components and their clients instead of LPC. Therefore, it is same to create the DCOM object with the COM object, only need to join the name of the machine parameter.

The architecture of the distributed simulation based on DCOM is shown in Fig. 2.4.

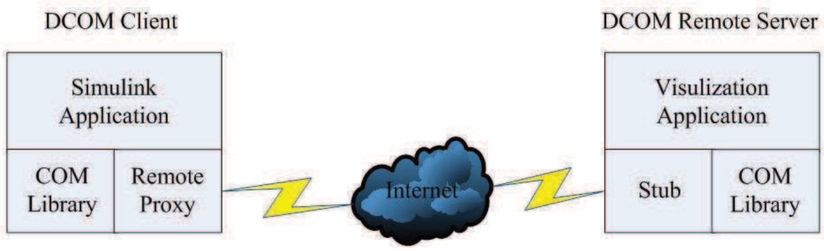


Figure 2.4: DCOM-based Distributed Simulation

2.4.1.3 Integration of simulation models

Since DCOM is a seamless extension of the COM, the simulation models could be integrated through the COM objects and the softwares.

Matlab has the feature of supporting COM object, integrating COM object into Simulink model is fairly straightforward, the M-file S-Function. The 3D visualization system is realized by integrating OGRE and MFC (Microsoft Foundation Classes) together, establishing a COM out-of-process server that exposes COM objects via Automation, which is a type of COM server that supports the OLE (Object Linking and Embedding) automation standard (Chappell 1996).

Automation servers are based on the IDispatch interface and it can be accessed by clients of all types, including scripting clients. The IDispatch interface exposes the object's functionality through a set of public methods, properties, and events. Several methods and properties are set in the COM object for inputting or outputting the parameters of vehicle, such as velocities, accelerations, orientations, *et al.*

As a COM client, Simulink could access existing applications (COM out-of-process server). Since the client and the server run in separate processes, the server could be created on any system of the same network as the client. If the COM server provides a user interface, its window is separated from the client application (Luo 2012a).

2.4.2 HLA-based distributed simulation

2.4.2.1 HLA and RTI

HLA is a kind of computer simulation standard after DIS (Distributed Interactive Simulation) and ALSP (Aggregate Level Simulation Protocol) established by American Department of Defense in August, 1996, which is accepted by IEEE as an industrial standard, that is IEEE 1516, and definitely prescribed as the system frame of distributed interactive simulation replacing the passing DIS standard (Wang 2007).

HLA was developed to establish common high-level simulation architecture to facilitate the interoperability of all types of models and simulations among themselves. HLA is designed to promote standardization in the M & S (Modeling and Simulation)community and to facilitate the reuse of M & S components. It is a general simulation framework, which defines the functions of each simulation part and the relationships between them, rather than a series of data exchange standards. It also plans the rules for simulation development, modeling the whole design process to be followed from the high level. HLA is intended to have wide applicability, across a full range of simulation application areas, including training, analysis, and engineering functions, at a variety of levels of resolution (Dahmann 1999).

HLA is mainly comprised by rules, Object Model Template (OMT) and Run Time Infrastructure (RTI) interface specification (IEEE-Std-1516-2000 2000). In the simulation system of HLA, federation refers to a distributed simulation system that is employed for a particular aim. Federates are applications that may be or is currently coupled with other software applications in the running system. HLA rules are the basis for the simulation to achieve the correct interaction, describing the responsibilities and relationships of all the federates. The restriction condition insures the compatibility of all federates under the HLA structure in order to realize the interoperability of all federates. OMT offers a standard document format (such as Fed, XML, *et al.*) to describe the object model information of federation and federates, promoting the interoperability of simulation applications. Object oriented methods are used to realize the layering description and definition, which is good for the interoperability of simulation components. OMT is made up of Federation Object Model (FOM) and Simulation Object Model (SOM). RTI is the kernel component of HLA simulation, which provides common services including callable services and call back services to simulation system. RTI aims to separate the simulation application from the bottom communication and foundation function. During the simulation system running, all simulation softwares and their management entities can plug on the flexible bus like plug-in unit, which accordingly supports the interconnection and interoperability of the simulation platforms, support the reusability among federates and realize the extension of distributed simulation (Han 2010).

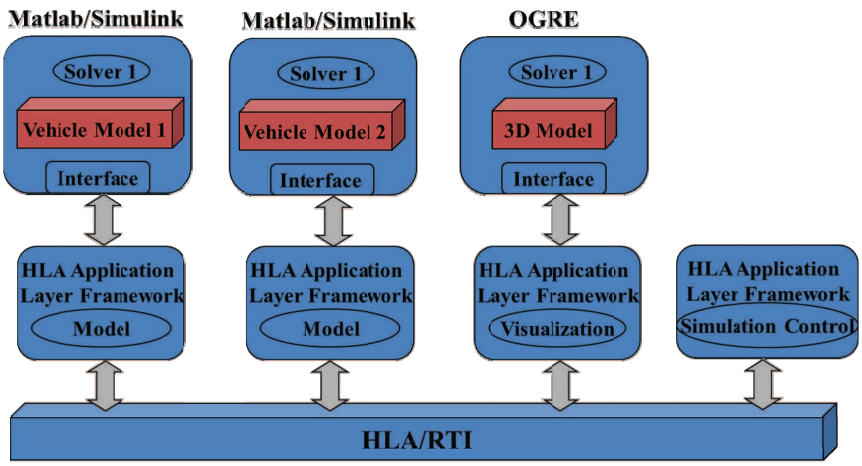


Figure 2.5: HLA-based Distributed Simulation

2.4.2.2 Architecture of HLA-based distributed simulation

The VR-ISSV incudes the vehicle federate, the road/environment federate, the 3D visualization display federate and the simulation director federate, *et al.* The architecture of the distributed simulation based on HLA is shown in Fig. 2.5.

2.4.2.3 Integration of simulation models

In the HLA-based distributed simulation, the intelligent vehicle model in Matlab/Simulink is changed into HLA-compliant model by Matlab/RTW (Real-Time Workshop), which could realize to integrate the vehicle model, control model and RTI. RTW is an automatic C/C++ language code generator for Matlab/Simulink. The vehicle model and control model which we have developed in Matlab/Simulink can be transferred into C++ simulation models by RTW, packaged into DLL (Dynamic Link Library) models, and integrated with HLA/RTI to develop the Vehicle Model Federate in the real-time distributed interactive simulation for intelligent vehicles, shown in Fig. 2.6.

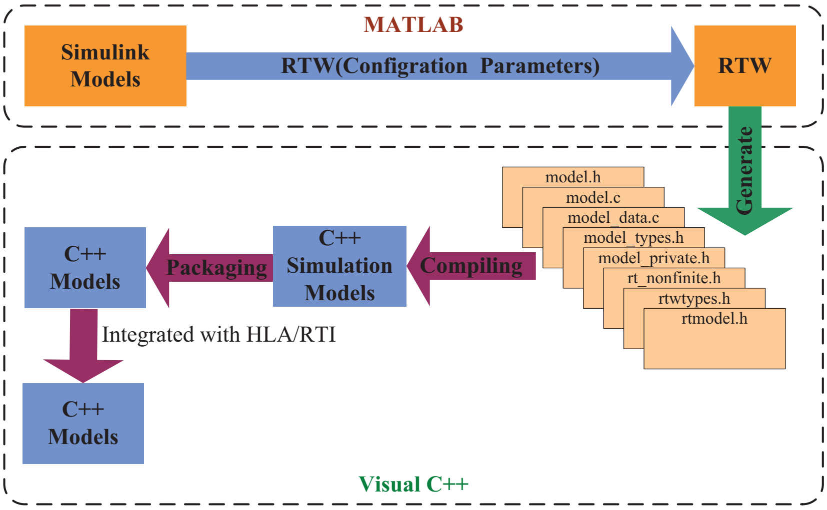


Figure 2.6: Integration with RTI by RTW

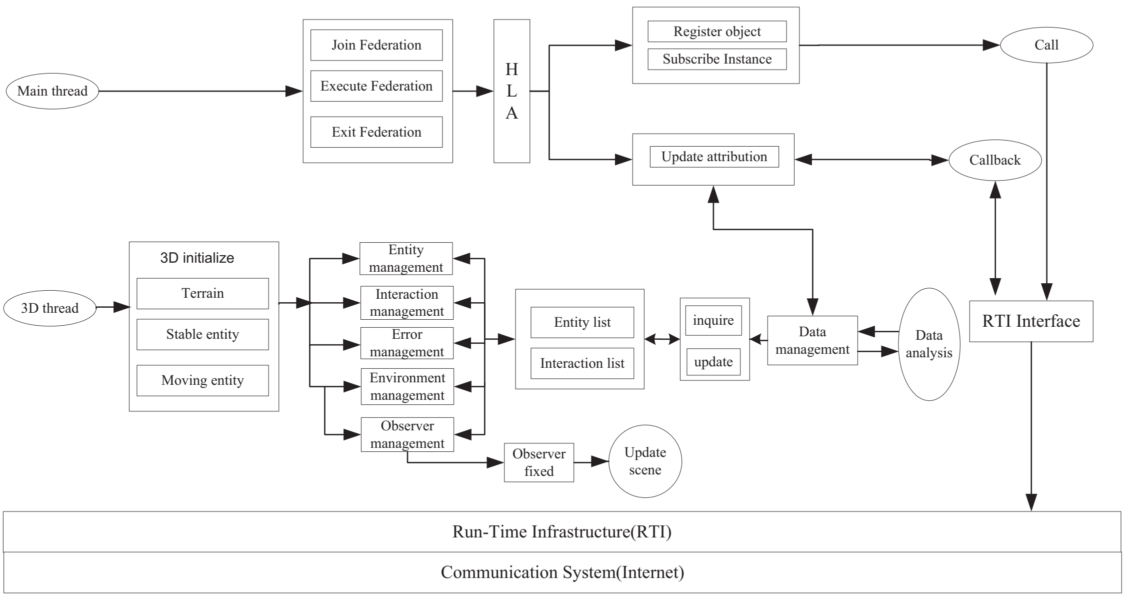


Figure 2.7: Structure of 3D Visualization Subsystem

To integrate the virtual reality and RTI, two threads operation mode is used, the data between two threads exchanges through common data area. The main thread is mainly responsible for network communication, exchanges data with other nodes in simulation by RTI. The received data are analyzed, filtered and saved in the common data area. The 3D thread firstly finishes 3D initialization before simulation. During the simulation progress, the 3D thread scans the common data area, updates the 3D scene according to the entity data and interaction data in common data area. Because the system uses multi-thread operation mode and the data exchange between the threads is through the common data area, it is necessary to use threads synchronization mechanism to solve the problem of the synchronization between threads, the cross operation, deadlock, *et al.* Therefore, in the system logical design progress, thread exclusive lock technology is introduced, which effectively prevents from the problems that thread competition brings for shared data interoperability. Fig. 2.7 shows the structure of 3D visualization subsystem, the details could be seen in (Yu 2012a).

2.4.2.4 Simulation flow of the federates

Fig. 2.8 is the simulation flow of the federates, when the simulation starts, the federation is created, all the federates join in the federation and publish/subscribe the Object Class (such as vehicle entity and environment entity) and Interactive Class (such as simulation control commands). During the simulation process, the federates execute the simulation and send information, RTI provides a set of services that supports the simulation in carrying out the interaction among the federates.

2.4.3 Comparison of two simulation supporting methods

DCOM-based distributed traffic simulation is connect-and-play simulation which enables real-time interaction between the intelligent vehicle control algorithm model and the virtual environment. DCOM-based distributed traffic simulation integrates the object oriented dynamic system simulation package Simulink in the client, that is to say, the Matlab/Simulink environment works in the simulation process. The advantage of this way is redundant conversion processes could be avoided if the vehicle control algorithms change. The disadvantage is the vehicle dynamic models and the vehicle control models are calculated in Simulink, the computational efficiency of Matlab language is not high and the programs can not be executed in parallel, so the simulation efficiency is low.

HLA-based distributed traffic simulation is plug-and-play simulation which enables decoupled component (subsystem) design and interaction. In the HLA-based distributed traffic simulation, the intelligent vehicle model in Matlab/Simulink is changed into HLA-compliant model by RTW. The advantage is the simulation efficiency is high because the simulation application is outside the Mat-

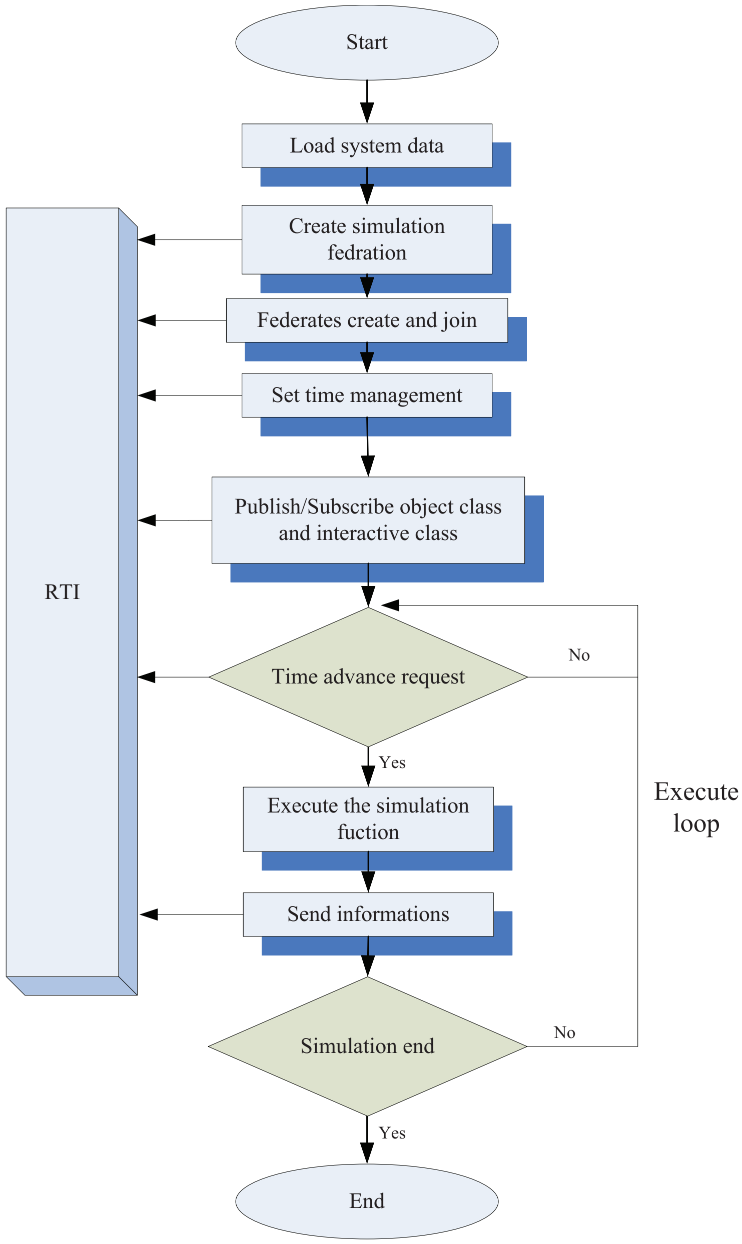


Figure 2.8: Simulation Flow of the Federates

lab/Simulink environment and enables the system with the characters of extension, flexibility and scalability. The disadvantage is the conversion between the models in Matlab/Simulink and HLA-compliant models is complicated and it has to repeat the conversion process if the vehicle control algorithms and vehicle models change.

Based on the mentioned above, the DCOM-based distributed traffic simulation is proper for the vehicle control algorithm design and verification, the HLA-based distributed traffic simulation could be used for simulation implementation and be extended into large scale traffic simulation and vehicle simulator.

Table 2.1 shows the comparison of the two methods.

Table 2.1: Comparison of Two Simulation Supporting Service

	DCOM-based distributed simulation	HLA-based distributed simulation
Simulation way	connect-and-play simulation	plug-and-play simulation
Simulation environment	Inside Matlab/Simulation environment	Outside Matlab/Simulation environment
advantages	Avoiding redundant conversion processes.	High simulation efficiency and the system with the characters of extension, flexibility and scalability.
disadvantages	Low simulation efficiency.	Complicated conversion between the models in Matlab/Simulink and HLA-compliant models.
application	Vehicle control algorithm design and verification.	Simulation implementation and be extended into large scale traffic simulation and vehicle simulator.

2.5 Platform simulation

2.5.1 Rapid construction with AppWizard

AppWizard is application wizard, which is one of powerful programming tools in Visual Studio, could be used to create different types of programs, such as Win 32 application, ATL, MFC Application, *et al.* Custom AppWizard is the specific type of wizards, which is used to create and manage the projects. The designer can create its own wizard. Wizard refers to an application program or library which could be compiled and certain codes could be added or be deleted via the wizard interface. This wizard defines the entire original template of the basic project for users, so that the users do not need program template codes, which gives some relief to the designers and allows them to pay much attention on the high level system work. All the files needed in the projects could be generated through the configuration of the wizard (MSDN 2010).

VR-ISSV could realize rapid construction of the projects through the Custom AppWizard in Visual Studio. By defining Custom AppWizard, the wizard of VR-ISSV could be realized, including different application solution of service agents, environment agents and entity agents. The simulation system required project files, source code files, header files, resource files and additional library files could be added through the configuration of wizard according to the simulation requirements. In this way, VR-ISSV could realize the advantages of intelligence and generality, the simulation system is capable in normal state with the changes of vehicle model, service method or environment model.

(a) (b)

Figure 2.9: Visualization Scenes (Different Virtual World)

Two application visualization scenes are shown in Fig. 2.9. Because the vehicle, the terrain and the simulation supporting service are modeled as an independent agent, all the models could be reused in other simulation application and the simulation system could run well with the modifications of these models. The 3D terrain model in Fig. 2.9(a) is achieved through the 3D modeling tools, the distributed supporting service uses the method of HLA/RTI to realize the data changes. The 3D terrain model in Fig. 2.9(b) is realized through DEM data and satellite image, the distributed supporting service uses the method of DCOM to realize the data changes.

2.5.2 Performance analysis

VR-ISSV is distributed simulation, realizing the whole system to be distributed in different nodes and accomplishing the same task collaboratively through computer network. An intelligent vehicle virtual reality (IVVR) platform has been proposed in (Luo 2011), based on the concepts mentioned in this chapter, this platform could be extended as distributed simulation platform. Distributed simulation has improved the implementation efficiency of the simulation system. Fig. 2.10 shows the simulation performance analysis comparing the VR-ISSV with IVVR. The simulation time in Fig. 2.10 means the real time required to complete the simulation. FPS (Frame Per Second) means the picture frames transmitted within one second, namely the times that the graphic processor refreshes per second. FPS reflects the display effect, the more the better. With distributed simulation, the simulation time has been shortened, the FPS has been improved and the load of CPU (Central Processing Unit) has been decreased.

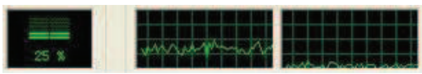
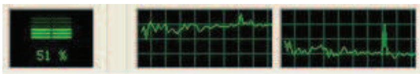
	Simulation time	FPS	Load of CPU
VR-ISSV	92s	32	
IVVR	356s	25	

Figure 2.10: Simulation Performance Analysis

2.6 Conclusions

In this chapter, VR-ISSV based on multi-agent has been proposed to simulate intelligent traffic, which is a hierarchical modular modeling and simulation system. VR-ISSV could improve the reusability, the reconfigurability, the scalability and the intelligence of traffic simulation system. With this concept, the microscopic traffic simulation system could be constructed rapidly and conveniently with different vehicle models, environment models and distributed services.

In the application results, two application examples (DCOM-based simulation and HLA-based simulation) have been shown to prove the feasibility of the proposed methodology and its ability to produce an effective simulation system, this system could be used for research on the interaction among the vehicles, the traffic situation and the environment information. This chapter is the base for the further research of microscopic traffic behavior analysis and the effect of environment affecting on the vehicles.

Chapter 3

Microscopic Traffic Behavior

Contents

3.1 Introduction

Research on driving maneuver to improve highway safety and efficiency is one of the most extensively studied topics in the field of ITS. Traffic behaviors are complex and the traffic information is heterogeneous (Miyajima 2007). Computer traffic simulations form a cost-effective method for analyzing traffic behavior, which are prospective solutions to cope with the problems of highway congestion, accidents, transportation delays and vehicle emissions in the transportation system. In addition, traffic simulations can evaluate the improvements not only under normal circumstances, but also in hypothetical situations that would be difficult to create in the real world (Ehlert 2001).

Traffic simulation models play a major role in allowing traffic engineers to evaluate complex traffic situations. According to how the set of vehicles comprising the traffic is analyzed, traffic models can be classified into three groups. Macroscopic models study the phenomenon of traffic from a global point of view, without going into the details of individual vehicle interaction. Microscopic models study traffic phenomena by taking each individual vehicle as a starting point and analyzing how it interacts with the other vehicles. Mesoscopic models bring together the characteristics of both previous two types by taking individual vehicle behavior into account as well as global traffic parameters (Maroto 2006). This thesis focuses on the research of microscopic models.

Different microscopic simulation models have been developed to deal with different and complex traffic situations/locations. AIMSUM (Barcelo 1996), VISSIM (Fellendorf 1994), and PARAMICS (Duncan 1995) are examples of such widely applied microscopic simulation models. However, there have been several limitations in dealing with replicating drivers' behavior at specific situations. In addition, most models do not consider the cooperative behavior of drivers (Al-Obaedi 2012).

Although many microscopic behavior models are available, current researches on virtual reality traffic simulation have paid little attention on modeling microscopic behavior. Moreover, the virtual reality traffic simulation is an useful method in the analysis of microscopic traffic behavior. In Chapter 2, VR-ISSV has been proposed to prepare the virtual reality traffic simulation system. Therefore, it is necessary to focus on the context of modeling microscopic behaviors in virtual reality simulation system and of realizing intelligent virtual vehicle model with the consideration of driver state and traffic situation.

The microscopic driving maneuver of intelligent vehicle could be divided into three main maneuvers: road following, car following and overtaking. The automation of these maneuvers has been considered to be one of the toughest challenges in the development of vehicle (Naranjo 2008).

Autonomous road following is one of the major research topics in the area of intelligent vehicle. (Yang 2012) realized that the intelligent vehicle can track random trajectory through controlling the linear velocity and the angular velocity, with the design of a sliding mode controller, based on the structures and motion model. (Sumer 2010) considered a tracking problem for a car moving at a constant speed under various off-nominal conditions, including unknown bank and inclination angles. (Raffo 2009) presented a Model Predictive Controller (MPC) structure for solving the path-tracking problem of terrestrial autonomous vehicles, with the controller architecture considering both the kinematic and the dynamic control in a cascade structure.

There are various approaches to study car following. The car following models were classified into five groups as follows: Gazis-Herman-Rothery (GHR) model, collision-avoidance model (CA), linear model, psychophysical or action-point model (AP), and fuzzy logic-based model (Panwai 2005). (Khodayari 2012) achieved the control of car following behavior through MPC approach. (Pan 2008) builded a linear, continuous and time-delay model of car following, which was suitable for data processing of the computer. The evaluation of car following models have also been studied, (Panwai 2005) presented findings from a comparative evaluation of car-following behavior in a number of traffic simulators, (Zheng 2012) evaluated car following models by using field trajectory data and genetic algorithm based calibration method.

Compared with car following, the studies of overtaking models have been presented in recent years. (Milanés 2012) was based on a stereo vision system responsible for detecting any preceding vehicle and triggering the autonomous overtaking maneuver, and a fuzzy logic based controller was developed to emulate how humans overtake. (Ngai 2011) presented a learning method to solve the vehicle overtaking problem, which demands a multiple criteria. (Chen 2010b) introduced a model based on the cellular automata method (CA method) for two lane traffic flows, in this model, the effect of vehicular density and signal cycle time on traffic flow were investigated. (Wang 2009) proposed an overtaking control method based on the estimation of conflict probability. (Naranjo 2007) and (Naranjo 2008) proposed a fuzzy control system that essentially changes the driving mode according to the three phases. (Naranjo 2007) developed fuzzy control systems so that vehicles can manage driving actuators in a way similar to humans, such as overtaking the mobile or immobile obstacles. (Naranjo 2008) used fuzzy controllers that mimic human behavior and reactions during overtaking maneuvers and offered a rule to estimate the distance of an overtaking maneuver.

Based on the proposed multi-agent based VR-ISSV in Chapter 2, in this chapter, an intelligent vehicle agent in virtual reality simulation system is proposed (Yu 2013a), which is well suited to incorporate and simulate driver's cognitive processes and personalities' mechanism in the complex traffic situation. The car following behavior and the overtaking behavior based on the intelligent vehicle agent are realized, which is better understanding of the human factors to analyze car following behavior and the traffic situation to analyze overtaking behavior in traffic (Yu 2013b). The road is in the straight lane in this chapter, so autonomous road following is not discussed. In Chapter 5, autonomous road following, car following and overtaking behaviors considering environment effect will be presented.

The main contribution of this chapter is to propose intelligent vehicle agent model and to present the microscopic traffic behaviors (car following and overtaking) based on intelligent vehicle agent, especially the agent-based multi-controller is designed in the intelligent vehicle agent, the coordination of multi-controller could realize microscopic behavior. This chapter is organized as follows: Section 3.2 will propose the architecture of intelligent vehicle model, which is a comprehensive model of 3D virtual vehicle combining with perception module, motion module, cognition and behavior module, and internal properties. Section 3.3 will show car following behavior in detail. Car following behavior of virtual vehicle will be realized by the coordination mechanism of agent-based multi-controller, which will be determined by predetermined perceptual threshold levels. In Section 3.4, overtaking behavior model based on the intelligent vehicle will be introduced in detail, the lane changing model will be analyzed because it is the base of overtaking behavior.

3.2 Modeling intelligent vehicle agent

Intelligent vehicle agent belongs to the entity agents in the multi-agent layer, shown in Fig. 2 of Chapter 2. As the most important part of the system, the intelligent vehicle agent could reflect the microscopic traffic behavior considering environment effects and traffic situation.

The intelligent vehicle agent is an autonomous virtual vehicle, which is architected as a hierarchical model incorporating perception module, motion module, cognition and behavior module, and internal properties, shown in Fig. 3.

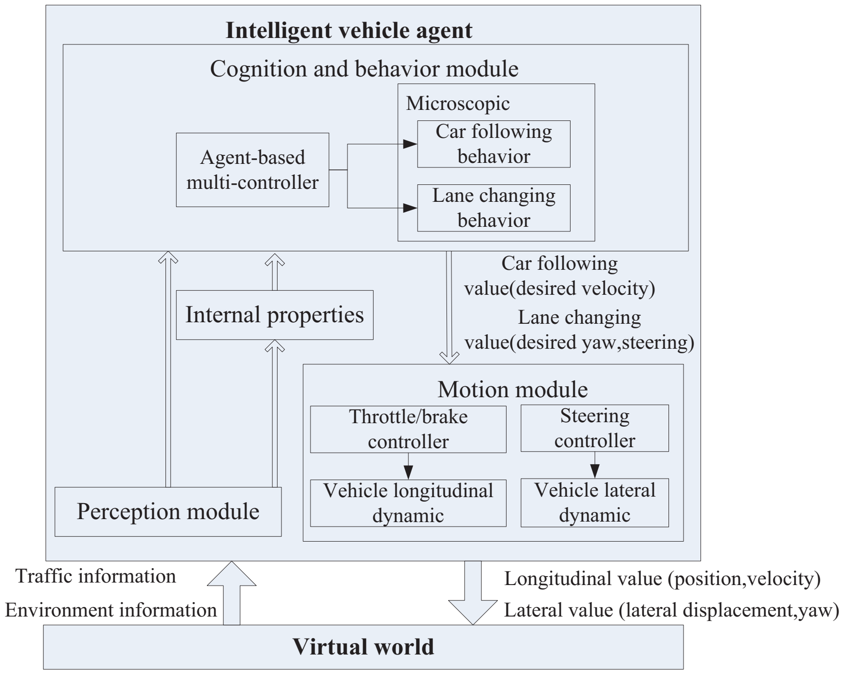


Figure 3.1: Framework of Intelligent Vehicle Agent

3.2.1 Perception module

Perception module monitors messages from human and other agents, which identifies the relevant events in virtual reality traffic simulation system. A 3D vehicle corresponding to the intelligent vehicle agent is created in the virtual world. In this way, the perception module can acquire information about its surrounding environment through the interaction among 3D models, such as collision detection. The distance between vehicles could be calculated in the virtual world. With this module, the intelligent vehicle agent could perceive the traffic information and the environment information, then all these information are sent to the internal properties and the cognition and behavior module for further decision making (Yu 2013a).

3.2.2 Internal properties

Internal properties reflect the agent's personalities impacting on cognition and behavior module. In real traffic, the reactions of different drivers are not same according to different traffic situation and environment information. Therefore, drivers' decisions are different. The internal properties could reflect the characteristics of different drivers' reactions. The internal properties include driver type and driver state. The driver type could be divided into passive, moderate and aggressive according to the degree of aggressiveness of the driver (Maroto 2006). The driver state could be divided into asleep, fatigue and normal according to the physical condition of the driver (Stuttsa 2003). Internal properties receive the information from the perception module. According to different driver type or driver state, the information that could affect drivers' decisions, such as driver's reaction time, is sent to cognition and behavior module to realize the decision making process.

3.2.3 Cognition and behavior module

Cognition and behavior module is the brain of the intelligent vehicle agent, which could achieve more sophisticated tasks, such as behavior choice, navigation and drivers' decision making according to the traffic situation and the environment information. The cognition and behavior module is modeled as agent-based multi-controller instead of a single control algorithm. In this way, the agent-based architecture is open so that controllers can be easily added, removed or changed, so it is useful for the future extension and the verification of vehicle control algorithms.

In view of the agent-based framework for designing multi-controller system proposed by (Breemen 2000), the organization of agent-based cognition and behavior module could be described precisely by Fig. 4. The controller agent at top is called the top controller agent. A controller agency consists of a pool of controller agents and a coordination object. A controller agent behaves in two ways: either it behaves as being 'active' or it behaves as being 'inactive'. The active request signal transmitted from the controller agent to the coordination object, specifies whether the controller agent wants to become active or not; the acknowledge signal transmitted from coordination object decides whether the controller agent to be active or not (shown as the red line in Fig. 4). The input information from other modules could be sent to all the controller agents (shown as the black solid line in Fig. 4). The output information is sent to coordination objects for further decision then sent to other modules (shown as the black dotted line in Fig. 4). The intelligent vehicle is the top controller agent, which contains two sub controllers agents: longitudinal controller agent and lateral controller agent. The longitudinal controller agent is used for controlling the velocity and the inter-space; while the lateral controller agent is used for controlling the lateral displacement and the yaw angle.

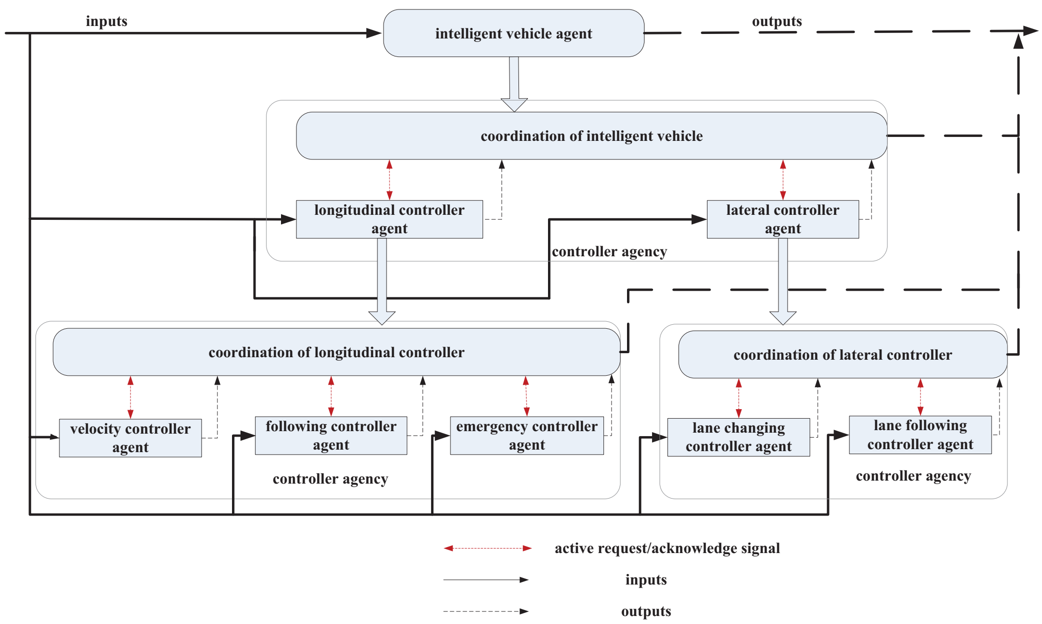


Figure 3.2: Agent-Based Multi-Controller Intelligent Vehicle

According to the typical driving scenarios, when the human driver controls the vehicle in an appointed lane, he/she performs four main tasks. The first is to maintain an optimal speed as much as possible when no vehicle is in sight. The second task is to keep a safe distance from any car ahead. The third task is to deal with the situation when a sudden car cuts in the driving lane. The last is to react immediately as a response to an emergency which usually implies a hard brake. The designed longitudinal controller should be able to perform all these four tasks (Cai 2010). Therefore, the longitudinal controller agent in this study is designed to consist of three sub controllers agents: velocity controller agent, following controller agent and emergency controller agent. The coordination of the three controllers makes the model intelligent to distinguish different traffic scenarios and select suitable mode to operate. The input information of longitudinal controller agent includes the speeds of vehicles, the distance between the vehicle and a vehicle in front, the road geometry, *et al.* The output information is desired velocity, desired distance to front vehicle, *et al.*

Lateral controller is not active when the car is in the straight road and lane changing does not happen. Lateral controller agent realizes lane keeping and lane changing function of intelligent vehicle. The input information of lateral controller agent includes velocity, acceleration, road geometry features and wind speed, *et al.* The output information is desired yaw angle, desired lateral displacement, *et al.*

The coordination mechanism of the longitudinal controller agent and the lateral controller agent is parallel, the longitudinal controller agent and the lateral controller agent work independently, because they don't use the same resource.

The coordination mechanism of the emergency controller agent, the following controller agent and the velocity controller agent is fixed priority. The priority index of the controller agents is as following: emergency controller agent > following controller agent > velocity controller agent. That is to say, the emergency controller agent that wants to be active gets active, if the following controller agent or the velocity controller agent with a lower was active, this one gets inactive. And if the emergency controller agent is inactive, the following controller agent gets active whenever it wants.

According to the decision making based on the multi-controller in cognition and behavior module, the desired vehicle movement parameters could be calculated to realize the microscopic behavior, such as desired velocity, desired yaw angle and desired steering angle, *et al.*, and these parameters are sent to the motion module.

3.2.4 Motion module

Motion module receives the desired movement parameters from cognition and behavior module and realizes the movement implementation of the intelligent vehicle agent. Vehicle dynamic models and vehicle control models are realized in this module, which are decoupled as longitudinal motion model and lateral motion model. The longitudinal motion model consists of coordinated throttle/brake fuzzy controllers and longitudinal vehicle dynamic model; and the lateral motion model consists of steering fuzzy controllers and lateral vehicle dynamic model. With these models and controllers, the vehicle tries to follow the designed movements by modifying and acting on the control parameters of the vehicle (steering, throttle and brake). Motion module sends the vehicle movement values, such as position, velocity, lateral displacement, yaw angle, *et al.*, to the virtual world, which could be used in the calculation of traffic information and environment information and also could be used in the visualization.

The coordination of agent-based multi-controller can realize microscopic traffic behavior simulation. In this chapter, we focus on the analysis of car following behavior and overtaking behavior. To analyze these microscopic behavior model, the motion module is constructed by the coordinated throttle and brake fuzzy controller and longitudinal vehicle dynamic model proposed in (Zhao 2010a), and a multi-model fuzzy controller and lateral vehicle dynamic model proposed in (Zhao 2010b). The car following behavior and the overtaking behavior are researched in straight lane in this chapter, so only the lane changing controller is used in overtaking behavior, the lane keeping controller will be presented in Chapter 5. The lateral controller in this chapter means lane changing lateral controller.

3.3 Car following behavior

The car following behavior is divided into three driving modes (driving free, following a car and decelerating with emergency). Each mode is controlled by an agent-based controller. The car following behavior model is realized through the coordination of the emergency controller, the following controller and the velocity controller. The car following behavior switches from one mode to another according to the coordination of the three controllers, this switching process is determined by predetermined perceptual threshold levels. These thresholds are defined as a combination of speed and distance differences.

3.3.1 Distribution of thresholds

Thresholds are defined as following:

(1) Following distance (l_{FD}) represents a comfortable distance of the vehicles. The vehicle follows the front vehicle at the desired following distance, which meets the conditions that if the front vehicle accelerates/decelerates in normal, the following vehicle could accelerate/decelerate to avoid the collision. The following distance is defined through human range policy, which could be in the form of a quadratic curve (Zhou 2005).

In the steady state of car following, the speed of the following vehicle (v_i) is the same with the leading vehicle (v_{i-1}), so the l_{FD} is defined as following:

$$l_{FD} = \gamma \frac{{v_i}^2}{2a_{i\,\max}} + L + \tau v_i, \tag{3.1}$$

where L is the safety margin which denotes the separation between two vehicles when they stop; $a_{i\,\max}$ is the maximum deceleration; τ is the driver's reaction time; γ is the safe coefficient (Zhao 2009), a parameter that could be selected by the user, which relevant to road conditions. For instance, the use can select a bigger value of safe coefficient if the road surface is wet.

(2) Brake distance (l_{BD}) represents conditions when distance is too closing for comfortable driving. The following vehicle brakes with its maximum deceleration to avoid collision. During the braking process, by considering the safety margin L and the reaction time of driver τ, the following expression must be satisfied:

$$x_i + \frac{v_i^2}{2a_{i\max}} - (x_{i-1} + \frac{v_{i-1}^2}{2a_{i-1\max}}) \geq L + \tau v_i, \tag{3.2}$$

where x_{i-1} is the position of leading vehicle; x_i is the position of following vehicle. Thus the l_{BD} is defined as following:

$$l_{BD} = \gamma(\frac{v_i^2}{2a_{i\max}} - \frac{v_{i-1}^2}{2a_{i-1\max}}) + L + \tau v_i. \tag{3.3}$$

(3) Collision distance (l_{CD}) represents conditions when the leading vehicle drives at a constant speed, the minimum distance for collision avoidance even if the following vehicle decelerates at the max deceleration.

The distance of two vehicles ($S(t)$) is:

$$S(t) = v_i t - \frac{1}{2} a_{i\max} t^2 - v_{i-1} t. \tag{3.4}$$

The collision distance needs to meet:

$$l_{CD} - L = \max_{t \in (0,\infty)} (S(t)) = \max_{t \in (0,\infty)} (v_i t - \frac{1}{2} a_{i\max} t^2 - v_{i-1} t). \tag{3.5}$$

Differentiating $S(t)$, we can get the maximum value when:

$$t = \frac{v_i - v_{i-1}}{a_{i\max}}. \tag{3.6}$$

Thus the collision will happen when:

$$v_i \geq v_{i-1}, \tag{3.7}$$

and:

$$l_{CD} \leq \frac{(v_i - v_{i-1})^2}{2a_{i\max}} + L. \tag{3.8}$$

Considering the real situation, the max deceleration can not be reached when the sudden brake happens, the discount factor is defined as μ, $\mu \in (0, 1)$, and the l_{CD} is defined as following:

$$l_{CD} = \frac{(v_i - v_{i-1})^2}{2\mu a_{i\max}} + L \ (v_i \geq v_{i-1}). \tag{3.9}$$

3.3.2 Coordination of longitudinal controller

The coordination of the emergency controller, the following controller and the velocity controller affected by the thresholds are as following:

(1) $S(t) \geq (1.5 \sim 2.5)l_{FD}$, velocity controller is active, which represents the behavior of maintaining an optimal speed when no vehicle is in sight.

(2) $l_{BD} < S(t) < (1.5 \sim 2.5)l_{FD}$, following controller is active, which represents the behavior of keeping a distance from any vehicle ahead.

(3) $l_{CD} < S(t) < l_{BD}$, emergency controller is active, which represents the behavior of reacting to an emergency which usually implies a hard brake.

But the coordination of the longitudinal controller is not only affected by the inter-space between the vehicles, but also the difference of the velocity between two vehicles and the acceleration of front vehicle. Considering all the factors, the coordination of the longitudinal controller is shown in Fig. 5.

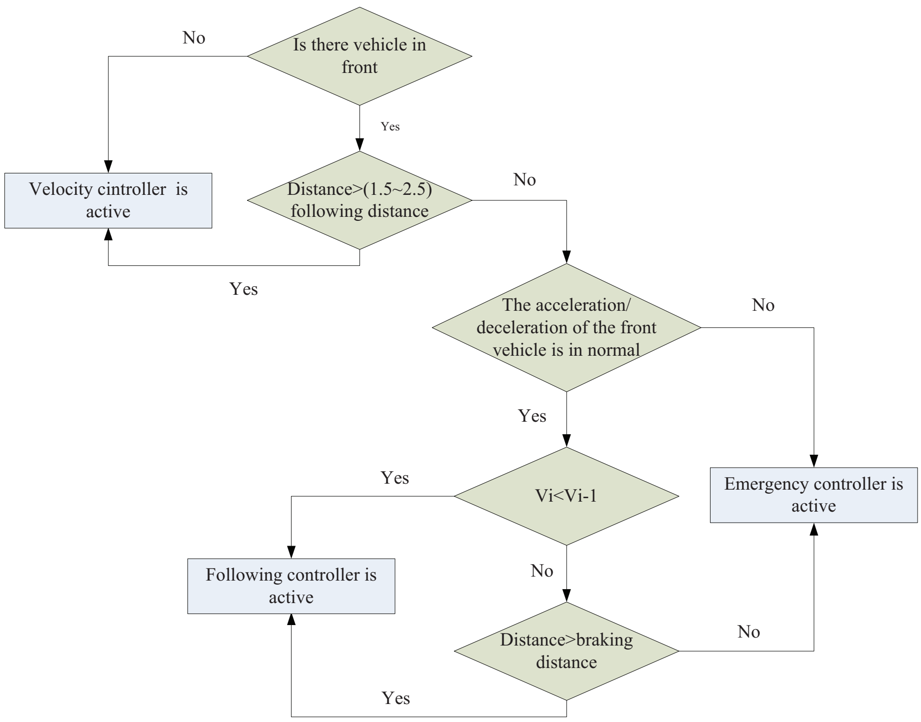


Figure 3.3: Coordination of the Longitudinal Controller

3.3.3 Controller design

The controller is used to design the proper acceleration/deceleration according to different driving traffic scenario.

(1) Velocity controller: maintain the vehicle driving at the desired speed.

If $v_i < v_{des}$, the desired acceleration is $a_i = a_{acc}$.
If $v_i = v_{des}$, the desired acceleration is $a_i = 0$.
If $v_i > v_{des}$, the desired acceleration is $a_i = a_{dec}$.
Where v_{des} is the desired speed, a_{acc} is the comfortable acceleration, a_{dec} is the comfortable deceleration.

(2) Following controller: maintain a safe distance between the controller vehicle and the immediate preceding vehicle. According to the desired safety following distance (l_{FD}):

$$a_i = -(\lambda\delta_i + v_i - v_{i-1})/(t_d + \frac{\gamma}{a_{i\max}}v_i), \tag{3.10}$$

where $\delta_i = x_i - x_{i-1} + l_{FD}$; λ is a positive control gain.

(3) Emergency controller: make the vehicle stop immediately. The deceleration is $a_i = a_{i\max}$.

In manual driving for 125 people, 98% of the accelerations were between -2.17 and $1.77m/s^2$ (Moona 2006). Most drivers and passengers feel significantly uncomfortable when the vehicle deceleration is greater than $3-4m/s^2$ (in absolutely value) only when they really need to apply severe braking to prevent the vehicle to vehicle distance from dropping to an unsafe level (Moona 2009). Thus in normal driving situation, a_{acc}/a_{des} is designed between -2.17 and $1.77m/s^2$, and $a_{\max}$ is designed to be greater than $3m/s^2$ (in absolutely value). But when the vehicle drives in abnormal environment, the desired acceleration/deceleration is not in this scope.

3.3.4 Acceleration/Deceleration and jerk profiles for safety and comfort

The throttle/brake works gently so that the driver is not surprised by this action. That is to say, in real situation, the desired acceleration/deceleration is not instant action. Besides, acceleration/deceleration and jerk (time rate of change of acceleration/deceleration) have significant effect on ride comfort (Yi 2001).

In order to maintain smooth acceleration/deceleration, acceleration/deceleration profile has been designed for safety and comfort. A deceleration profile shown in Fig. 3.4 has been designed and it was used as desired deceleration.

The desired deceleration profile is divided into the following three phases:

Phase I:

$$t_1 \rightarrow t_2: \; a(t) = \frac{t - t_1}{t_a} a_{\max}, \tag{3.11}$$

where $t_a = t_2 - t_1$.

Phase II:

$$t_2 \rightarrow t_3 : a(t) = a_{\max}. \tag{3.12}$$

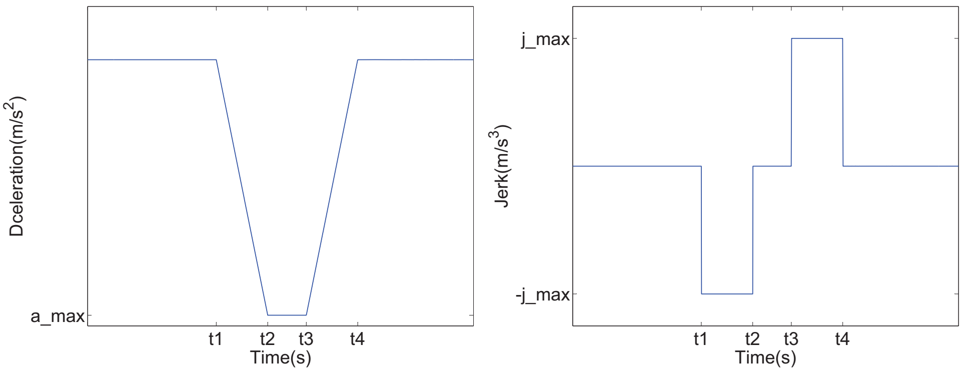


Figure 3.4: Deceleration and Jerk Profiles Designed for the Car Following Behavior Model

Phase III:

$$t_3 \rightarrow t_4: \; a(t) = a_{\max}(1 - \frac{t - t_3}{t_b}), \tag{3.13}$$

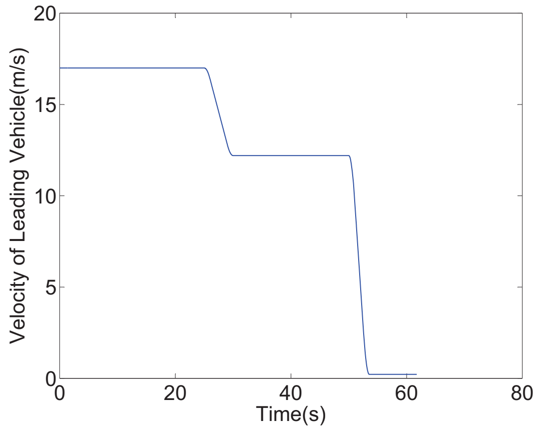
where $t_b = t_4 - t_3$.

In this study, t_a and t_b have been selected to limit the jerk as: $-10m/s^3 \leq j_{\max} \leq 10m/s^3$ (Yi 2001).

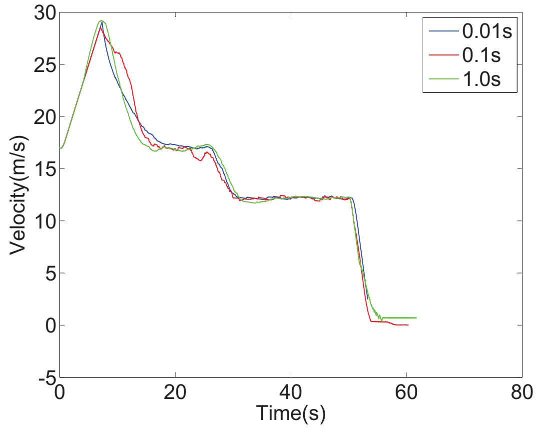
3.3.5 Simulation results

The car following maneuver is realized through the two-vehicle platoon. The leading vehicle runs with $17m/s$ at beginning, and decelerates to $12.5m/s$ in 5 seconds (from $25s$ to $30s$). At $t = 50s$, it brakes hardly to $0.2m/s$ in 2 seconds. The designed velocity of leading vehicle could be seen in Fig. 3.5(a).

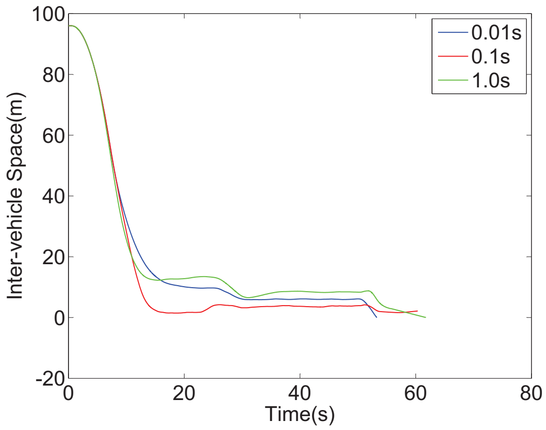
To research the car following behavior under different driver properties, considering the variables of internal properties of intelligent vehicle agent, the driver type and the driver state could be reflected through the driver's reaction time (τ). The velocity of the following vehicle and the inter-vehicle space under different driver's reaction time (τ) are shown in Fig. 3.5(b) and Fig. 3.5(c). The designed simulation time is $70s$, and the simulation will stop when collision happens between two vehicles or the velocity of vehicle is zero. We can see that when τ is $0.01s$ and $1.0s$, the collision happens because the leading car brakes hardly; when τ is $0.1s$, the following car could stop even if the leading vehicle is with severe deceleration. The car following behavior affected by the driver properties could be reflected in the simulation. The short driver's reaction time ($\tau = 0.01s$) presents the driver is aggressive. The long driver's reaction time ($\tau = 1.0s$) presents the driver is passive or fatigue. Proper driver's reaction time ($\tau = 1.0s$) presents the driver is normal. Only proper driver's reaction time could avoid the collision.



(a) Designed Velocity of Leading Vehicle



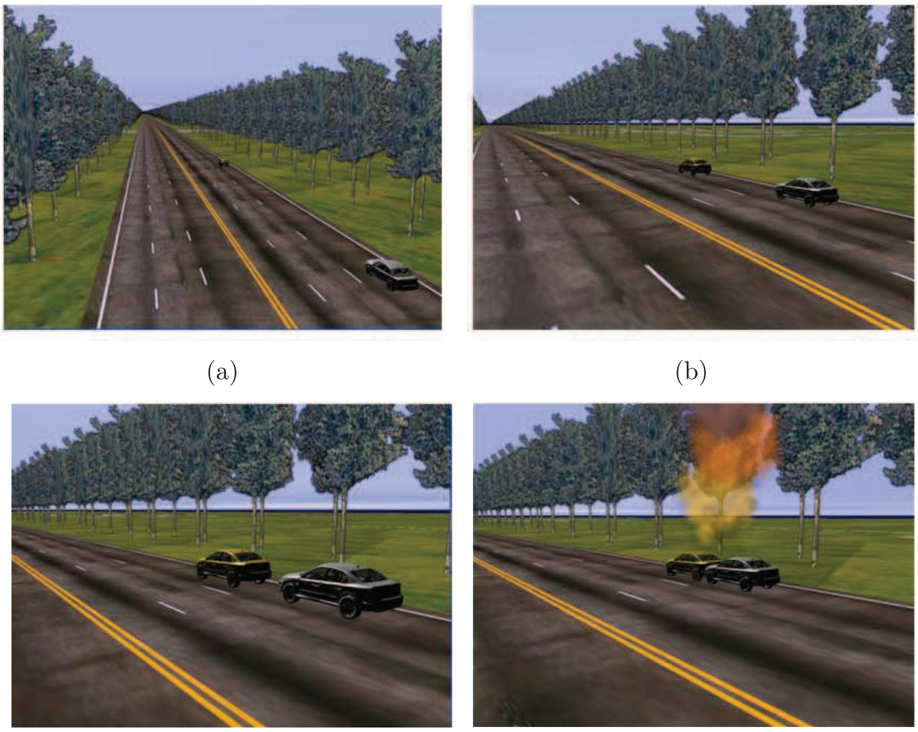
(b) Velocity of Vehicle under Different Driver's Reaction Time



(c) Inter-vehicle Space

Figure 3.5: Car Following Maneuver Simulation Results

Fig. 3.6 shows the visualization scenes corresponding to the car following maneuver. At beginning, the inter-vehicle space is large and the velocity controller is active, shown in Fig. 3.6(a). Fig. 3.6(b) presents the following controller is active, the following vehicle runs with the leading vehicle to keep a safe distance. Fig. 3.6(c) displays the following vehicle stops without collision ($\tau = 0.1s$), when the leading vehicle decelerates severely. The collision scene is shown in Fig. 3.6(d).



(a) (b) (c) (d)

Figure 3.6: Visualization Scenes

3.4 Overtaking behavior

Overtaking is a complex traffic simulation maneuver. An overtaking maneuver consists of three phrases: (1) diverting from the original lane; (2) driving straight in the adjacent lane; (3) returning to the original lane. From the three phrases, the relationship between lane changing and overtaking is obvious, lane changing is an important part of overtaking process, it is the base of overtaking. Therefore, the lane changing behavior model will be considered (Usman 2009).

3.4.1 Lane changing behavior model

Lane changing behavior model is a vital component in microscopic traffic behavior, and the rules describing drivers' lane changing maneuvers are well described in the literature (Gipps 1986). The lane changing behavior model in this study is realized through the coordination of longitudinal controller and lateral controller. In the traffic simulation of straight lane, the longitudinal controller is active all the time, and the lateral controller gets active (for lane changing) when lane changing feasibility meets. The lane changing process and the lane changing feasibility will be discussed in detail.

3.4.1.1 Lane changing process

Fig. 6 shows the image of the lane changing process. The controlled vehicle is defined as the subject vehicle; the vehicle running in the front of the subject vehicle on the same lane is defined as leading vehicle; the vehicles running in the front and the rear of the subject vehicle are defined as forward vehicle and backward vehicle. Based on this process, the input information of the subject vehicle that is the intelligent vehicle, includes the velocity of subject vehicle (V_s), the velocity of the vehicle in front (V_l), the distance to the leading vehicle ($S(t)$) in the original lane, the velocity of the vehicles (V) in the adjacent lane, the distance to the front vehicle ($S_f(t)$) and the distance to the backward vehicle ($S_b(t)$) in the adjacent lane. The output information is desired velocity, lateral position and yaw angle.

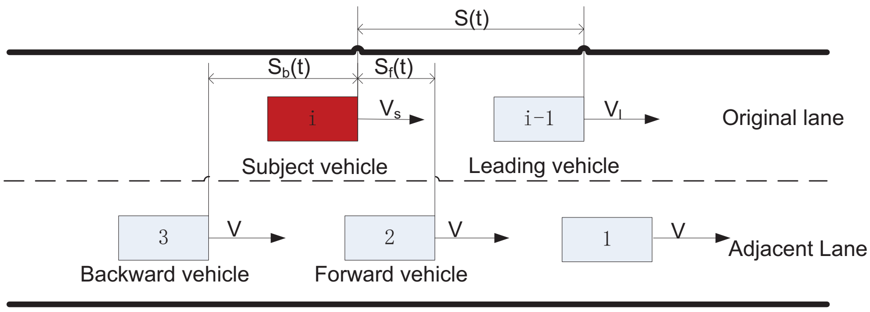


Figure 3.7: Image of the Lane Changing Process

During the lane changing process, the longitudinal velocity of the subject vehicle is adjusting with the forward vehicle due to the coordination of the longitudinal controller. Based on the judgment of lane changing feasibility, the collisions between the vehicles could be avoided during the lane changing process.

3.4.1.2 Lane changing feasibility

In the context of lane changing model, a lane changing is considered feasible if there is a gap of sufficient size in the target lane so that the vehicle can move into the target lane safely, cooperating with other vehicles in the target lane. To determine the feasibility of the maneuver, first a search, in the adjacent lane, is conducted to find the vehicle just in front, and the vehicle just behind the subject vehicle. These would become the new leader and the new follower respectively of the subject vehicle if the lane changing could be feasible. According to the lane changing process in Fig. 6, the lane changing feasibility is divided into two situations:

(1) $V_s < V$, for the forward vehicle, the lane changing happens when:

$$S_f\,(t) \geq S_f\,(min) = L, \tag{3.14}$$

for the backward vehicle, the lane changing happens when:

$$S_b\,(t) \geq S_b\,(min) = \frac{V^2 - {V_s}^2}{2j_b} + \tau V + L, \tag{3.15}$$

(2) $V_s > V$, for the backward vehicle, the lane changing happens when:

$$S_b\,(t) \geq S_b\,(min) = L, \tag{3.16}$$

for the forward vehicle, the lane changing happens when:

$$S_f\,(t) \geq S_f\,(min) = \frac{{V_s}^2 - V^2}{2j} + \tau V_s + L, \tag{3.17}$$

where $S_f(min)$ is the minimum distance to the forward vehicle to avoid the collision; $S_b(min)$ is the minimum distance to the backward vehicle to avoid the collision; j_b is the maximum deceleration of the backward vehicle; j is the maximum deceleration of the subject vehicle; τ is the driver's reaction time; L is a constant distance between two vehicles when they stop.

3.4.1.3 Coordination of longitudinal controller and lateral controller

In real traffic, a driver prefers to change lane to a higher speed lane if the velocity of the vehicle or the velocity of the leader vehicle is lower than the desired speed. Thus the lane changing is desirable when the speed of the vehicle will be improved based on assessing the traffic situation in the new lane or when the overtaking maneuver happens.

The coordination of the longitudinal controller and the lateral controller is shown in Fig. 3.8. As other lane changing model, the lateral controller actives considering the desirability and feasibility of lane changing process. The longitudinal controller actives all the time but the information used for the coordination of the longitudinal controller changes with the lane changing process. During the lane changing, the longitudinal controller is used for controlling the longitudinal velocity to maintain a safe distance between the subject vehicle and the immediate preceding vehicle. The desired safety distance is the same with the models in car following behavior.

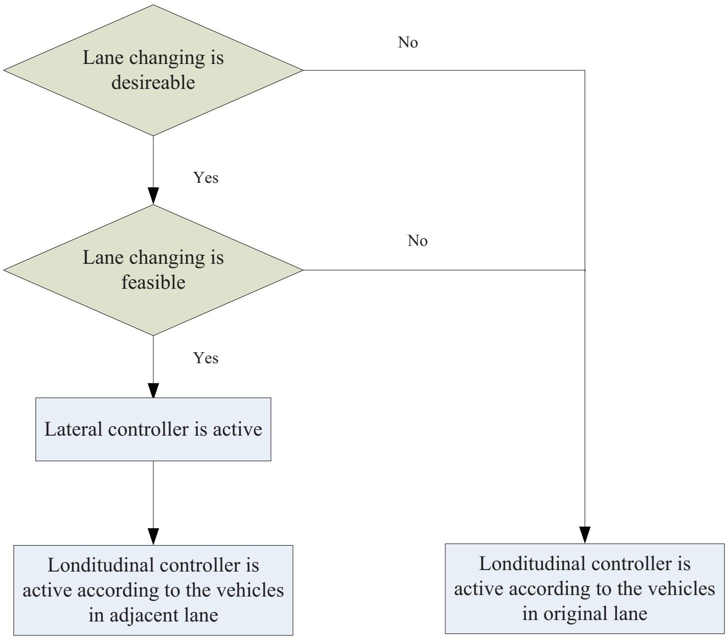


Figure 3.8: Coordination of the Longitudinal Controller and the Lateral Controller

3.4.1.4 Traffic situation model

To evaluate the lane changing model in different traffic situation, the velocity and the space between the vehicles in the adjacent lane are decided by the traffic situation model. The traffic situation model is based on the process developed by Skycomp to classify and characterize road traffic congestion (Bauza 2012), which provides their associated Level-of-Service (LOS) by analyzing the traffic data collected through aerial surveys of different freeway.

According to the classified level of congestion, the traffic situation model is shown in Table 3.1.

For the security of the adjacent lane, the traffic situation model supposes that the vehicle can accelerate only there is not vehicle in front or decelerate only there is not vehicle at behind.

Table 3.1: Traffic Situation Classification

Level of congestion	Density(veh/km/lane)	Speed(km/h)
Free flow(0)	<29	>60
Slight congestion	[29-37]	[48-81]
Moderate congestion	[37-50]	[24-64]
Severe congestion	>50	<40

3.4.2 Flow chart of overtaking maneuver

Each overtaking maneuver includes two lane changing and a car following component. Consequently, the speed and the steering of intelligent vehicle need to be managed. Based on the model in this study, the controllers are considered to be partially decoupled. The complex overtaking maneuver could be realized through the coordination of the agent-based multi-controller. According to the lane changing behavior model, the flow chart of the overtaking maneuver is shown in Fig. 3.9.

3.4.3 Simulation results

In this section, simulation results are shown to verify the correctness and effectiveness of our approach for modeling overtaking behavior. In the VR-ISSV, the intelligent vehicle could realize overtaking maneuver through the coordination of agent-based multi-controller considering the different traffic situations. As shown in Fig. 6, five vehicles have been simulated in the overtaking maneuver. Two vehicles run in the original lane and three vehicles run in the adjacent lane. The initial speed of all the vehicles is set to $17m/s$. The congested traffic situation and the free flow traffic situation have been experimented. In the two situations, the velocity and the space between the vehicles in the adjacent lane are different, which is determined by the traffic situation model.

3.4.3.1 Congested traffic situation

During the congested traffic situation, based on the traffic situation model, in the adjacent lane, the density (ρ) is set to $50veh/km/lane$; the speed of the vehicle (V) is set to $10m/s$. The relationship between the density and the inter-space is $\mathrm{G} = 1/\rho$, so the distance between two vehicles in the adjacent lane is $20m$. Shown as Fig. 6, we assume that at time $t = 0s$; the position of vehicle 1 $P_1 = 250m$; the position of vehicle 2 $P_2 = 230m$; the position of vehicle 3 $P_3 = 210m$; the position of leading vehicle $i-1$ $P_{i-1} = 0m$; the position of subject vehicle i $P_i = 16m$; the simulation results are shown in Fig. 3.10.

In Fig. 3.10(a), the red line shows the inter-vehicle space between the subject

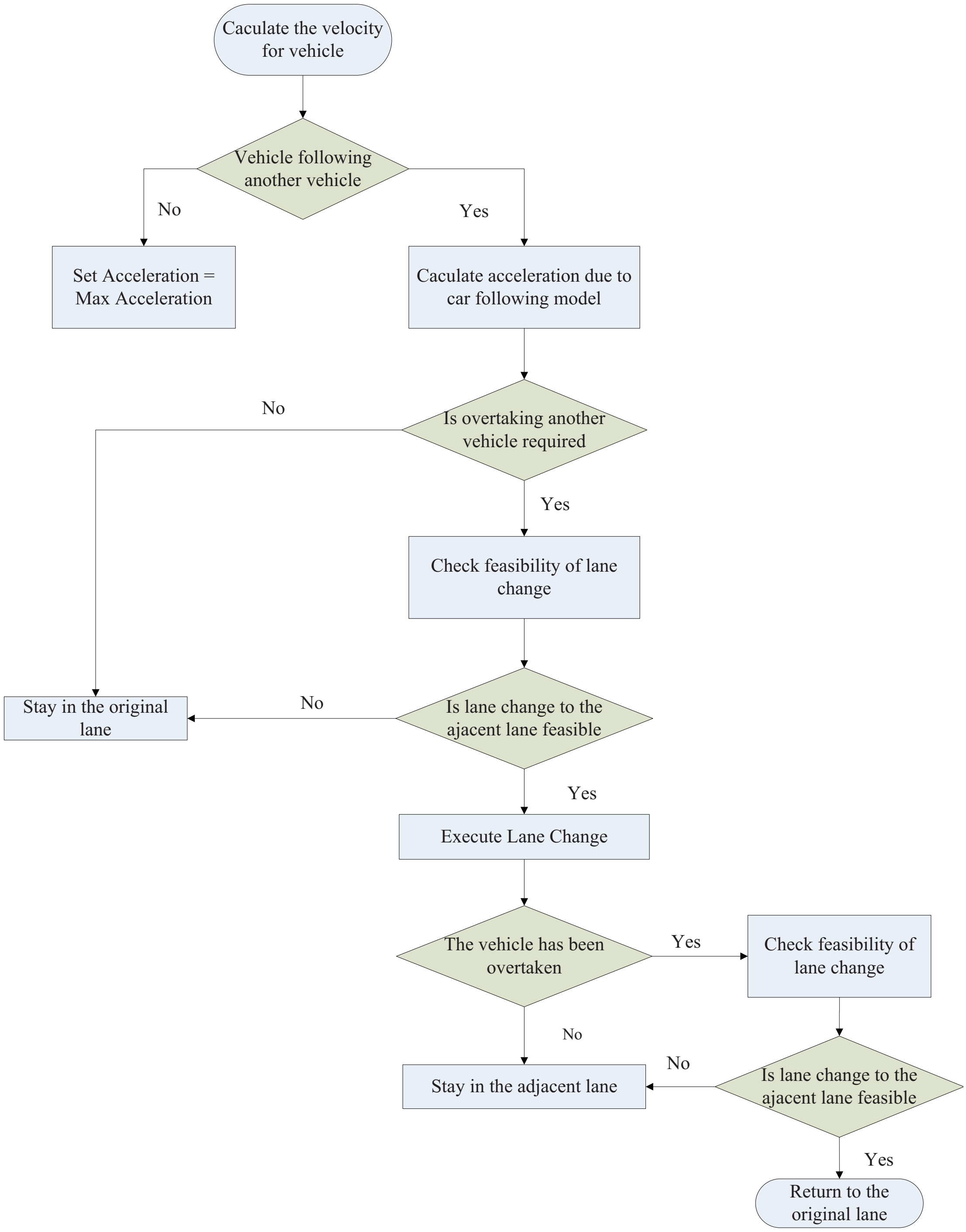


Figure 3.9: Flow Chart of the Overtaking Maneuver

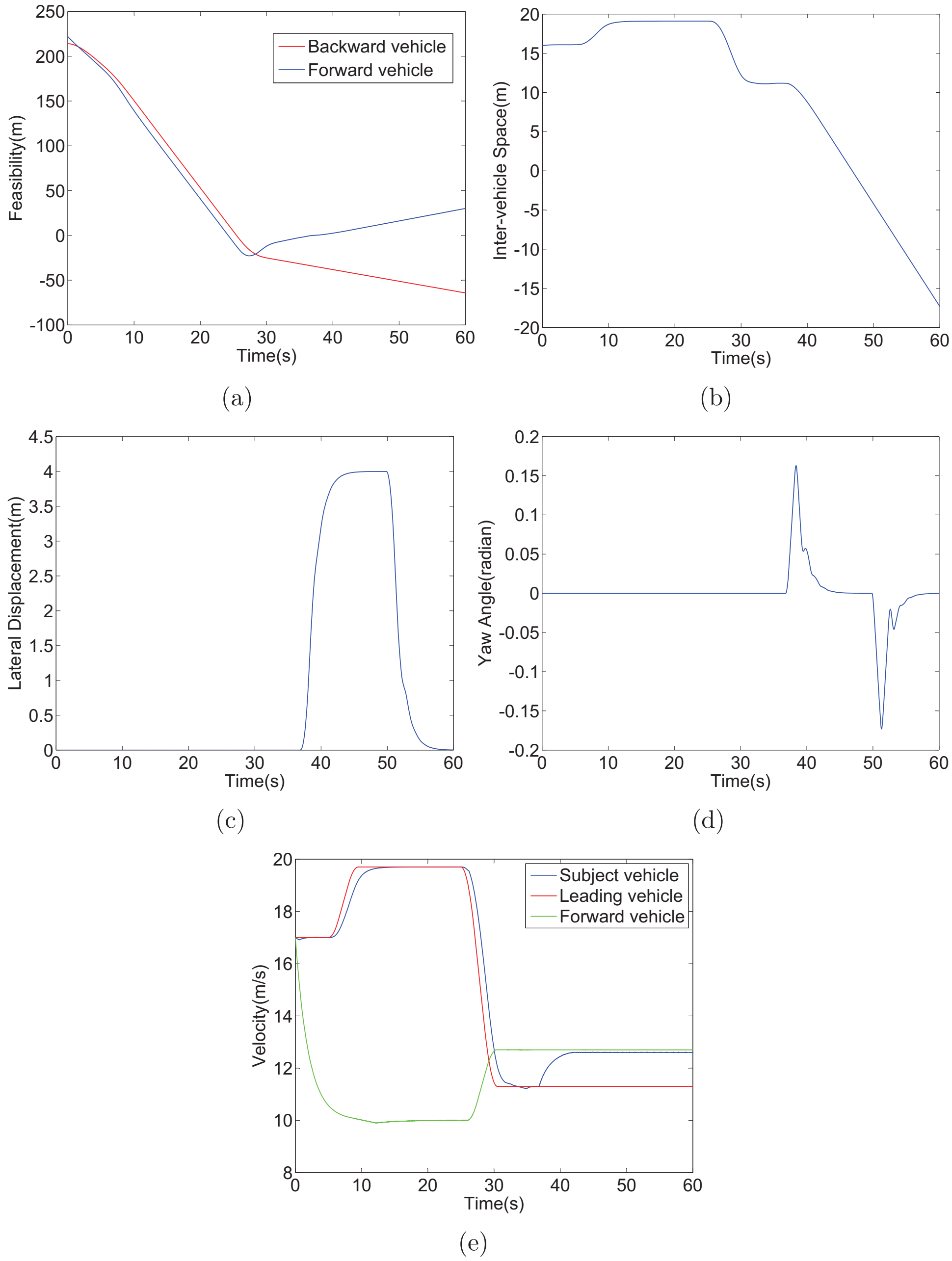


Figure 3.10: Simulation Results under Congested Traffic Situation

vehicle and the backward vehicle, which is $P_2 - P_i$; the blue line is $(P_1 - P_i) - S_f(min)$. According to the lane change model, lane change feasibility is $P_2 - P_i < -L, (P_1 - P_i) - S_f(min) > 0$.

The lateral controller gets active twice when the overtaking behavior happens. The first is that the subject vehicle moves to the adjacent lane; the second is that the subject vehicle returns to the original lane. The lateral controller gets inactive when the lane changing finishes. At the first time, the lateral controller gets active according to lane changing feasibility (shown in Fig. 3.10(a)), the longitudinal controller coordinates according to the vehicles in the adjacent lane. At the second time, the lateral controller gets active according to the gap to leading vehicle (shown in Fig. 3.10(b)), the longitudinal controller coordinates according to the vehicles in the original lane. The lateral displacement and the yaw angle of the subject vehicle could be seen in Fig. 3.10(c) and Fig. 3.10(d).

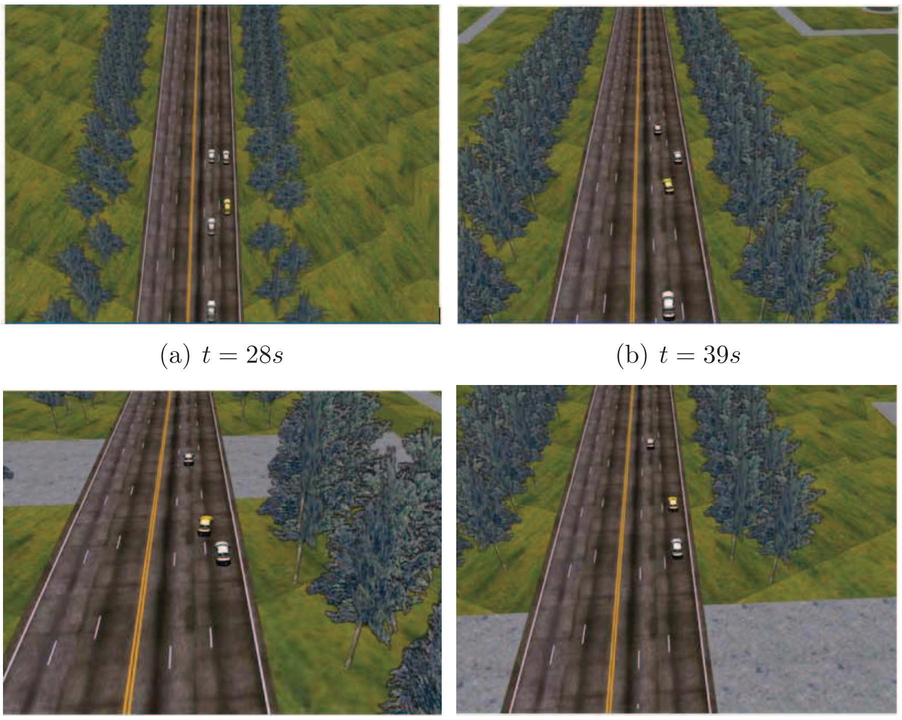
The overtaking maneuver is as following. When $t = 25.9s$, for the backward vehicle, $P_2 - P_i < -L$ meets, but for the forward vehicle, $(P_1 - P_i) - S_f(min) > 0$ cannot meet. So at $t = 25.9s$, forward vehicle begins to accelerate and the lane changing feasibility meets at $t = 37s$, the lateral controller gets active, the subject vehicle begins to change lane. The subject vehicle runs in the adjacent lane following vehicle 1 until it finds that it has overtaken the leading vehicle and the feasibility of lane change meets (in Fig. 3.10(b), $t = 49s$, $|\ Gap\ to\ the\ leading\ vehicle\ | = L$), it changes back to the original lane and finishes the overtaking maneuver. Fig. 3.10(e) shows the velocity of vehicles during the process. The visualization scenes corresponding to the overtaking maneuver are shown in Fig. 3.11. The yellow car is the subject vehicle. Fig. 3.11(a) displays the lane changing feasibility for backward vehicle meets. In Fig. 3.11(b), the subject vehicle changes to the adjacent lane. Fig. 3.11(c) presents the subject vehicle returns to the original lane. The overtaking behavior is finished in Fig. 3.11(d).

3.4.3.2 Free flow traffic situation

During the free flow traffic situation, in the adjacent lane, the density (ρ) is set to $20veh/km/lane$; the speed of the vehicle (V) is set to $25m/s$, therefore, the distance between two vehicles in the adjacent lane is $50m$. We assume that at time $t = 0s$; the position of vehicle 1 $P_1 = 100m$; the position of vehicle 2 $P_2 = 50m$; the position of leading vehicle 3 $P_3 = 0m$; the position of subject vehicle $i-1$ $P_{i-1} = 150m$; the position of vehicle i $P_i = 166m$. The simulation results are shown in Fig. 3.12.

In Fig. 3.12(a), the red line shows the inter-vehicle space between the subject vehicle and the forward vehicle, which is $P_2 - P_i$; the blue line is $(P_i - P_3) - S_b(min)$. According to the lane change model, lane change feasibility is $P_2 - P_i > L,\ (P_i - P_3) - S_b(min) > 0$.

From $t = 0s$ to $t = 20s$, the subject vehicle i follows the leading vehicle $i-1$, but the leading vehicle (V_{i-1}) starts to decelerate when $t = 20s$ and the subject



(a) $t = 28s$ (b) $t = 39s$

(c) $t = 51s$ (d) $t = 57s$

Figure 3.11: Visualization Scenes under Congested Traffic Situation

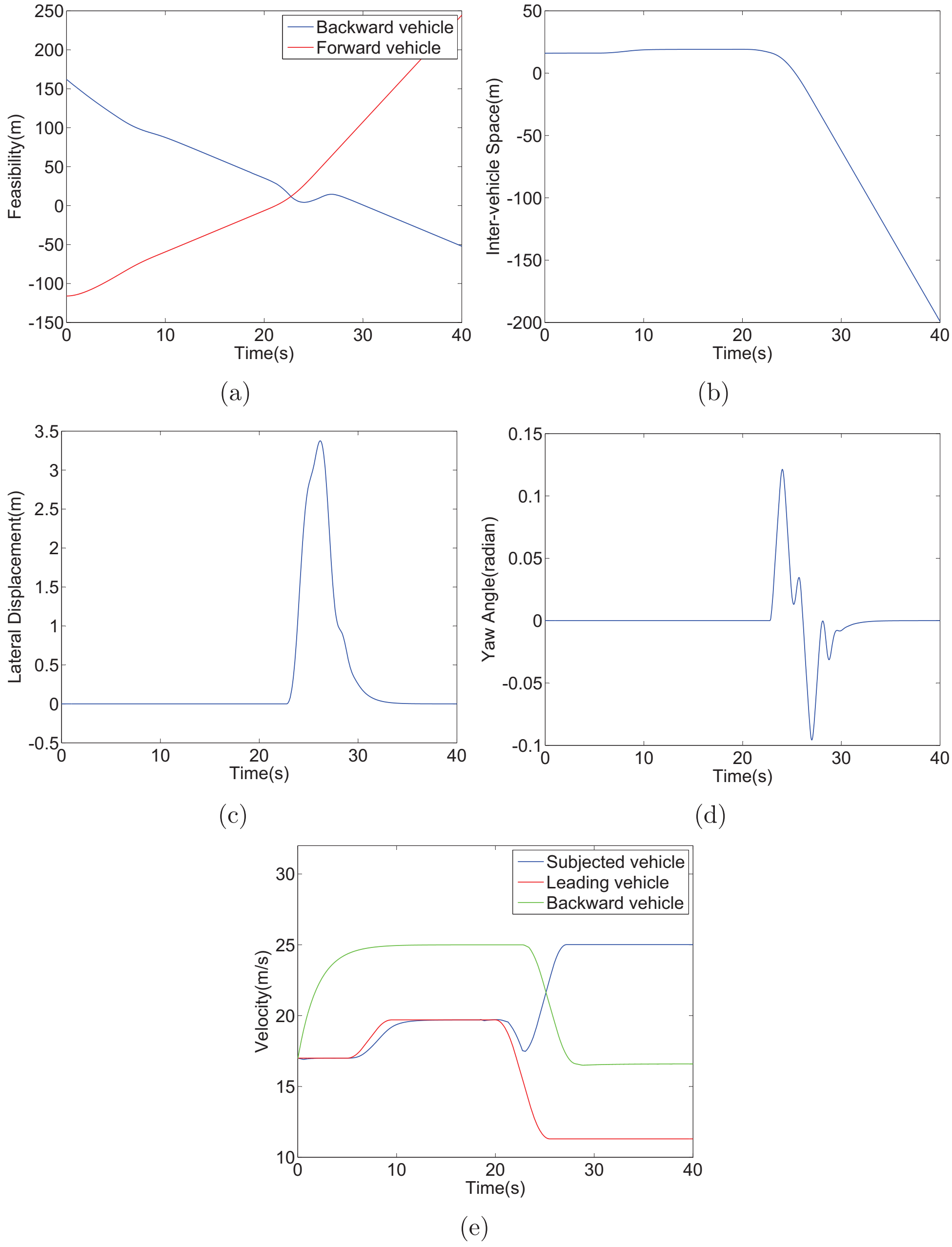
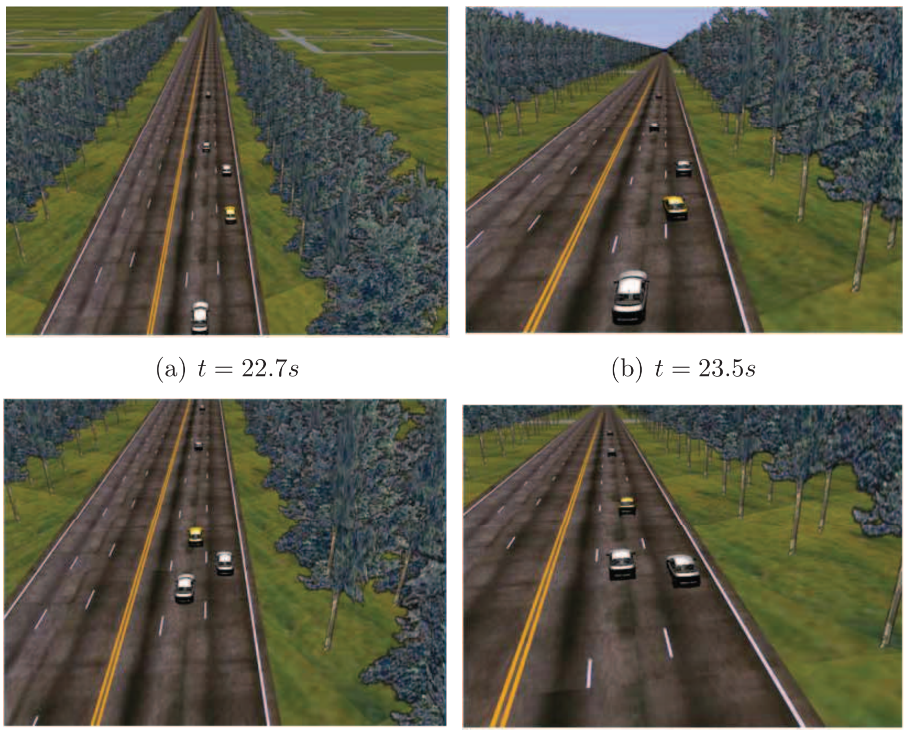


Figure 3.12: Simulation Results under Free Traffic Situation

vehicle desires to change lane; the lateral controller waits to get active until the feasibility of lane change meets. During waiting, the subject vehicle decelerates to maintain the gap between itself and the leading vehicle according to car following model. So when $t = 22.7s$, the lateral controller gets active, the subject vehicle begins to change lane and the backward vehicle begins to decelerate. After lane change finishes, $t = 25.9s$, the subject vehicle finds it has overtaken the leading vehicle and the feasibility of lane change meets($|$ $Gap\ to\ the\ front\ vehicle$ $| > L$ in Fig. 3.12(b)). It changes back to the original lane and finishes the overtaking maneuver. The lateral displacement and the yaw angle of the subjected vehicle could be seen in Fig. 3.12(c) and Fig. 3.12(d). Fig. 3.12(e) shows the velocity of vehicles during the process. Fig. 3.13. shows the visualization scenes corresponding to this process. Fig. 3.13(a) presents the lane changing feasibility meets. In Fig. 3.13(b), the subjected vehicle changes to the adjacent lane. Fig. 3.13(c) displays the subjected vehicle has overtaken the leading vehicle. In Fig. 3.13(d), the subjected vehicle returns to the original lane.



(a) $t = 22.7s$ (b) $t = 23.5s$

(c) $t = 25.9s$ (d) $t = 26.5s$

Figure 3.13: Visualization Scenes under Free Traffic Situation

3.5 Conclusions

In this chapter, an intelligent vehicle agent model has been proposed. The car following behavior and the overtaking behavior in the straight lane have been realized in virtual reality traffic simulation system. A decentralized design paradigm has been used for developing the multi-controller based intelligent vehicle, whereby the car following behavior and the overtaking behavior could be realized by the coordination of the multi-controller.

The car following model and the overtaking model have been presented in detail in this chapter. The lane changing behavior model has been analyzed, because it is the base of overtaking behavior. Traffic simulation maneuvers have been shown to verify the correctness and effectiveness of these models in virtual reality traffic simulation system. The car following behavior has been simulated by considering different driver properties. Different traffic situations have been taken into the consideration of modeling overtaking behavior.

Chapter 4

Synthetic Natural Environment

Contents

4.1 Introduction

In the developed countries worldwide, road accidents are causing more injuries and casualties than any other man-made or natural hazard (Snæbjörnsson 2007). In the European Union, more than 40,000 people die and over one million are injured every year because of road accidents (CARE). There has been a great deal of research effort in recent years in developing road safety theory (*i.e.* why an accident has occurred) and the factors affecting road safety (*i.e.* what caused or contributed to an accident). There is a broad range of factors affecting road accidents. These factors are usually related to traffic and road characteristics, drivers and other road users, vehicles, and environment (Wang 2013a). Crashes due to adverse naturel environments usually cause serious traffic congestion and further deteriorate driving conditions on highways (Chen 2010c).

Over the past decade, a number of researchers have been working on traffic safety assessment under the specific driving condition consist of wind, inclement weather, complex terrain, and adverse driving manners (Chen 2011). (Snæbjörnsson 2007) indicated that at windy location, wind may be a causative factors leading to up-to 20% of road accidents. (Chen 2004) improved the accident risk assessment by introducing fully-coupled dynamic interaction models of vehicles, bridge and wind, respectively. (Chen 2009) studied the single-vehicle crash risk assessment under adverse environmental conditions.

Modeling and Simulation (M & S) could be used to in the traffic safety research with the conception of Synthetic Natural Environment (SNE) conception. Environment and vehicle interact with each other in real life, environment could affect the traffic safety and the vehicle could affect the environment protection.

Therefore, to research on the traffic safety, it is necessary to pay attention that how the environment could affect the vehicle. There are some contributions in the related areas of traffic natural environment. (Ghani 2001) described the development of natural climatic conditions in a closed loop full-scale automotive wind tunnel. The tunnel simulated the wind, the different rainfalls, a range of air temperature as well as several road conditions. (Chen 2010d) recently developed an advanced deterministic dynamic simulation model which can consider more realistic driving environments. Single-vehicle accident performance can be simulated under different combinations of crosswind conditions, road surface conditions (*i.e.* wet, icy or snow-covered) and specific topographical conditions (*i.e.* curve, superelevation and grade) by using the advanced transient dynamic equations, improved accident criteria and critical variables. Virtual reality based simulation of intelligent vehicle affected by natural environment could be seen in (Luo 2012b), describing the weather related simulation with different frictions (sunny, rainy, snowy and icy). However, the road geometry and wind effects have been ignored. Thus the studies related to the influences of road geometry and wind on vehicle behaviors for the aim of improving the road security are waiting to be enriched.

Nevertheless, most existed researches on traffic simulation with virtual reality have done little work to profit the Virtual Reality (VR) system to provide realistic environment information for simulation. Combining Geographic Information System (GIS) and VR to realize the terrain visualization could enhance the authenticity. In this study, based on this method, the traffic behavior could be analyzed in the VR simulation system with realistic environment information and the traffic simulation could be much more valid.

Based on the proposed multi-agent based VR-ISSV in Chapter 2, the environment agent in the simulation system is introduced in this chapter. The environment agent is constructed through the SNE conception, the interaction between environment and vehicle behaviors is researched. The dynamic features of the real world are considered in the simulation system in order to improve the microscopic traffic analysis and vehicle control algorithms design (Yu 2013d). This chapter mainly reflects how the road geometry and the wind will affect the vehicle behaviors. Therefore, there are two contributions of this chapter: one is to profit the VR system to provide realistic environment information for simulation; the other is to research on interaction among the vehicles and the environment in virtual reality traffic simulation system.

This chapter is organized as following: Section 4.2 will present the modeling of Synthetic Natural Environment agent. In Section 4.3, the vehicle dynamic models considering the road geometry and the wind will be introduced in detail. Section 4.4 will analyze the effects that the road geometry and the wind affecting on vehicle.

4.2 Modeling synthetic natural environment agent

With the development of modeling and simulation technology, the natural environment simulation is proposed new requirements. Natural environment has an important impact on efficiency of vehicles and microscopic traffic behaviors. The authenticity of natural environment has an important impact on the fidelity and the credibility of the entire simulation system. The concept of SNE, enhancing simulation with the addition of realistic surroundings, is used in many places, such as military manoeuvre, medical training, driving simulator, *et al.* (Swickard 2012).

4.2.1 Synthetic natural environment

A Synthetic Environment has been defined by the Defense Modeling and Simulation Office (DMSO) as an environment within which humans may interact through simulation(s) and /or simulators at multiple networked sites using compliant architecture, modeling, protocols, standards, and databases. SNE is the representation of natural environment in M & S systems (Liu 2004). From the Terrain Modeling Program Office's glossary, a SNE consists of the natural physical environment surrounding the simulation entities including land, oceans, atmosphere, near-space, and cultural information. An instance of a SNE can represent portions of the following environment depending on the needs of the simulation: the terrain, terrain features (both natural and man-made), 3-D models of vehicles and personnel, the ocean (both on and below the surface), the ocean bottom including features on the ocean floor, the atmosphere including environmental phenomena, and near space. In addition to physical objects, the SNE includes the specific attributes of these environmental objects as well as their relationships (Ma 2009).

The complete modeling of entities within a synthetic environment can be divided into the following components, as shown in Fig. 4.1. Static SNE representation is the environmental parameters that represent, for example, the terrain surface, 3-D model structures and states, and other SNE characteristics. SNE effects models simulate the ambient SNE effects (*e.g.* atmospheric and transmission effects) and local SNE effects (*e.g.* smoke and rain). Physical models simulate entity component capabilities (*e.g.* sensors, movement platforms and weapons). Behavior models simulate the entity decision processes which result in observed entity actions, these actions feed back to the synthetic natural environmental ground truth (Proctor 1999).

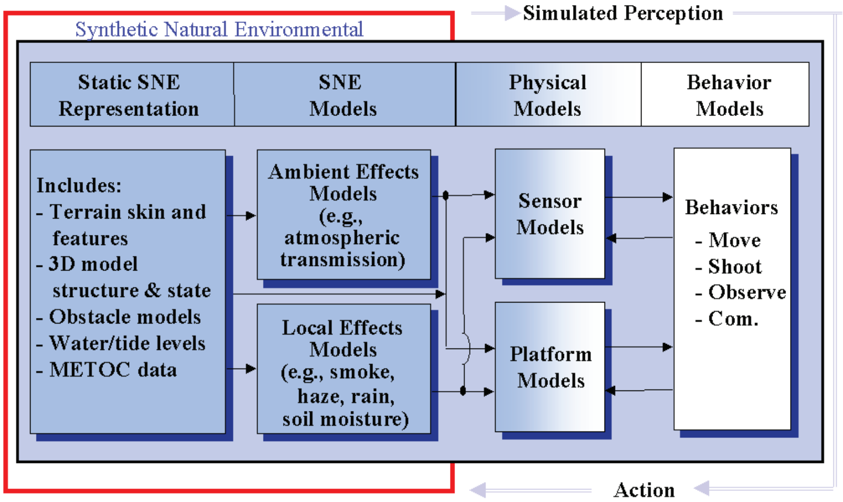


Figure 4.1: Components of the Synthetic Environment

The typical SNE database generation process includes the steps of collecting the desired environment data from a set of data sources and integrating the collected data into a cohesive representation of a specific SNE. Simulation applications must then compile this representation into a run-time effective format that contains only that portion of the SNE relevant to the application. As shown in Fig. 4.2, databases containing SNE data are generated by integration and data fusion from a variety of terrain and environmental data (Proctor 1999).

The research work about SNE has expanded from single environment domain simulation to comprehensive multiple domains simulation, from simple static environment state modeling to complex dynamic modeling. Moreover, with the widely used of Synthetic Environment Data Representation and Interchange Specification (SEDRIS), the environment representation is becoming standard (Wang 2008b).

Therefore, the synthetic natural environment agent is constructed in VR-ISSV to improve simulation fidelity. The research of SNE is not the natural

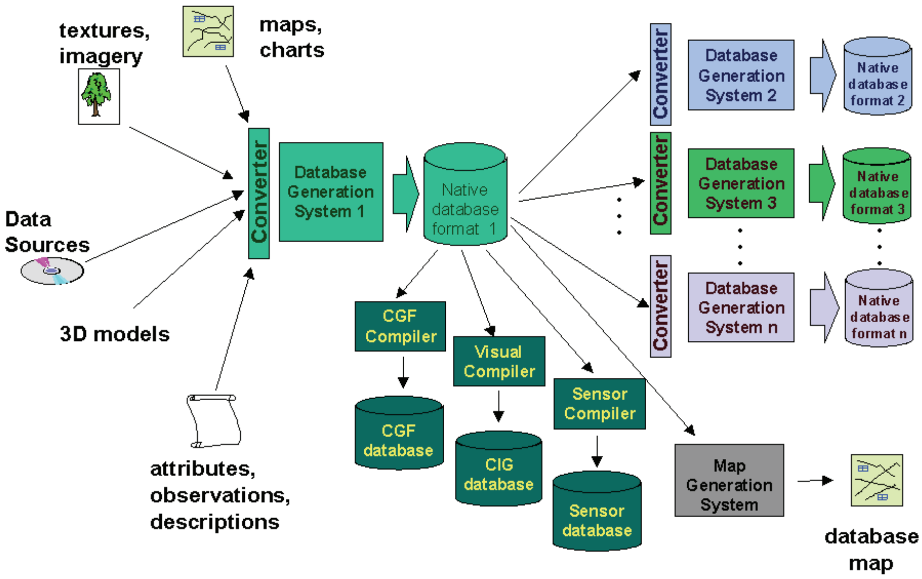


Figure 4.2: Database Generation

environment itself, but the interaction between the environment and the entity model. To establish the SNE agent, not only it is necessary to construct realistic environment model and consider those attributes in the environment which will affect the performance of the vehicle, but also we need to consider the data requirements of other simulation subsystem, such as visualization. SNE agent in this thesis is realized in a virtual world based on VR technology. Not only the virtual world will be used in visualization for the traffic simulation, but also the virtual world will provide realistic environment information to the traffic simulation. Virtual world modeling will be introduced in Section 4.2.2. The 3D terrain model is the most important part in this study, so it will be presented in Section 4.2.3.

4.2.2 Virtual world modeling

A virtual world is constructed in VR-ISSV, which could realize simulation visualization. To build a "reality" and "immersion" virtual reality traffic simulation system, the visualization system uses large scene modeling, distributed virtual scene modeling, visual model of regional segmentation, dynamic control of viewpoint and multi-level details of the model (LOD) technology, *et al.* The rendering models in the visualization system include the terrains, the stable models and the

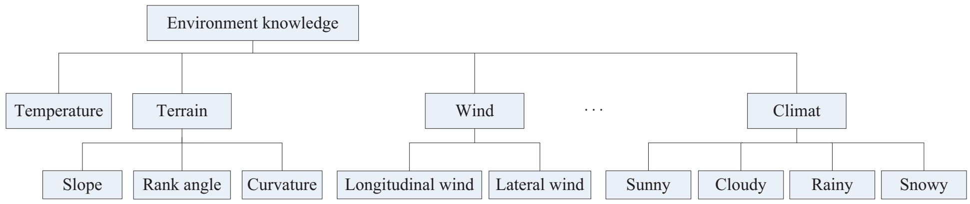


Figure 4.3: Virtual Environment Knowledge Model

moving models. The stable models, such as roads, traffic signs, trees, are modeled by the modeling software and loaded in the scene in real-time. The moving models, such as vehicles, are modeled by modeling software and update the position and orientation in simulation. However, great difference will be resulted in between the virtual world and the real world, if there are only geometric entities in the virtual world without physical model of natural environment or the natural environment is too simple (Yu 2013d).

Therefore, the SNE agent in the simulation system is established in the virtual world. SNE agent model includes environment data model and environment physical model (Liu 2004). Environment data model defines the characteristic of environment objets in the simulation, the attributes and the values, the interaction between the environment objects. Environment physical model mainly includes the environment internal dynamic model, the effect of the environment affecting on the vehicle and the effect of the vehicle affecting on the environment. This study focuses on the effect of the environment affecting on the vehicle.

To develop the valid SNE agent model, virtual environment knowledge model is proposed, namely environment data model, which organizes the environment information in the virtual world. The virtual environment knowledge model represents and organizes the knowledge in virtual world through the object-based method, shown as in Fig. 4.3. The environment value of environment knowledge could be obtained in two ways: one is real time calculating environment math models; the other is querying the environment database. The previous one is used for simple models, such as temperature; the latter one is used for complex models, such as the terrain.

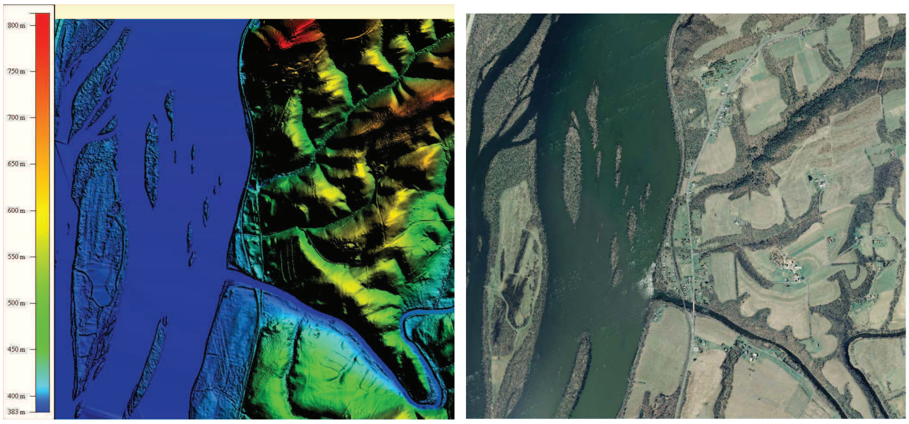
4.2.3 Terrain model

The terrain model plays an important role in the SNE agent model, which could affect the motion of vehicle in the virtual world. To research on the terrain model and its effect on the vehicle, the authenticity of the terrain model need to be guaranteed.

Geographic Information System (GIS) has been used in transportation research and management, and real-world transportation problems tend to involves large amounts of geo-referenced data (Thill 2000b). (Valsecchi 1999) described the prototype development of an inter-operable system for integration of real-time traffic data within GIS. (Brown 2002) presented a GIS-based environmental modeling system, termed TRAEMS, for use by transport planners in assessing the environmental effects of road traffic plans. In this research, GIS combines virtual reality to realize the terrain visualization, which is the main research of terrain model generation in virtual reality system. With this method, the simulation system could have more realistic information.

Digital Elevation Model (DEM) is an important part of GIS, which is the basic data for the GIS application in terrain analysis. DEM is a digital map of elevation data of an area, it is useful in better understanding of terrain characteristics and can lead to the creation of 3D view of the terrain. Such 3D image of earth surface provides significant information for many research activities and many others applications (Srivastava 2012). Thus DEM provides basic information on elevation of Earth's surface and can be used in the research of intelligent vehicle and microscopic traffic behavior.

DEM could be used to develop the real terrain model to supply real road information in the virtual world. The DEM data used for the construction of the 3D terrain model is from PAMAP data that is Light Detection And Ranging (LiDAR) data of Pennsylvania (Program 2008). PAMAP data are organized into blocks, which do not have gaps or overlaps, each block represent 10,000 feet by 10,000 feet on the ground. The 3D terrain model used in this paper is from one block of PAMAP data, shown in Fig. 7. Digital Elevation Model of PAMAP data is a 3.2-foot pixel (1-meter equivalent) raster GeoTIFF Digital Elevation Model (DEM). Each pixel in the DEM has an interpolated elevation value. The 3D terrain model converted from DEM data by the software Terragen and Global Mapper, the sampling spacing is 0.3 feet.



(a) Height Map of Terrain (b) Texture Image of Terrain

Figure 4.4: Terrain Visualization

There are two methods for rendering the terrain models. One is loading the 3D terrain models into the scene; the other one is loading the height maps and the textures. The 3D terrain model constructed through DEM data is realized by the second method.

To construct the 3D terrain model through DEM data and satellite images, the height maps could be converted from DEM data with the software Terragen, and the texture images could be obtained from satellite images with the software Global Mapper. Fig. 5.26(a) shows the height map and Fig. 5.26(b) shows the texture image, which are the 3D terrain model used in the analysis of the road geometry effects affecting on vehicle in this study.

4.3 Vehicle dynamic models considering road geometry and wind

To research on the interaction between the vehicle and the environment, the dynamic models of the vehicle considering road geometry and wind are established. The road geometry parameters affecting on the vehicle include curvature, rank, slope and friction coefficient. This study focuses on the parameters of curvature, rank, and slope. The friction coefficient can be included in our system, to focus on the other parameters, the friction coefficient is assumed to be constant in the simulation results. The effect of different friction coefficient affecting on vehicle is discussed in (Luo 2012b).

Shown as in Fig. 4.5, two coordinate systems are used in this analysis: the global coordinate system is fixed to the ground, denoted by X, Y, Z axes; the body fixed coordinated system is fixed to the vehicle body, denoted by x, y, z axes. α is the angle of inclination of the road on which the vehicle is traveling. β is the road bank angle. To realize following the road, the velocity of the vehicle is V. The longitudinal and lateral movements of the vehicle are decoupled to analyze the different phenomenon in vehicle dynamic models. The wind is defined in the global coordinate system, to analyze the wind affecting on the vehicle, it is necessary to convert the velocity of the wind into body fixed coordinate system of the vehicle.

The vehicle dynamic models could be seen in Fig. 4.6. All the parameters in these figures will be introduced in next subsections.

4.3.1 Lateral vehicle dynamic model

According to the Newton's second law for motion along the y axes:

$$ma_y = F_{sr} + F_{sf}\cos(\delta) - F_{aeroy} + F_{bank}, \tag{4.1}$$

where a_y is the inertial acceleration of vehicle at the C.G. (center of gravity) in the direction of the y axes, F_{sf}, F_{sr} are the lateral tire forces of front vehicle

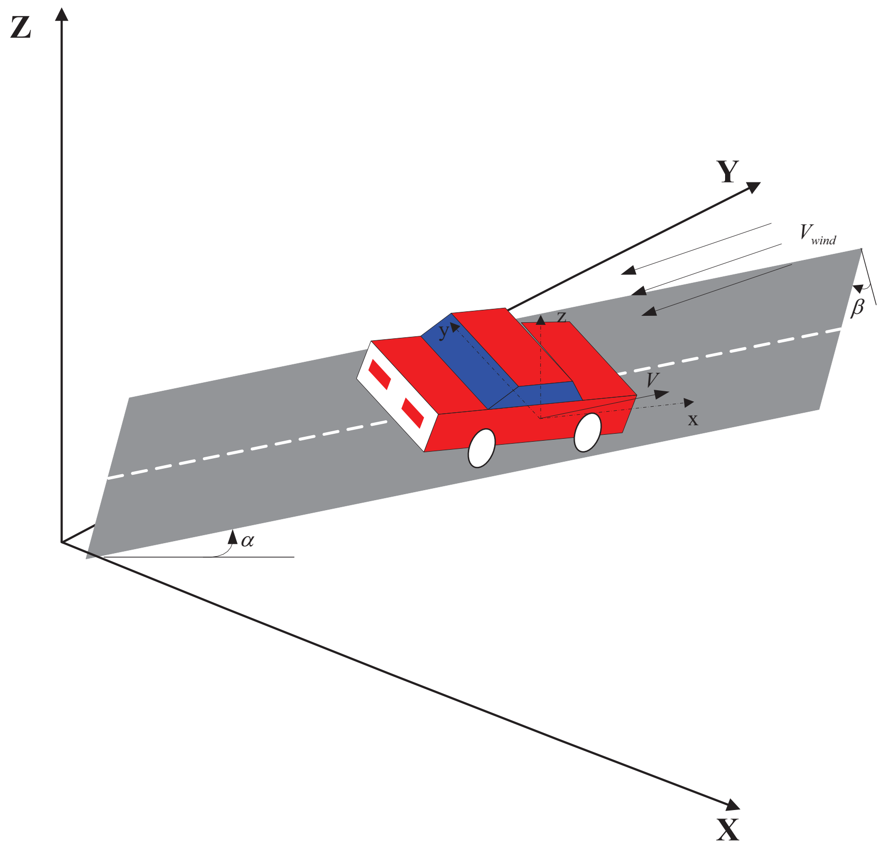


Figure 4.5: Coordinate Systems

and rear wheels respectively, F_{aeroy} is lateral aerodynamic force, m is the mass of the vehicle, δ is steering angle, F_{bank} is the influence of road bank angle, and $F_{bank} = mg\sin(\beta)$.

Two terms contribute to a_y: the acceleration $\ddot{y}$ which is due to motion along the y axes and the centripetal acceleration $V_x\dot{\psi}$. Thus:

$$a_y = \ddot{y} + V_x\dot{\psi}, \tag{4.2}$$

where ψ is the vehicle orientation with respect to X axes, V_x is the vehicle velocity along x axes, namely V_x is the longitudinal vehicle velocity.

Substituting from (4.2) into (4.1), and we assume $\cos(\delta) \approx 1$ (the steering angle is small), the equation for the lateral motion of vehicle is obtained as:

$$m(\ddot{y} + V_x\dot{\psi}) = F_{sr} + F_{sf} - F_{aeroy} + F_{bank}. \tag{4.3}$$

Moment balance about the z axes yields the equation for the yaw dynamics as:

$$I_z\ddot{\psi} = l_f F_{sf} - l_r F_{sr} - l_c F_{aeroy}, \tag{4.4}$$

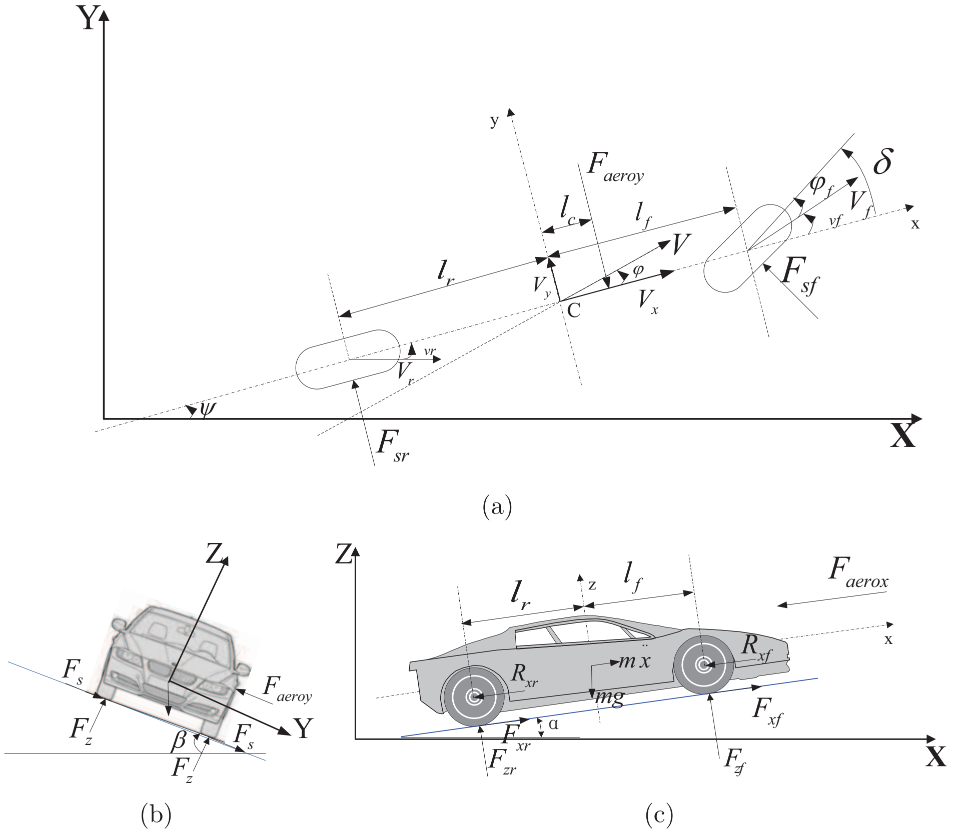


Figure 4.6: Vehicle Dynamic Model

where I_z is the yaw moment of inertia, l_f/l_r is the distance between the C.G. and the front/rear wheels, l_c is the distance between the C.G. and the center of aerodynamic force.

Next is to model lateral tire forces F_{sf}, F_{sr} and lateral aerodynamic force F_{aeroy} that act on the vehicle. Experiments show that the lateral tire force of a tire is proportional to the slip angle for small angles.

The slip angle of the front wheel (α_f) and rear wheel (α_r) are:

$$\alpha_f = \delta - \theta_{vf}, \tag{4.5}$$

and:

$$\alpha_r = -\theta_{vr}, \tag{4.6}$$

where θ_{vf} is the angle between the velocity vector of the front wheel and the x axes of the vehicle, while θ_{vr} is the angle between the velocity vector of the rear wheel and the x axes of the vehicle.

Therefore, the lateral tire forces F_{sf}, F_{sr} are proportional to slip angle, and are represented as:

$$F_{sf} = 2C_{\alpha f}(\delta - \theta_{vf}), \tag{4.7}$$

and:

$$F_{sr} = 2C_{\alpha r}(-\theta_{vr}), \tag{4.8}$$

where the proportionality constant $C_{\alpha f}$, $C_{\alpha r}$ are called the cornering stiffness of the front tire and the rear tire.

The following relations could be used to calculate θ_{vf} and θ_{vr}:

$$\tan(\theta_{vf}) = \frac{V_y + l_f\,\dot{\psi}}{V_x}, \tag{4.9}$$

and:

$$\tan(\theta_{vr}) = \frac{V_y - l_r\,\dot{\psi}}{V_x}. \tag{4.10}$$

Using small angle approximations and using the notation $V_y = \dot{y}$, we get:

$$\theta_{vf} = \frac{\dot{y} + l_f\,\dot{\psi}}{V_x}, \tag{4.11}$$

and:

$$\theta_{vr} = \frac{\dot{y} - l_r\,\dot{\psi}}{V_x}. \tag{4.12}$$

The lateral aerodynamic force could be represented as:

$$F_{aeroy} = \frac{1}{2}\rho C_s A_s (V_y + V_{windy})^2 = \frac{1}{2}\rho C_s A_s (\dot{y} + V_{windy})^2, \tag{4.13}$$

where ρ is the mass density of air, C_s is the aerodynamic side coefficient, A_s is the side area of the vehicle, V_y is the lateral vehicle velocity, V_{windy} is the wind velocity along y axes.

Substituting from equations (4.7), (4.8), (4.11), (4.12), (4.13) into equations (4.3) and (4.4), we can get the lateral vehicle dynamic model considering the road geometry and the wind:

$$\begin{cases} \ddot{y} = \frac{2C_{\alpha f}}{m}\delta - \frac{2C_{\alpha f} + 2C_{\alpha r}}{mV_x}\,\dot{y} + (\frac{-2C_{\alpha f} l_f + 2C_{\alpha r} l_r}{mV_x} - V_x)\,\dot{\psi} - \\ \frac{\rho C_s A_s}{2m}(\dot{y} + V_{windy})^2 + g\sin(\beta), \\ I_z\,\ddot{\psi} = 2C_{\alpha f} l_f \delta + \frac{-2C_{\alpha f} l_f + 2C_{\alpha r} l_r}{V_x}\,\dot{y} + \frac{-2C_{\alpha f} l_f^2 - 2C_{\alpha r} l_r^2}{V_x}\,\dot{\psi} - \\ \frac{\rho C_s A_s l_c}{2}(\dot{y} + V_{windy})^2. \end{cases} \tag{4.14}$$

To developing a steering control system for automatic lane keeping, it is useful to utilize a dynamic model in which the variables are in terms of position and orientation error with respect to the road. Two variables are defined as following (Rajamani 2006):

e_1 : the distance of the C.G. of the vehicle from the center line of the lane.

e_2 : the orientation error of the vehicle with respect to road.

Considering that a vehicle travels with a longitudinal velocity V_x on a road of radius R, the rate of change of the desired orientation of the vehicle is:

$$\dot{\psi}_{des} = \frac{V_x}{R}. \tag{4.15}$$

Defining:

$$\ddot{e}_1 = (\ddot{y} + V_x \ddot{\psi}) - \frac{V_x^2}{R} = \ddot{y} + V_x(\dot{\psi} - \dot{\psi}_{des}), \tag{4.16}$$

and:

$$e_2 = \psi - \psi_{des}. \tag{4.17}$$

Defining:

$$\dot{e}_1 = \dot{y} + V_x(\psi - \psi_{des}) = \dot{y} + V_x e_2. \tag{4.18}$$

Equation (4.18) is consistent with equation (4.16) if the velocity is constant.

Substituting from equation (4.16) and (4.18) into equation (4.14), the lateral dynamic model considering e_1 and e_2 are:

$$\begin{cases} \ddot{e}_1 = \frac{2C_{\alpha f}}{m}\delta - \frac{2C_{\alpha f} + 2C_{\alpha r}}{mV_x}\dot{e}_1 + \frac{2C_{\alpha f} + 2C_{\alpha r}}{m}e_2 + \frac{-2C_{\alpha f}l_f + 2C_{\alpha r}l_r}{mV_x}\dot{e}_2 + \\ (\frac{-2C_{\alpha f}l_f + 2C_{\alpha r}l_r}{mV_x} - V_x)\dot{\psi}_{des} - \frac{\rho C_s A_s}{2m}(\dot{e}_1 - V_x e_2 + V_{windy})^2 + g\sin(\beta), \\ I_z\ddot{e}_2 = 2C_{\alpha f}l_f\delta + \frac{-2C_{\alpha f}l_f + 2C_{\alpha r}l_r}{V_x}\dot{e}_1 + (2C_{\alpha f}l_f - 2C_{\alpha r}l_r)e_2 + \\ \frac{-2C_{\alpha f}l_f^2 - 2C_{\alpha r}l_r^2}{V_x}\dot{e}_2 + \frac{-2C_{\alpha f}l_f^2 - 2C_{\alpha r}l_r^2}{V_x}\dot{\psi}_{des} - \frac{\rho C_s A_s l_c}{2}(\dot{e}_1 - V_x e_2 + V_{windy})^2. \end{cases} \tag{4.19}$$

4.3.2 Longitudinal vehicle dynamic model

A force balance along the vehicle x axes yields:

$$m\ddot{x} = F_{xf} + F_{xr} - F_{aerox} - R_{xf} - R_{xr} - mg\sin(\alpha), \tag{4.20}$$

where F_{xf} is the longitudinal tire force at the front tires, F_{xr} is the longitudinal tire force at the rear tires, F_{areox} is the equivalent longitudinal aerodynamic drag force, R_{xf} is the force due to rolling resistance at the front tires, R_{xr} is the force due to rolling resistance at the rear tires.

The equivalent aerodynamic drag force on a vehicle can be represented as:

$$F_{aerox} = \frac{1}{2}\rho C_d A_F (V_x + V_{windx})^2, \tag{4.21}$$

where ρ is the mass density of air, C_d is the aerodynamic drag coefficient, A_F is the frontal area of the vehicle, V_{windx} is the wind velocity along x axes.

The dynamic models described above are based on body fixed coordinated. To obtain a global picture of the trajectory traversed by the vehicle, however, the time history of the body fixed coordinates must be converted into trajectories in global coordinates (Rajamani 2006).

The position of vehicle in global coordinates is therefore given by:

$$X = X_{des} - e_1 \sin(\psi), \tag{4.22}$$

and:

$$Y = Y_{des} + e_1 \cos(\psi), \tag{4.23}$$

where (X_{des}, Y_{des}) are global coordinates of the point on the road centerline which lies on a line along the x axes of the vehicle.

Using $X_{des} = \int_0^t V \cos(\psi_{des})dt$, $Y_{des} = \int_0^t V \sin(\psi_{des})dt$ and replacing ψ by equation (4.17), the global coordinates of the vehicle are obtained as:

$$X = \int_0^t V \cos(\psi_{des})dt - e_1 \sin(e_2 + \psi_{des}), \tag{4.24}$$

and:

$$Y = \int_0^t V \sin(\psi_{des})dt - e_1 \cos(e_2 + \psi_{des}). \tag{4.25}$$

To research on the interaction between the intelligent vehicle and the environment, the vehicle dynamic models considering environment, especially the road and wind have been established in this section. Thus in next section, the effect of environment (road geometry and wind) affecting on vehicle will be analyzed.

4.4 Effect of environment affecting on vehicle

In SNE agent model, based on the VR-ISSV system and the dynamic models, the road geometry and the wind affecting on the vehicle will be researched in the simulation system, it is useful for designing vehicle control algorithm and analyzing microscopic traffic behavior. The effect of environment affecting on the vehicle will be analyzed in this chapter, the results could be used for designing vehicle controllers involving road geometry and wind in Chapter 5.

In this chapter, to analyze the effect of environment affecting on vehicle, the intelligent vehicle agent mentioned in chapter 3 is used with the motion module constructed by the coordinated throttle and brake fuzzy controller and longitudinal vehicle dynamic model proposed in (Zhao 2010a), and a multi-model

Table 4.1: Vehicle Dynamic Models' Parameters

Parameter	Typical value
Mass of the vehicle m	1250 kg
Aerodynamic drag coefficient C_d	0.5
Aerodynamic side coefficient C_s	0.3
Front area of the vehicle A_F	1.5 m^2
Side area of the vehicle A_s	3.0 m^2
Mass density of air ρ	1.225 kg/m^3
Distance between C.G. and front wheels l_f	1.1 m
Distance between C.G. and rear wheels l_r	1.58 m
Distance between C.G. and center of aerodynamic force l_c	1.0 m
Yaw moment of inertia I_z	2872 $kg * m^3$
Cornering stiffness of front/rear tire $C_{\alpha f}/C_{\alpha r}$	4200 N/rad

fuzzy controller and lateral vehicle dynamic model proposed in (Zhao 2010b). The values of the vehicle dynamic models' parameters used in this analysis are listed in Table 4.1.

4.4.1 Road effect

Road traffic safety has become a serious issue in the modern society. The design of the intelligent vehicle need to consider the effect affected by road geometry. By collision detection between 3D models in virtual world, the road slope and rank angle information could be calculated from DEM data, shown as in Fig. 4.7.

According to the virtual world structure in Fig. 4.8, the road altitude information from the DEM data is used to calculate the slope and the rank angle as follows:

$$\begin{cases} \alpha = \sin^{-1}(\dfrac{(z_{fl} + z_{fr}) - (z_{bl} + z_{br})}{2(x_{fl} - x_{bl})}), \\ \beta = \sin^{-1}(\dfrac{(z_{fl} + z_{bl}) - (z_{fr} + z_{br})}{2(y_{fl} - y_{fr})}), \end{cases} \tag{4.26}$$

where z_{fl}, z_{fr}, z_{bl}, z_{br} are the altitudes of the front-left wheel, the front-right wheel, the back-left wheel, the back-right wheel which are calculated through DEM data by the collision detection between the wheels and the terrain (shown as the red line in Fig. 4.8). x_{fl}, x_{bl} are the position of front-left wheel and the position of back-left wheel along x axes. y_{fl}, y_{fr} are the position of front-left wheel and the position of front-right wheel along y axes. The road curvature is obtained from the predefined map in the virtual world. All these values are calculated in real time.

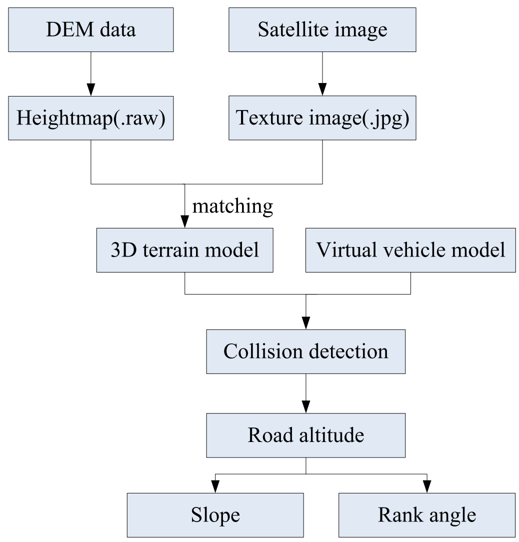


Figure 4.7: Road Geometry Calculating from DEM Data

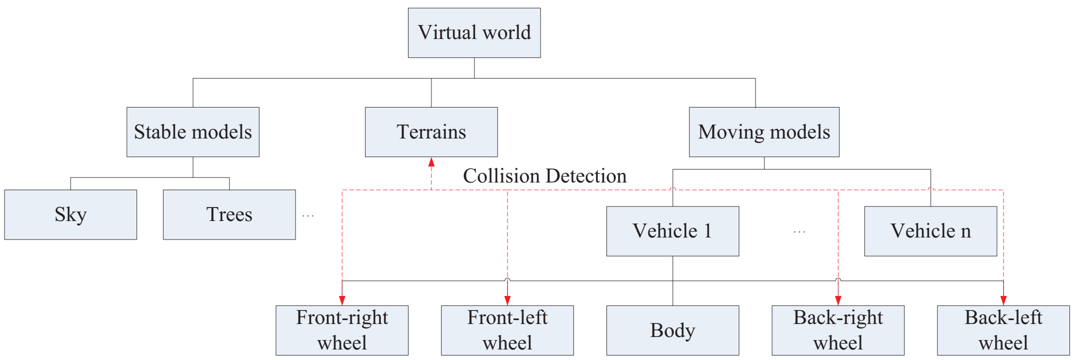
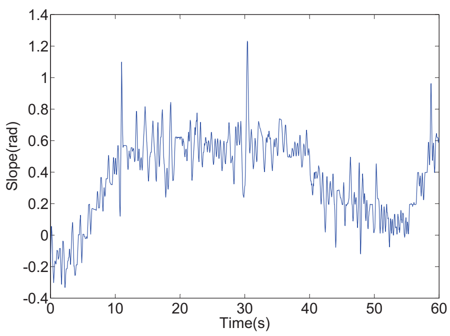


Figure 4.8: Virtual World Structure

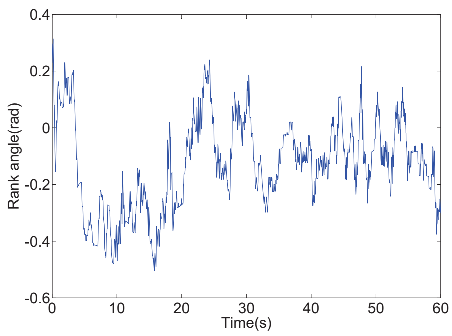
Fig. 4.9 shows the road geometry information getting from the virtual world. The vehicle states (velocity, steering angle, lateral displacement and yaw angle) affected by the road geometry could be seen in Fig. 4.10. The desired velocity of vehicle is 17 m/s.

4.4.2 Wind effect

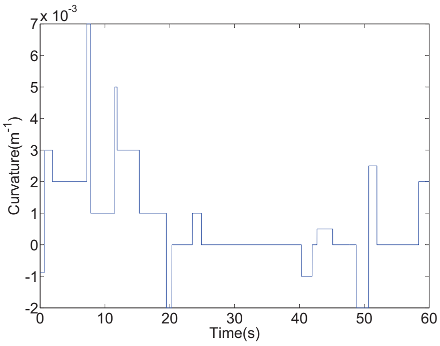
When the vehicle is running in the highway, considering the influence of the wind, there are some situations affecting the vehicle.



(a)



(b)



(c)

Figure 4.9: Road Geometry

(1) If the vehicle travels in the curve road with the influence of the crosswind whose direction is outside of the road, the lateral dynamic force may exceed the maximum lateral adhesion force between the wheel and the ground, leading to big lateral offset and abnormal driving situation.

(2) Besides the force balance, the vehicle needs to consider the moment balance in the lateral motion. Because the lateral dynamic force and the inertial force are not in the same position, if the moment balance is not ensured, the vehicle happens to overturn in the road.

(3) In the longitudinal motion, the vehicle runs in the uphill road, and the wind direction is against the velocity direction, the vehicle is in danger if the wind is strong, because the sum of the aerodynamic drag force and the resistance force is bigger than the tire driving force.

(4) If the vehicle runs in the downhill road and the wind direction is same with the velocity direction, the vehicle is not safe when the maximum braking force is smaller than the sum of the aerodynamic force and the gravity force.

To test the vehicle affected by the different winds, different wind velocities

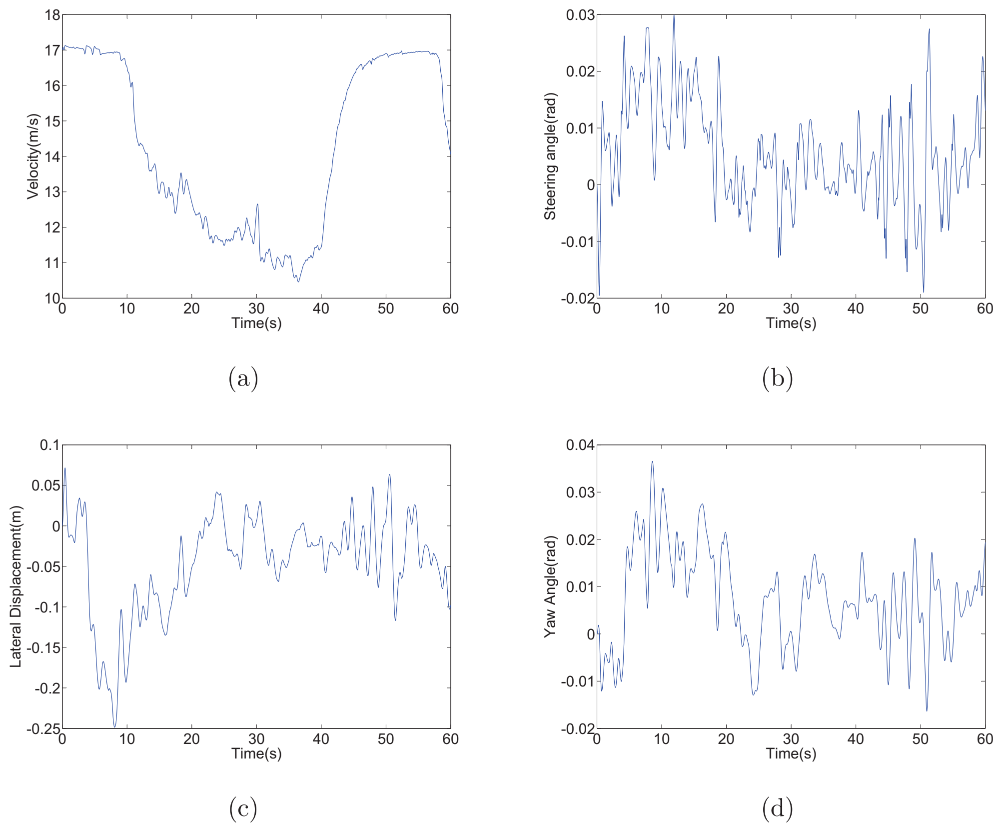


Figure 4.10: Vehicle Affected by Road Geometry

could be set in the simulation system. In the simulation results, the longitudinal wind velocity and the lateral wind velocity are supposed to be same.

Fig. 4.11 shows the vehicle state under different wind speed. We could see that if the wind speed is not very big ($\leq 30m/s$), the vehicle state could be controlled in normal situation.

Fig. 4.12 shows the vehicle is in abnormal situation when the wind speeds are set to $50m/s$ and $-50m/s$. The wind speed is so big that the vehicle could not be controlled in normal situation. The vehicle stops when the wind speed is $50m/s$ and the vehicle runs out of the desired lane when the wind speed is -50 m/s.

The corresponding visualization scene could be seen in Fig. 4.13, the following vehicle is the researched vehicle. The vehicle state in normal situation is shown in Fig. 4.13(a). Fig. 4.13(b) shows the vehicle runs out of the desired lane when the wind speed is $-50m/s$.

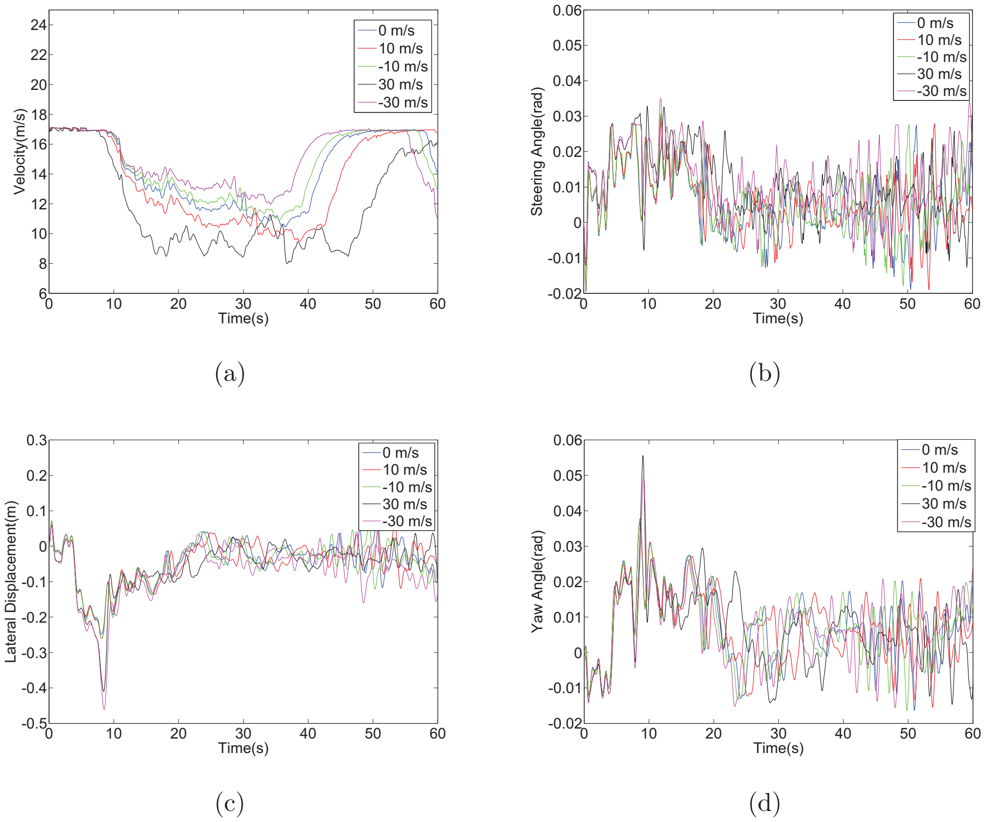
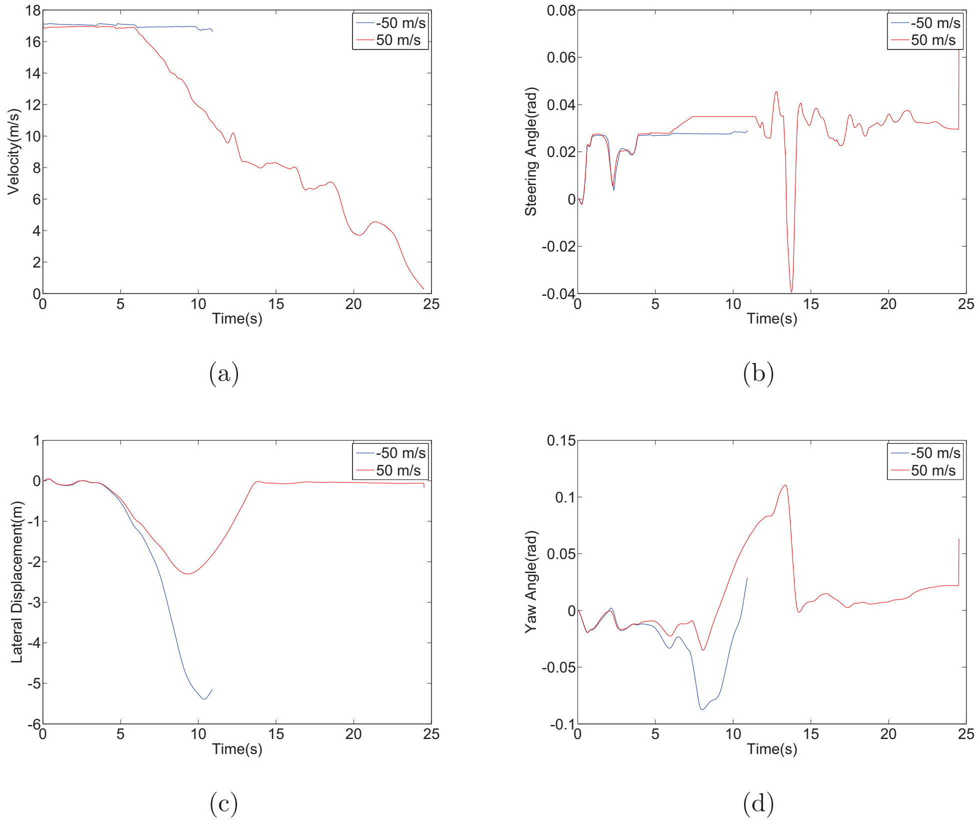
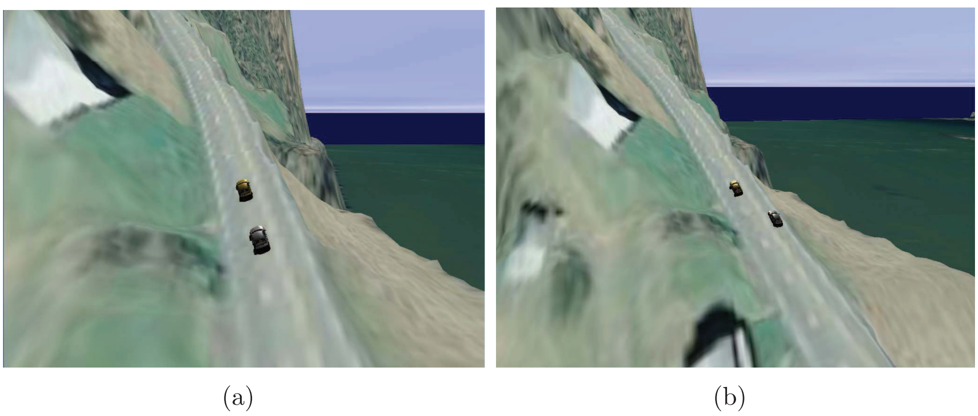


Figure 4.11: Vehicle Affected by Different Wind Speed in normal Situation



(a) (b) (c) (d)

Figure 4.12: Vehicle Affected by Wind in Abnormal Situation



(a) (b)

Figure 4.13: Visualization Scenes under Different Wind

4.5 Conclusions

Researches on the environment model and its impact on vehicle control play an important role in traffic safety. Based on the VR-ISSV, environment agent has been established with the conception of SNE in this chapter, the effects of road geometry and wind affecting on vehicle have been analyzed. GIS has been used in the simulation system to construct SNE agent. With this method, not only the virtual world created in VR-ISSV is used for the visualization, but also it could supply realistic environment information for the microscopic traffic behaviors analysis and vehicle control algorithm design. Moreover, in this way, the simulation fidelity has been enhanced.

To improve the traffic safety, the improvements of intelligent vehicle control including longitudinal and lateral aspects are needed. The vehicle control algorithm should be adaptive to the complex road geometry and the different wind conditions. Thus the intelligent vehicle controllers considering road geometry and wind effect will be researched in Chapter 5.

Chapter 5

Intelligent Vehicle Control

Contents

5.1 Introduction

Research on developing intelligent vehicles to improve highway safety and efficiency is one of the most extensively studied topics in the field of Intelligent Transportation System (ITS) (Milanés 2012). Intelligent vehicle control is the vital part of ITS applications. A variable vehicle control systems are being developed. Studies of the intelligent vehicle control are basically divided into two areas: the study of lateral control and the study of longitudinal control. The vehicle control is the basic part for the traffic behavior.

As introduced in Section 3.1, microscopic traffic behaviors are complex and the traffic information is heterogeneous (Miyajima 2007). Throughout the previous studies concerning microscopic traffic behaviors, the natural environment (such as road, wind, weather, *et al.*) affecting on the vehicle has been ignored in the modeling of traffic behavior. As mentioned in Chapter 4, environment effect plays an important role in traffic safety; the effect of the road geometry and the wind affecting on the vehicle has been analyzed. To improve the traffic safety and to research on the microscopic traffic behavior, the intelligent vehicle control involves the environment information should be considered. Thus it is necessary to research on the intelligent vehicle control affected by the road geometry and wind.

Actually, there are already some contributions in the related areas of the vehicle control with respect to the road geometry and the wind. (Jang 2010) suggested a longitudinal control algorithm for vehicles which drove on the slope road. (Nemeth 2010) focused on the design of a new adaptive cruise control which took into consideration the knowledge of the inclinations of the road along the track of the vehicle. (Reschka 2012) described how the autonomous vehicle was able to adapt its longitudinal control to changing road and weather conditions by calculating a so called Grip Value and gave an outlook how this parameter affected whole vehicle guidance. (Netto 2004) solved the vehicle lateral control problem by the self-tuning regulator with respect to road curvature and lateral wind.

Inspired by the exist researches mentioned above, intelligent vehicle controllers adapting to complex environment are researched. Based on the intelligent vehicle, modeling and simulation of the microscopic behavior involving road and wind effect in virtual reality system is realized in this chapter. With the proposed agent-based multi-controller intelligent vehicle agent model in Chapter 3, the lateral controllers and the longitudinal controllers coordinate to realize microscopic behaviors considering road geometry and wind effect. To realize the motion of the intelligent vehicle, fuzzy logic based controllers are designed for sending the appropriate output to the vehicle's actuators (the steering wheel and the throttle/brake pedals). The fuzzy logic controllers are designed to mimic human behavior in different road and wind environment. With the GIS information in VR-ISSV proposed in Chapter 4, the realistic road geometry could be provided for these microscopic traffic behavior simulations. To improve the traffic safety under different environment conditions, the purpose in this study is to better understand the road geometry and wind effect in traffic and to assist microptic behavior analysis in traffic simulation (Yu 2014). The main contribution of this chapter is the use of fuzzy logic in the design of intelligent vehicle controllers adapting to complex environment, these controllers could be applied in the modeling of microscopic traffic behavior involving the wind and the road geometry.

This chapter is organized as following: Section 5.2 will present the fuzzy logic based steering controllers, throttle/brake controllers with the consideration of road and wind effect, steering fuzzy controller for lane keeping, steering fuzzy controller for lane changing and throttle/brake fuzzy controller will be introduced. In Section 5.3, the autonomous road behavior, the car following behavior and the overtaking behavior with respect to road curvature and wind will be realized in VR-ISSV, and some simulation results will be given to explain the validity of the designed fuzzy controllers .

5.2 Fuzzy controllers considering road and wind effect

Intelligent control systems have emerged as highly efficient techniques over conventional control techniques, including fuzzy logic controller, neural networks, expert systems, neuro-fuzzy controllers, *et al* (Arif 2012). Fuzzy logic controllers are used here because it has two main advantages: (1) it does not require an exact mathematic model of the controlled system. This characteristic is very important when dealing with vehicle control problems, in which it is difficult to get the exact mathematical models; (2) it provides a means of converting a linguistic control strategy based on expert knowledge into automatic control strategy, which is like drivers because human drivers can drive a car smoothly with their driving expertise rather than knowledge on control theory (Fu 2010).

According to the microscopic behaviors (road following, car following and overtaking) mentioned in Chapter 3, two different fuzzy controller subsystems are used for two driving modes: lane keeping and lane changing. Both of the two subsystems include steering fuzzy controllers (lateral controllers) and throttle/brake fuzzy controllers (longitudinal controllers). The throttle/brake fuzzy controllers used in these two subsystems are same, but the steering fuzzy controllers are different.

5.2.1 Steering fuzzy controller for lane keeping

Steering control is an integral part of intelligent vehicle control systems. In recent years, this problem has been investigated worldwide by many research groups, especially in the U.S., Japan, and Europe (Shladover 1995). The control system is usually designed to detect any difference between the host vehicle and the reference line on the road via on-board sensors, which provide the feedback signals (Lin 2007). Steering fuzzy controller has been used widely in the steering control of intelligent vehicle. (Llorca 2011) suggested the using of automatic steering as a promising solution to avoid accidents with fuzzy controllers for the actuators that mimic human behavior and reactions. (Guo 2012) proposed an automatic steering controller that consists of the feedforward part and the feedback part developed based on simulating human "expected handling" and "compensating control" driving behavior. The fuzzy feedback controller was presented as a hierarchical control structure according to driving speed.

In this study, road curvature, rank angle and lateral wind are considered in the design of the three steering fuzzy controllers for lane keeping. Three fuzzy controllers are defined to execute lane keeping according to different road curvature, rank angle and lateral wind, and each fuzzy controller is selected from a high-level tactical layer. The three steering fuzzy controllers include that small steering fuzzy controller for the condition of small wind and small road geometry; big steering fuzzy controller for the condition of big wind and big road geometry; medium steering fuzzy controller for the other conditions. The basic structure of these fuzzy controllers is same. But the values of the membership function of the input and output variables are not always the same and the fuzzy control rules are different, which could reflect that the driver steers the car under different road and wind conditions.

5.2.1.1 Input and output variables

The steering fuzzy controller has two input variables: lateral error (the error between desired lateral displacement and real vehicle lateral displacement) $E1$ and orientation angular error (the error between desired yaw angle and real vehicle yaw angle) $E2$. The output is the steering angle of the front wheel δ. For each variable, there are 7 fuzzy sets, described as following:

$$\{E1, E2, \delta\} = \{L3, L2, L1, Ce, R1, R2, R3\}. \tag{5.1}$$

The meanings of each set are: $L3$: left large; $L2$: left medium; $L1$: left small; Ce : center; $R1$: right small; $R2$: right medium; $R3$: right large. $L3, L2, L1$ stand for steering left with different magnitude, Ce stands that steering magnitude is zero, $R3, R2, R1$ stand for steering right with different magnitude.

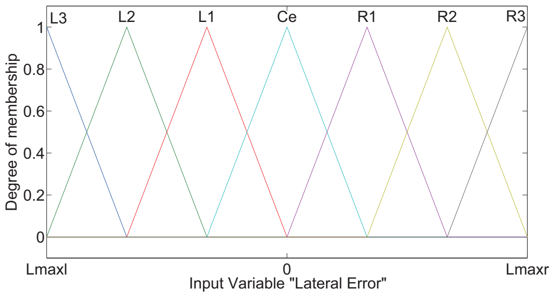
Fig. 5.1(a), Fig. 5.1(b) and Fig. 5.1(c) show the input and output variables' membership functions. The values of the variables presented in the figures are given in Table. 5.1. These values are given on the basis of expert experiences and extensive simulation experiments.

Table 5.1: Membership Function Variables of Steering Fuzzy Controllers

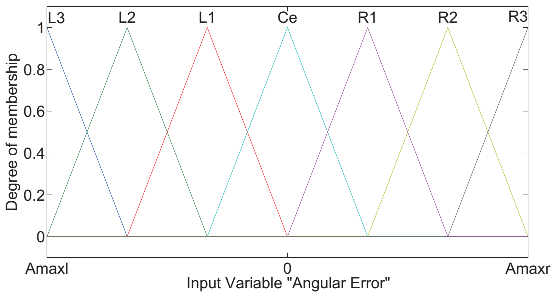
	small controller	medium controller	big controller
$L_{\max l}/L_{\max r}(m)$	-0.3/0.3	-0.4/0.4	-0.5/0.5
$A_{\max l}/A_{\max r}(deg)$	-6/6	-4/4	-3/3
$S_{\max l}/S_{\max r}(deg)$	-12/12	-8/8	-6/6

5.2.1.2 Fuzzy rules

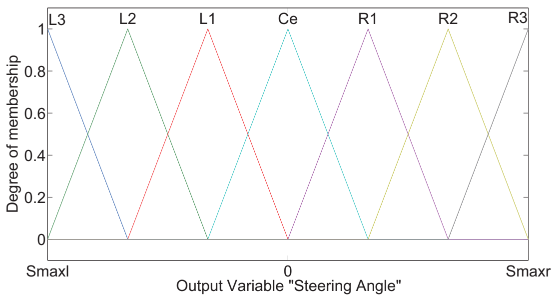
The fuzzy control rules are in the form of "IF(premise)THEN(consequent)". Fuzzy rules are supposed to represent the real human driving experience. These rules contain necessary information on how drivers execute their actions to keep the vehicle to the target road. Table. 5.2, Table. 5.3 and Table. 5.4 show the final fuzzy rules considering different road curvature, rank angle and lateral wind.



(a)



(b)



(c)

Figure 5.1: Membership Function Definition of Steering Fuzzy Controllers

The 3D surface plots associate with the three steering fuzzy controllers are shown in Fig. 5.2. These are representations of the mapping of the inputs and output based on the fuzzy rules. The smoothness of the surface is indicative of the reasonableness of the controller. The big steering control surface is highest adapting to the big road curvature, large rank angle and strong lateral wind. The flowchart of switch logic among the three steering fuzzy controllers in the tactical layer is shown in Fig. 5.3. The thresholds 20, 0.1, 0.003 are defined according to different road geometry and wind conditions for three fuzzy controllers. The bigger value of wind speed has the more influence on the vehicle. The bigger values of rank and curvature have more influence on the lateral vehicle movement.

Table 5.2: Small Steering Fuzzy Rule Base

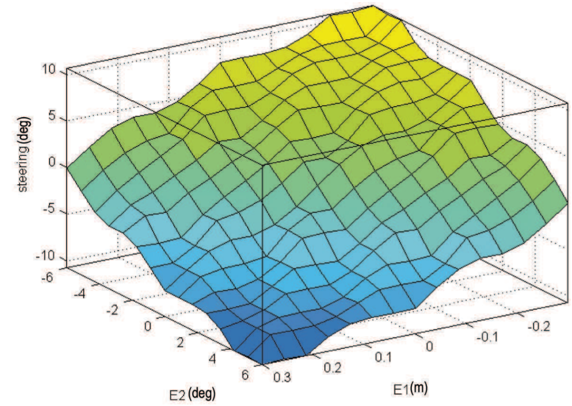
		Input 2: $E2$						
		L3	L2	L1	Ce	R1	R2	R3
Input 1:	L3	R3	R3	R2	R2	R1	R1	Ce
$E1$	L2	R3	R2	R2	R1	R1	Ce	L1
	L1	R2	R2	R1	R1	Ce	L1	L1
	Ce	R2	R1	R1	Ce	L1	L1	L2
	R1	R1	R1	Ce	L1	L1	L2	L2
	R2	R1	Ce	L1	L1	L2	L2	L3
	R3	Ce	L1	L1	L2	L2	L3	L3

Table 5.3: Medium Steering Fuzzy Rule Base

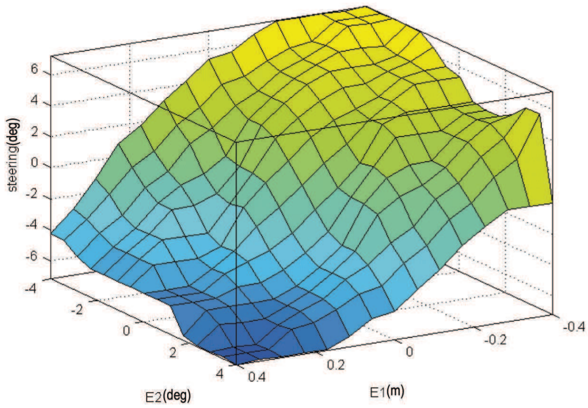
		Input 2: $E2$						
		L3	L2	L1	Ce	R1	R2	R3
Input 1:	L3	R3	R3	R3	R2	R2	R2	R1
$E1$	L2	R3	R3	R2	R2	R1	R1	Ce
	L1	R3	R2	R2	R1	R1	Ce	L1
	Ce	R2	R1	R1	Ce	L1	L1	L2
	R1	R1	Ce	L1	L1	L2	L2	L3
	R2	Ce	L1	L1	L2	L2	L3	L3
	R3	L1	L2	L2	L2	L3	L3	L3

Table 5.4: Big Steering Fuzzy Rule Base

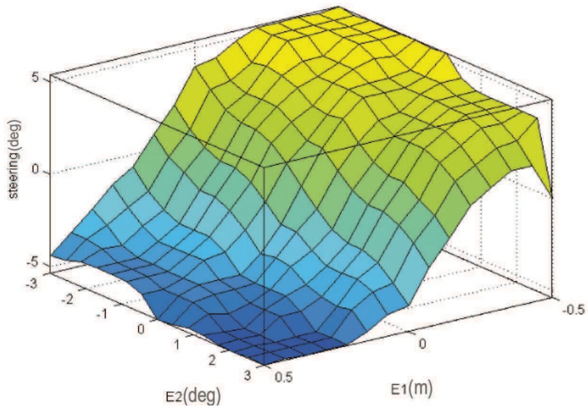
		Input 2: $E2$						
		L3	L2	L1	Ce	R1	R2	R3
Input 1:	L3	R3	R3	R3	R3	R2	R2	R2
$E1$	L2	R3	R3	R3	R2	R2	R2	R1
	L1	R3	R3	R2	R2	R1	R1	Ce
	Ce	R2	R1	R1	Ce	L1	L1	L2
	R1	Ce	L1	L1	L2	L2	L3	L3
	R2	L1	L2	L2	L2	L3	L3	L3
	R3	L2	L2	L2	L3	L3	L3	L3



(a) Small Steering Fuzzy Control Surface



(b) Medium Steering Fuzzy Control Surface



(c) Big Steering Fuzzy Control Surface

Figure 5.2: 3D Steering Fuzzy Control Surfaces for Lane Keeping

Therefore, the intelligent vehicle needs to steer proper magnitude to control the vehicle. With some experiments in the virtual reality system to research the influence, 20 is chosen to differ the big wind speed and the small wind speed; 0.1 and 0.003 are chosen to stand different road geometry for lateral vehicle movement.

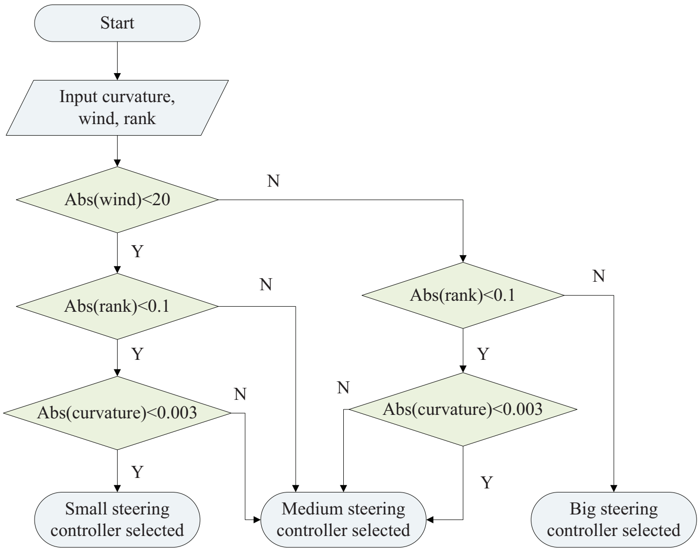


Figure 5.3: Flowchart of Switch Logic in Steering Controllers

5.2.1.3 Fuzzy reasoning process

The fuzzy reasoning process can be divided into three steps: fuzzification, inference engine and defuzzification. The triangle shaped membership function for fuzzification process as shown in Fig. 5.1. The Mamdani's inference method is employed to solve the fuzzy implication. The centroid method is used in defuzzication process.

5.2.2 Steering fuzzy controller for lane changing

The steering fuzzy controller used in lane changing is a multi-model fuzzy controller, which adapts to different longitudinal velocity of vehicle. The multi-model fuzzy controller includes four local controllers and a fusion block. The input variables and the output variable are the same with the steering fuzzy controller for lane keeping. Three fuzzy sets are defined for the input, five fuzzy sets are defined for the output, which could be seen in (Zhao 2010b) in detail.

5.2.3 Throttle/Brake fuzzy controller

In driving experience, on uphill road, the accelerator of a vehicle should be operated more largely compared with on flat road, in order to catch up the desired velocity. On downhill road, when the driver brakes a vehicle, it involves dangerousness making the braking distance multiplied. For example, if the distance between the vehicle and an obstacle (stable or mobile) is not big enough, or if the braking magnitude is not big enough, the collision will happen. The longitudinal wind has the same effect. A relationship between environment (slope of terrain, longitudinal wind speed) and vehicle velocity is constructed by fuzzy rules. Like the steering fuzzy controllers for lane keeping, for different longitudinal wind speed and slope range, three different throttle/brake fuzzy controllers have been defined to describe the behavior of drivers. For the three fuzzy logic controllers of throttle/brake, the basic structure of fuzzy controller and denazification method are same. However, the values of membership function of input and output variables, and the fuzzy rules are altered.

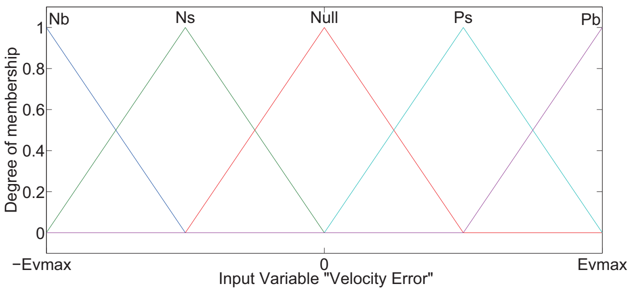
The input and output variables are the same with the coordinated throttle and brake fuzzy controller proposed in (Zhao 2010a). The input variable are the acceleration error E_a and the speed error E_v. The output is the *throttle/brake change* (%). Five fuzzy sets are designed for both the two inputs, as Nb, Ns, $Null$, Ps, Pb. Five fuzzy sets are designed for the output, as $Dinten$, $Dsof$, $Null$, $Asof$, $Ainten$.

Fig. 5.4 shows the input and output variables' membership functions. The values of the variables presented in the figures are given in Table. 5.5. These values are given on the basis of expert experiences and extensive simulation experiments.

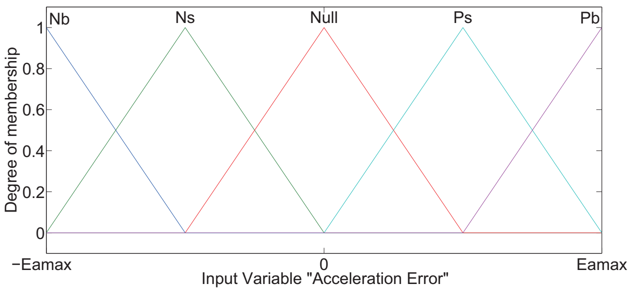
Table 5.5: Membership Function Variables of Throttle/Brake Fuzzy Controllers

	small controller	medium controller	big controller
$-E_{vmax}/E_{vmax}(m/s)$	-10/10	-5/5	-1.5/1.5
$-E_{amax}/E_{amax}(m/s^2)$	-5/5	-5/5	-3/3
$-Th/Th$	-0.6/0.6	-0.4/0.4	-0.4/0.4

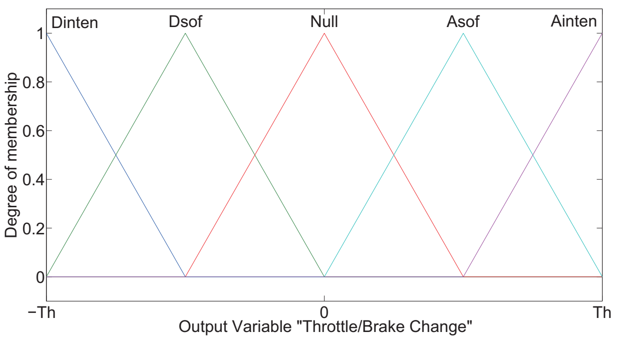
Fuzzy rules are supposed to represent the real human driving experience. The fuzzy control rules are in the form of "IF(premise)THEN(consequent)". Table. 5.6, Table. 5.7 and Table. 5.8 show the final fuzzy rules considering different road slope and longitudinal wind speed. The 3D surface plots associate with the three throttle/brake fuzzy controllers are shown in Fig. 5.5. The flowchart of switch logic among three throttle/brake fuzzy controllers in the tactical layer is shown in Fig. 5.6. The thresholds 20, 0.4 are defined according to different road geometry and wind conditions for three fuzzy controllers. The choice of 20 is the same with the steering fuzzy controller. The bigger value of slope has more influence on the longitudinal vehicle movement. Therefore, the intelligent vehicle needs to throttle/brake proper magnitude to control the vehicle; 0.4 is chosen to stand different road geometry for longitudinal vehicle movement.



(a)



(b)



(c)

Figure 5.4: Membership Function Definition of Throttle/Brake Fuzzy Controllers

Table 5.6: Small Throttle/Brake Fuzzy Rule Base

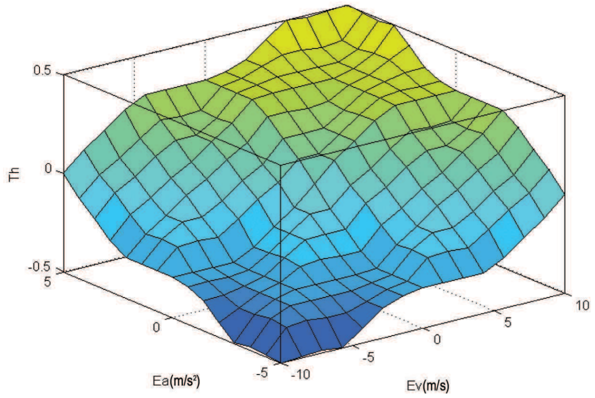
		Input 2: E_a				
		Nb	Ns	Null	Ps	Pb
Input 1:	Nb	Dinten	Dinten	Dsof	Dsof	Null
E_v	Ns	Dinten	Dsof	Dsof	Null	Asof
	Null	Dsof	Dsof	Null	Asof	Asof
	Ps	Dsof	Null	Asof	Asof	Ainten
	Pb	Null	Asof	Asof	Ainten	Ainten

Table 5.7: Medium Throttle/Brake Fuzzy Rule Base

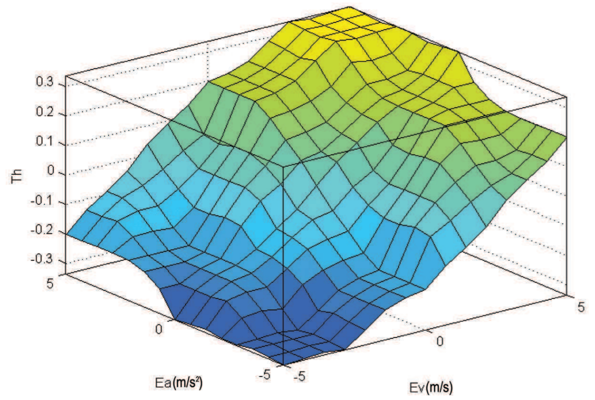
		Input 2: E_a				
		Nb	Ns	Null	Ps	Pb
Input 1:	Nb	Dinten	Dinten	Dinten	Dsof	Dsof
E_v	Ns	Dinten	Dinten	Dsof	Dsof	Null
	Null	Dsof	Dsof	Null	Asof	Asof
	Ps	Null	Asof	Asof	Ainten	Ainten
	Pb	Asof	Asof	Ainten	Ainten	Ainten

Table 5.8: Big Throttle/Brake Fuzzy Rule Base

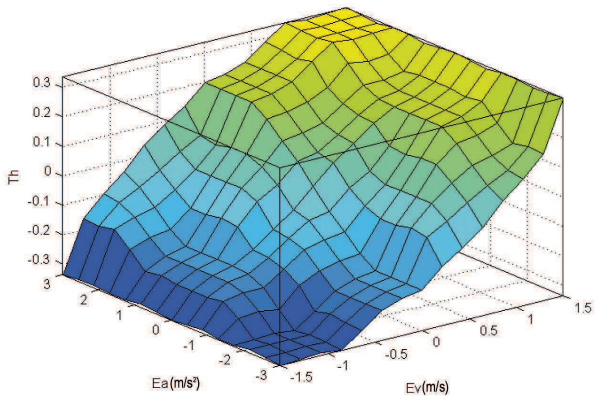
		Input 2: E_a				
		Nb	Ns	Null	Ps	Pb
Input 1:	Nb	Dinten	Dinten	Dinten	Dinten	Dinten
E_v	Ns	Dinten	Dinten	Dsof	Dsof	Null
	Null	Dsof	Dsof	Null	Asof	Asof
	Ps	Null	Asof	Asof	Ainten	Ainten
	Pb	Ainten	Ainten	Ainten	Ainten	Ainten



(a) Small Throttle/Brake Fuzzy Control Surface



(b) Medium Throttle/Brake Fuzzy Control Surface



(c) Big Throttle/Brake Fuzzy Control Surface

Figure 5.5: 3D Throttle/Brake Fuzzy Control Surfaces

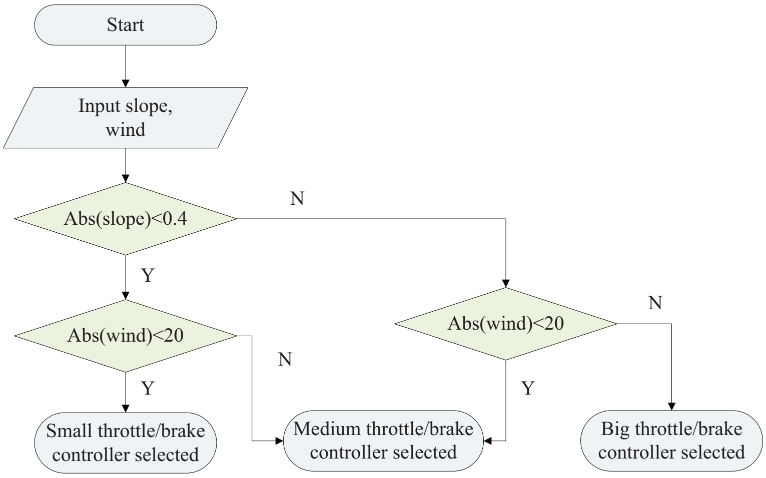


Figure 5.6: Flowchart of Switch Logic in Throttle/Brake Controllers

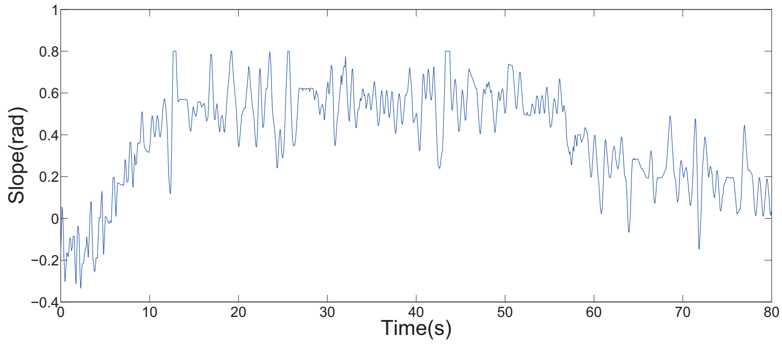
5.3 Simulation results

Simulations of autonomous road following, car following and overtaking behavior under different road geometry and wind speed are realized in VR-ISSV. As the same with Chapter 4, in the simulation results, the longitudinal wind velocity and the lateral wind velocity are supposed to be same. The vehicle dynamic models are also same with the models in Chapter 4.

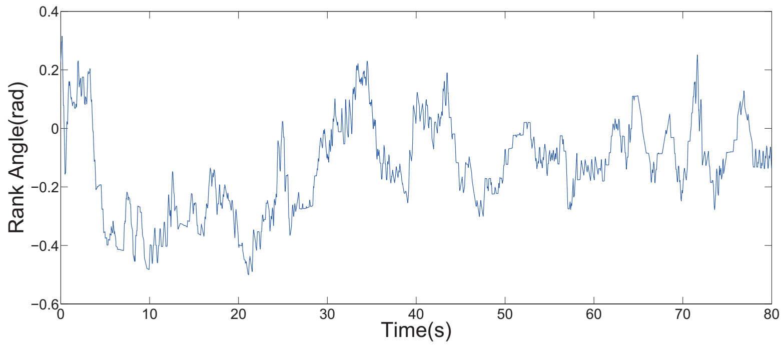
5.3.1 Autonomous road following

The autonomous road following is realized based on the fuzzy controllers designed in this chapter. The slope, rank and curvature are obtained based on the method in chapter 4 in real time from virtual world, shown in Fig. 5.7. The desired velocity of the vehicle is $17m/s$ at beginning, decelerates to $8m/s$ from $t = 7s$ to $t = 11.5s$, the velocity of the intelligent vehicle considering the road geometry and the wind effect are shown in Fig. 5.8(a), in which the wind speed is set $0m/s$, $10m/s$, $30m/s$, $-30m/s$ and $-50m/s$. The steering angle and the lateral movement of the intelligent affected by road geometry are shown in Fig. 5.8(b), Fig. 5.8(c) and Fig. 5.8(d). In Chapter 4, the vehicle runs out of the desired lane when the wind speed is -50 m/s. However, with the intelligent controllers designed in this chapter, from these results, we could find that even the wind speed is big ($-50m/s$), the intelligent vehicle is controlled well, which illustrates that the designed fuzzy vehicle controllers are valid to improve the traffic safety.

Fig. 5.9 shows the autonomous road following behavior visualization scenes when the wind speed is $-50m/s$.



(a)



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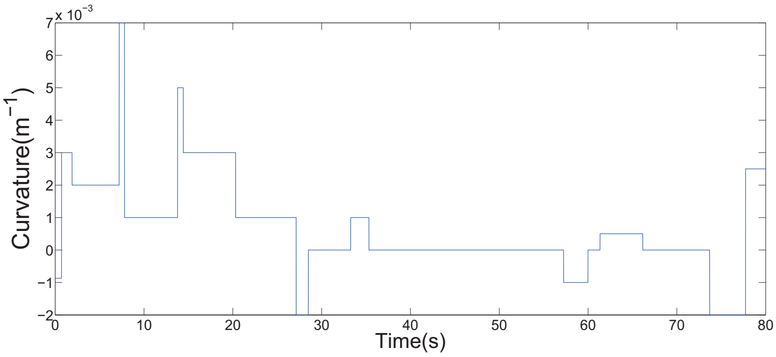
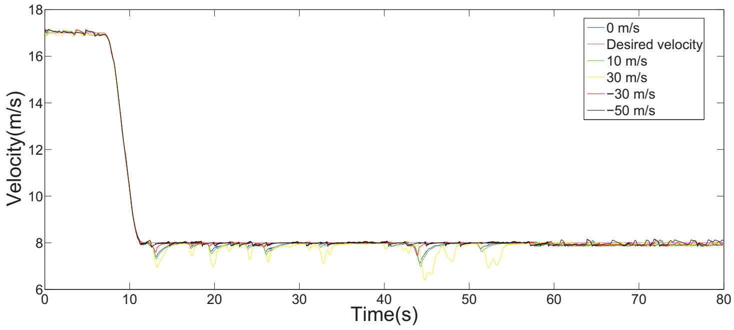
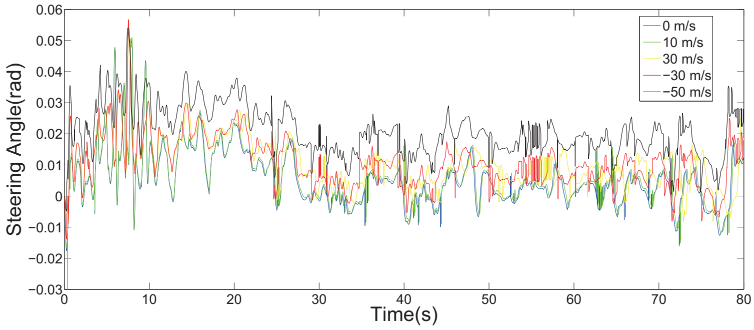


(c)

Figure 5.7: Road Geometry (Autonomous Road Following)



(a)



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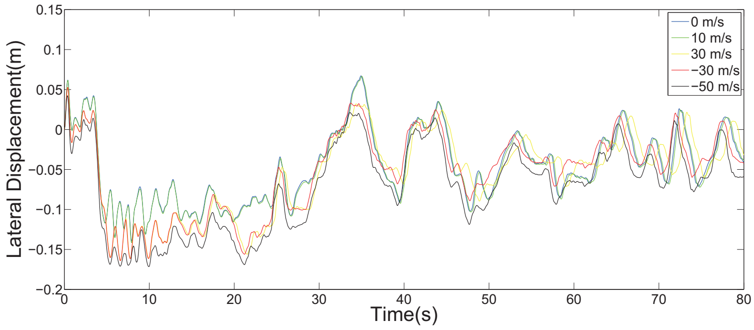

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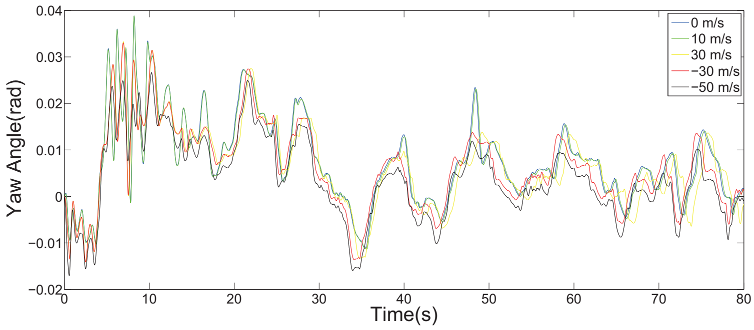
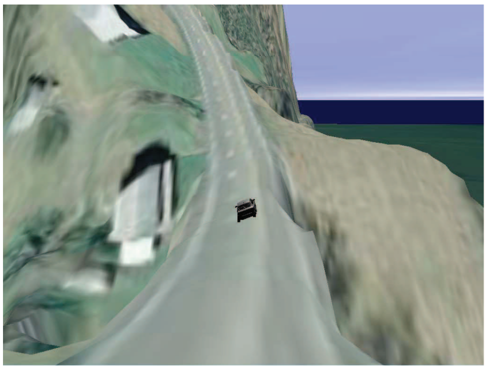


(d)

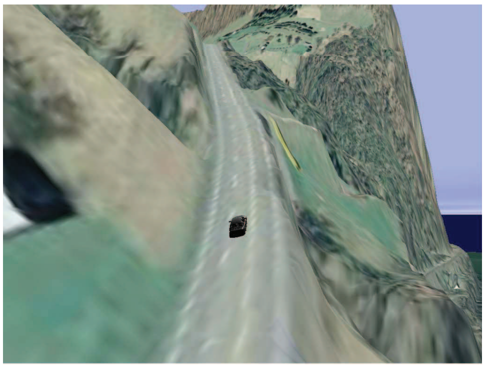
Figure 5.8: Autonomous Road Following

(a) Whole View



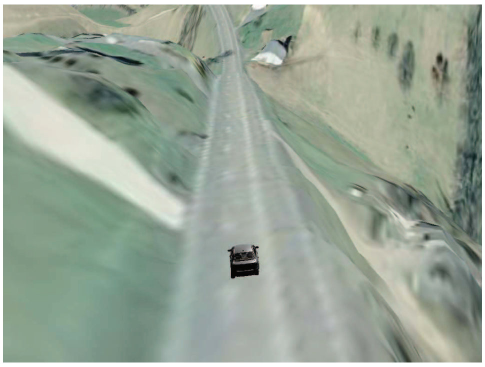
(b) t=5s

(c) t=8s



(d) t=15s

(e) t=30s



(f) t=60s

Figure 5.9: Visualization Scenes (Autonomous Road Following)

5.3.2 Car following

The car following behavior is realized through the two-vehicle platoon as in Chapter 3, which is established based on a desired spacing criterion. In the car following behavior, the following vehicle is the intelligent vehicle with the designed fuzzy controllers, the velocity of the following vehicle and the inter-space between two vehicles are affected by the previous vehicle, the road geometry and the wind. According to the following distance in Chapter 3, the desired spacing between two vehicles is:

$$D_{des} = L + \tau v_i + \kappa\gamma \frac{v_i^2}{2a_{imax}},$$

where L is the minimum range when two vehicles stop; τ is driver's reaction time; a_{imax} is the maximum deceleration of the following vehicle; v_i is the speed of the following vehicle; γ is the safe coefficient; κ is adjustment parameters for different wind speed and road slope.

According to the desired spacing (D_{des}), the desired acceleration is:

$$a_i = -(\lambda\delta_i + v_i - v_{i-1})/(\tau + \frac{\kappa\gamma}{a_{imax}} v_i),$$

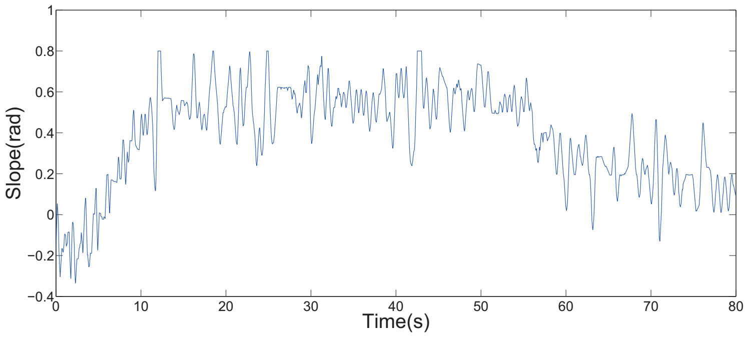
where $\delta_i = x_i - x_{i-1} + D_{des}$, x_i and x_{i-1} the position of the subject vehicle and the preceding vehicle, v_{i-1} is velocity of the preceding vehicle, λ is a positive control gain.

To research the car following behavior affected by road geometry and wind, the designed simulation time is $80s$, and the simulation will stop when collision happens between two vehicles. The following vehicle is established with the fuzzy controllers designed in this chapter.

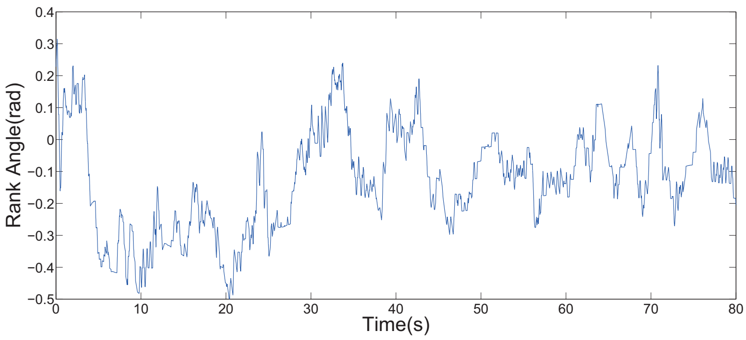
Two car following maneuvers are researched in this study. The first maneuver is that the desired velocity of the leading vehicle is the same with the desired velocity of the vehicle in autonomous road behavior, which is $17m/s$ at beginning, decelerates to $8m/s$ from $t = 7s$ to $t = 11.5s$, see Fig. 5.11(a). Because the desired velocity is in constant from $t = 8s$, this maneuver is named with car following in constant velocity. During this process, the road geometry features from virtual world are shown in Fig. 5.10.

The velocity of the intelligent vehicle in car following is not the same with the velocity in the autonomous road following behavior, because its velocity is affected by the leading vehicle, except the road geometry and wind, see Fig. 5.11(a). The inter-vehicle space could be seen in Fig. 5.11(b). The desired velocity and the desired acceleration according to the desired spacing criterion could be seen in Fig. 5.11(c), Fig. 5.11(d). The simulation results show that no collisions happen and the controllers are proper.

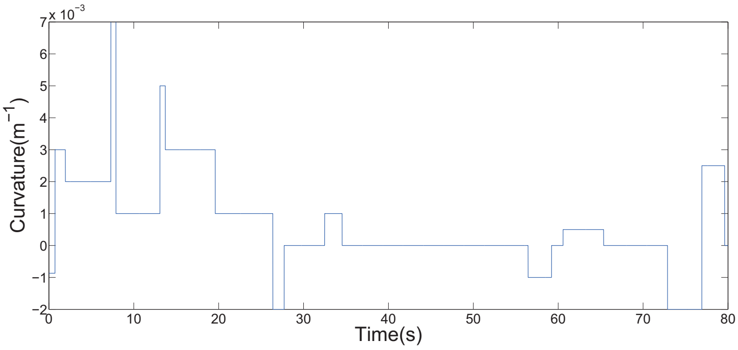
The second maneuver is that the leading vehicle runs with $17m/s$ at beginning, decelerates to $8m/s$ from $t = 7s$ to $t = 11.5s$. From $t = 20.5s$ to $t = 25s$, it decelerates to $5.75m/s$, and from $t = 27s$ to $t = 31.5s$, it accelerates to $8m/s$. From $t = 65s$ to $t = 69.5s$, it decelerates to $5.75m/s$, and from $t = 72s$ to $t = 76.5s$, it accelerates to $8m/s$. Because the desired velocity is not constant from $t = 8s$, this maneuver is named with car following in inconstant velocity. During this process, the road geometry features from virtual world are shown in Fig. 5.12.



(a)

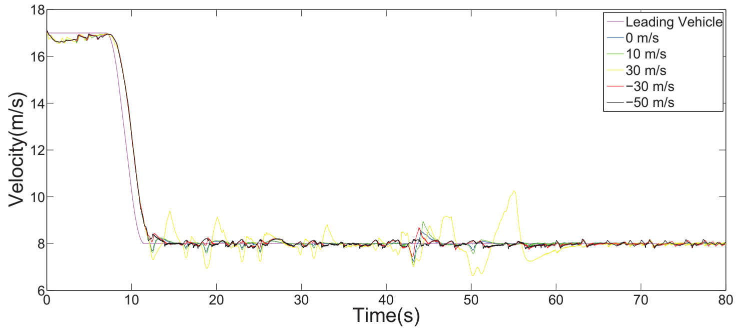


(b)

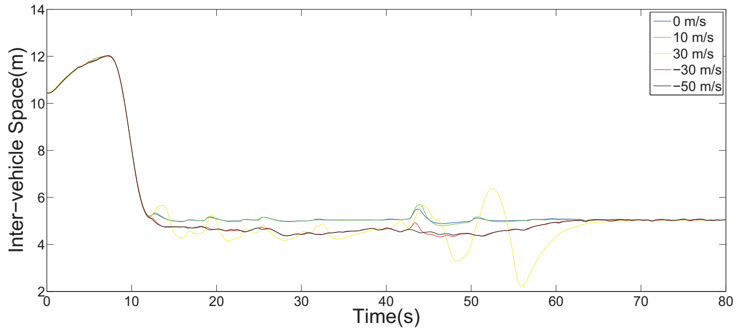


(c)

Figure 5.10: Road Geometry (Car Following in Constant Velocity)



(a)



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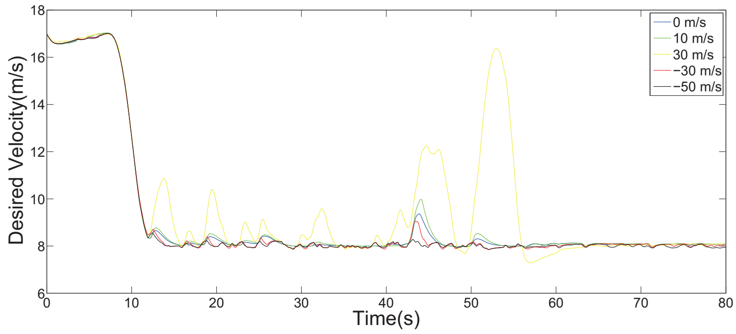
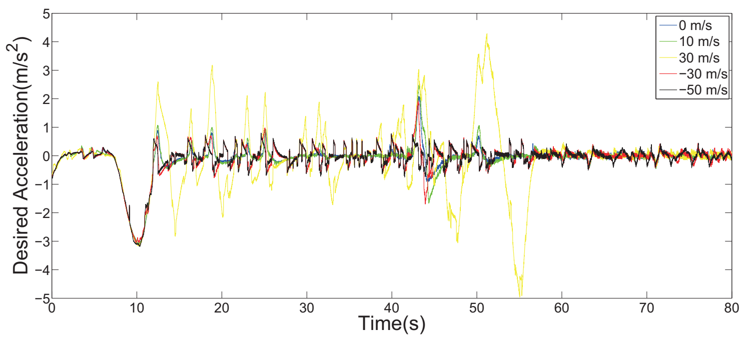


(c)



(d)

Figure 5.11: Car Following in Constant Velocity

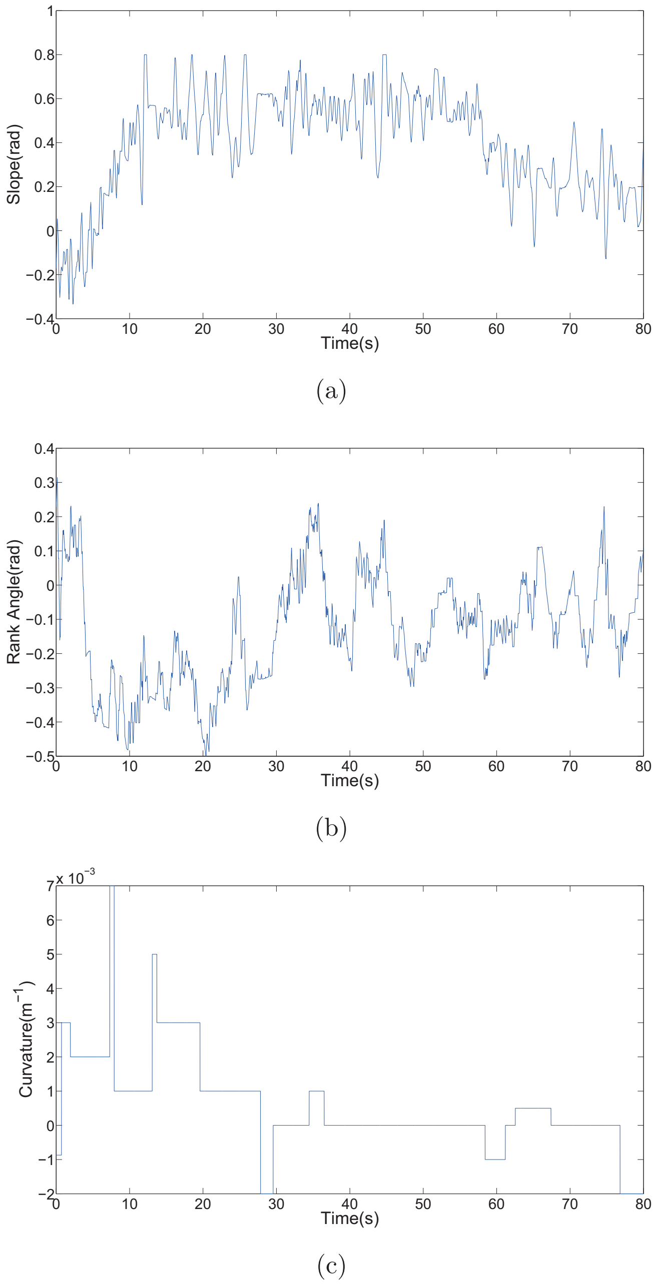
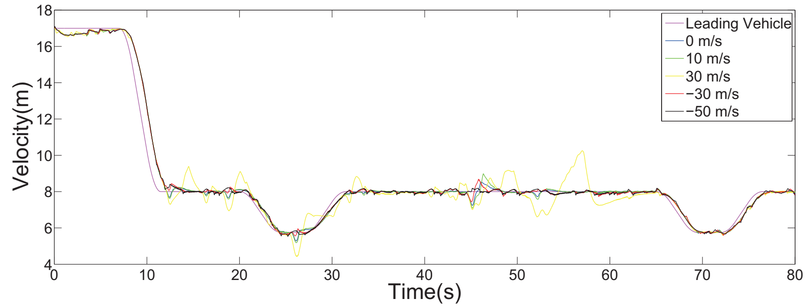
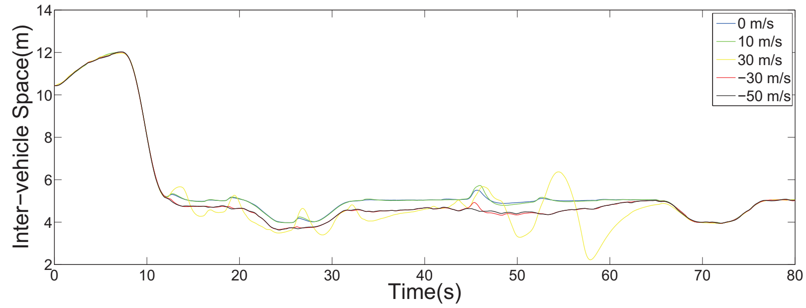


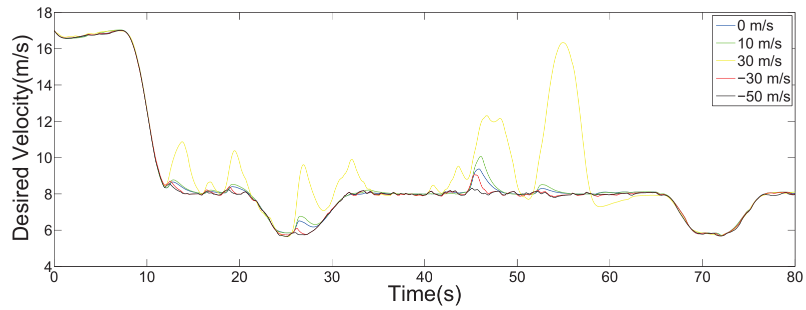
Figure 5.12: Road Geometry (Car Following in Inconstant Velocity)



(a)



(b)



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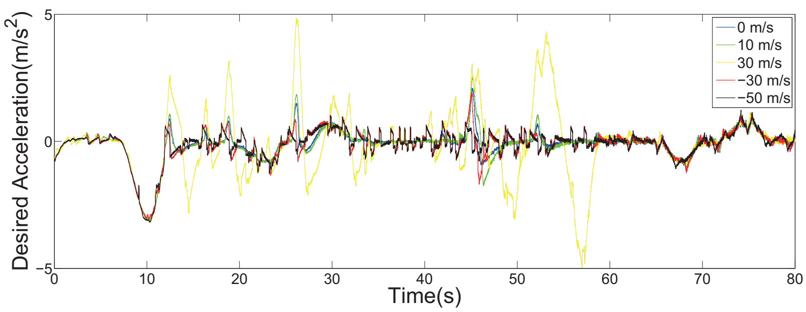


(d)

Figure 5.13: Car Following in Inconstant Velocity

With our fuzzy controllers and desired spacing, the following car performs well with the leading car under varied velocity. The velocities of following vehicle in different wind speeds are shown in Fig. 5.13(a). The inter-vehicle space could be seen in Fig. 5.13(b). The desired velocity and the desired acceleration could be seen in Fig. 5.13(c), Fig. 5.13(d). Fig. 5.14 shows the car following behavior visualization scenes when the wind speed is $30m/s$.

(a) t=2s

(b) t=7s

(c) t=13s

(d) t=29s

(e) t=52s

(f) t=59s

Figure 5.14: Visualization Scenes (Car Following)

5.3.3 Overtaking

Five vehicles have been simulated in the overtaking maneuver as in Chapter 3. Two vehicles run in the original lane and three vehicles run in the adjacent lane. The subject vehicle in the original lane is the intelligent vehicle. The initial speed of the intelligent vehicle is set to $17m/s$. The velocity profiles of adjacent vehicles and leading vehicle could be seen in Fig. 5.15. The desired velocity of the vehicles in adjacent lane are $17m/s$ at beginning, decelerates to $8m/s$ from $t = 4s$ to $t = 8.5m/s$, and then keeps $8m/s$. The leading vehicle runs with $17m/s$ a few seconds, decelerates to $8m/s$ from $t = 2s$ to $t = 6.5m/s$. After keeping the new velocity a few seconds, it starts to decelerate to $5.75m/s$ from $t = 11s$ to $t = 15.5m/s$, then keeps this speed.

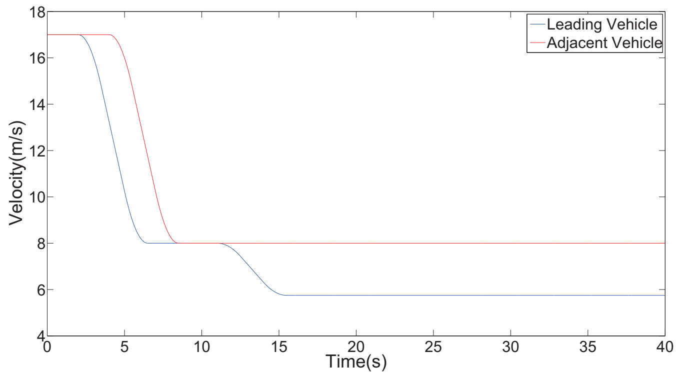
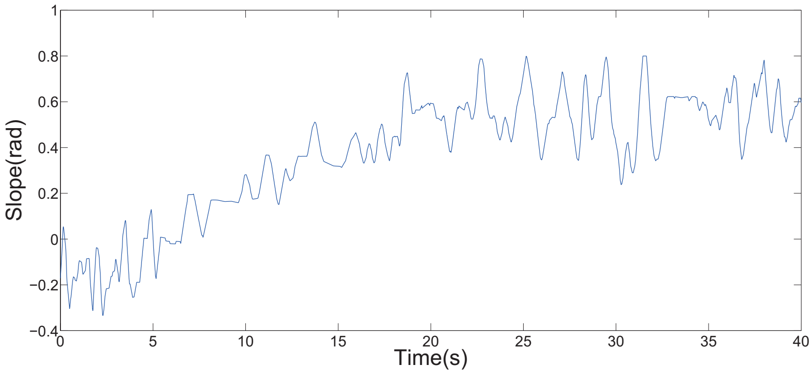
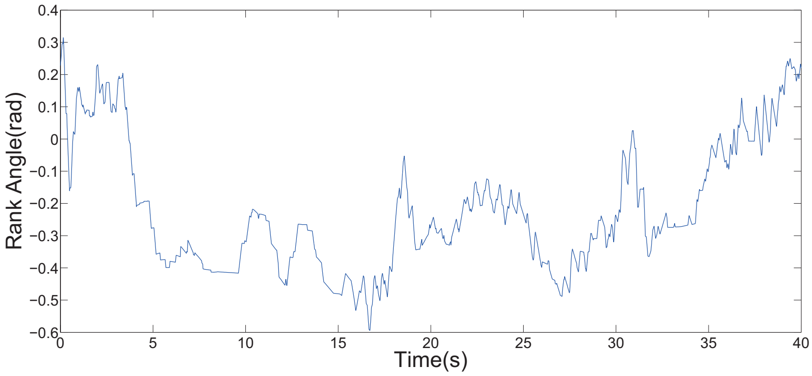


Figure 5.15: Velocity Profiles of Leading Vehicle and Adjacent Vehicle

The road geometry features are shown in Fig. 5.16. Fig. 5.17(a) shows the velocity of intelligent vehicle during overtaking process, considering the effect of the immediate vehicle, the road geometry and the wind. The steering angle, the lateral displacement and the yaw angle of the subject vehicle could be seen in Fig. 5.17(b), Fig. 5.17(c) and Fig. 5.17(d). The overtaking maneuver according with the wind speed of $10m/s$ is as following. From $t = 0s$ to $t = 11s$, the subject vehicle follows the leading vehicle. When the leading vehicle starts to decelerate at $t = 11s$, the subject vehicle desires to change lane. The lane changing controller waits to get active until the feasibility of lane change meets. When $t = 15s$, the subject vehicle begins to change lane. After lane change finishes, $t = 22.5s$, the subject vehicle finds it has overtaken the leading vehicle and the feasibility of lane change meets. It changes to the original lane and the overtaking behavior finishes at $t = 31.5$. From these results, we could find that with the fuzzy controllers, the lane following and the lane changing are realized and coordinated well, the overtaking behavior could perform well involving the road geometry and wind, even the wind speed is big, which illustrates that the fuzzy controllers designed in this chapter are valid.



(a)



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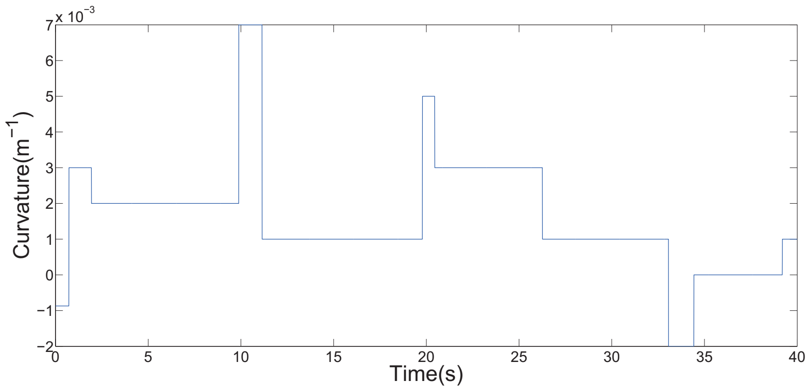
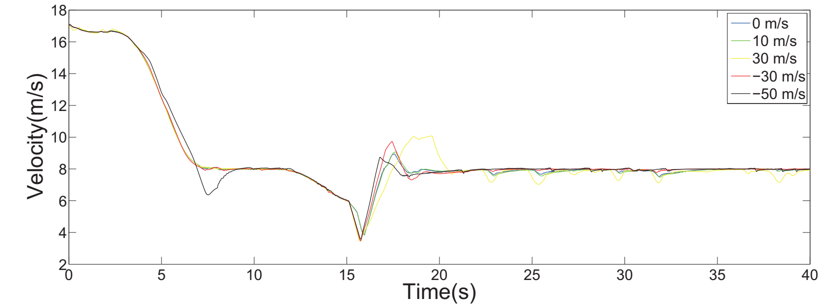
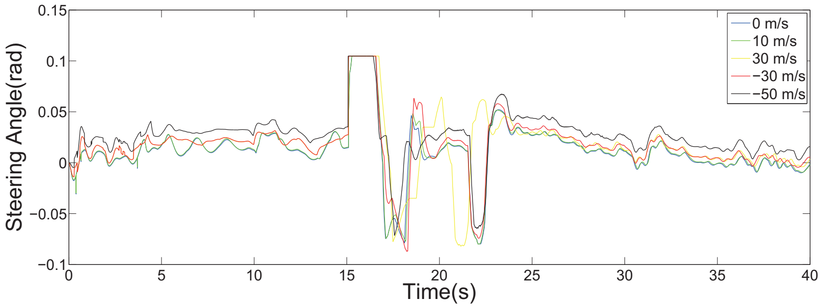


(c)

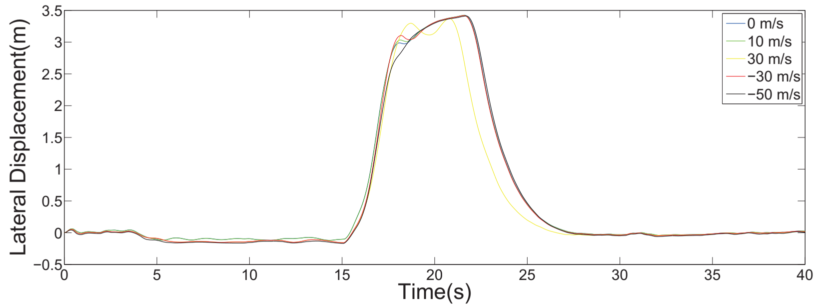
Figure 5.16: Road Geometry (Overtaking Behavior)



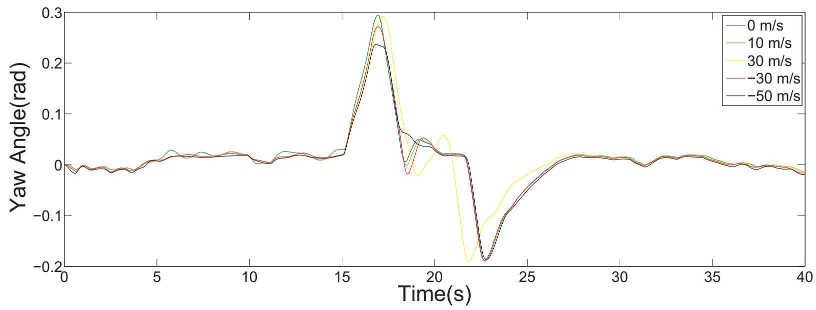
(a)



(b)



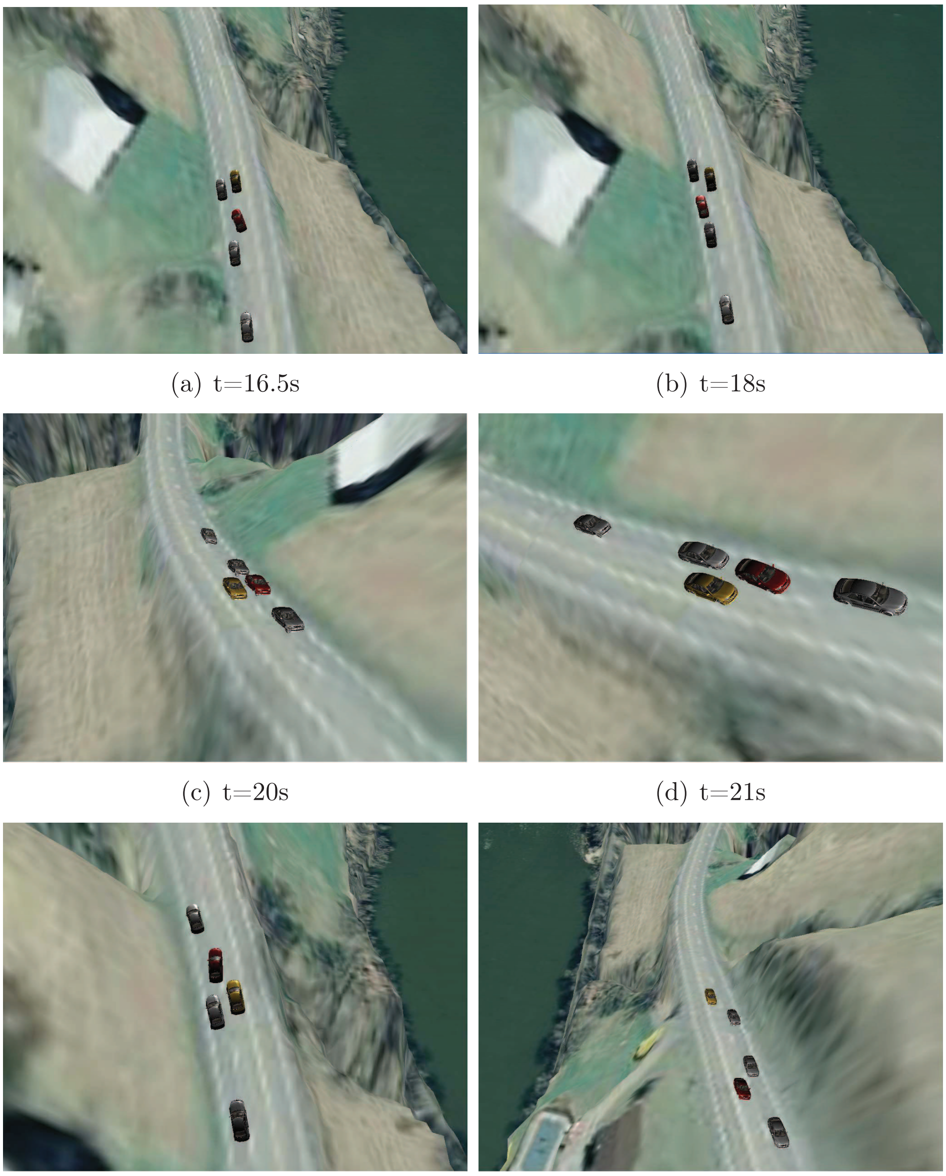
(c)



(d)

Figure 5.17: Overtaking Behavior

Fig. 5.18 shows the overtaking behavior visualization scenes when the wind speed is $-50m/s$. The red car is the subject vehicle. Fig. 5.18(a) displays the subject vehicle changes from the original lane to the adjacent lane. In Fig. 5.18(b), Fig. 5.18(c) and Fig. 5.18(d), the subject vehicle overtakes the leading vehicle in adjacent lane. Fig. 5.18(e) presents the subject vehicle returns to the original lane. The overtaking behavior is finished in Fig. 5.18(e).



(a) t=16.5s (b) t=18s

(c) t=20s (d) t=21s

(e) t=23s (f) t=34s

Figure 5.18: Visualization Scenes (Overtaking Behavior)

5.4 Conclusions

Researches on the intelligent vehicle control involving environment have magnificent meaning in the traffic safety. According to the analysis in Chapter 4, the fuzzy logic based intelligent vehicle controllers adapting to complex environment have been designed in this chapter, especially the road geometry and wind effects have been in the consideration. Based on VR-ISSV, the autonomous road behavior, the car following behavior and the overtaking behavior considering road geometry and wind have been realized with the proposed intelligent fuzzy controllers. The simulation results show that the fuzzy controllers are proper and reasonable, the controllers and the methods are useful in the improvement of traffic safety.

Conclusions and Perspectives

Conclusions

This thesis has been devoted to the modeling and simulation of microscopic traffic behavior in virtual reality system. It is an interdisciplinary area of Intelligent Transportation Systems (ITS), Virtual Reality (VR) and Multi-Agent System (MAS) technologies. This study has focused on two aspects that are important for virtual reality traffic simulation system: intelligent simulation framework and realistic dynamic features. The effects of natural environment affecting intelligent vehicle have been studied and the proper fuzzy intelligent vehicle controllers involving environment have been proposed to ensure traffic safety. Microscopic traffic behaviors considering the human factors, traffic situation and environment effects have been researched in virtual reality simulation system.

The work has been presented as follows:

Chapter 1 can be summarized in three parts: the first part has given the research motivation of providing a new method to research on microscopic traffic; the second part has reviewed the related research field of ITS, Modeling and Simulation (M & S), VR and MAS; the third part has presented VR and MAS applications in transportation systems. M & S, VR and MAS have already been used in microscopic traffic maneuver and have provided a solid research background for this thesis.

In **Chapter 2**, Virtual Reality Intelligent Simulation System of Vehicles (VR-ISSV) based on multi-agent has been proposed to simulate the intelligent microscopic traffic, which is a hierarchical modular modeling and simulation system consisting of hardware, network and operating system layer, visualization management layer, multi-agent layer, human-machine interface layer. VR-ISSV could improve the reusability, the reconfigurability, the scalability and the intelligence of traffic simulation system. With this concept, the microscopic traffic simulation system could be constructed rapidly and conveniently with different vehicle models, environment models and distributed services. In the application results, two application examples (DCOM-based simulation and HLA-based simulation) have been shown to prove the feasibility of the proposed methodology and its ability to produce an effective simulation system, this system could be used for researching on the interaction among the vehicles, the traffic situation and the environment information. The corresponding results have been published in (Yu 2012a; Yu 2013c).

Chapter 3 has focused on the intelligent vehicle agent model. The car following behavior and the overtaking behavior in the straight lane have been shown in detail. A decentralized design paradigm has been used for developing the multi-controller based intelligent vehicle, whereby the car following behavior and the overtaking behavior could be realized by the coordination of the multi-controller. The lane changing behavior model has been analyzed, because it is the base of overtaking behavior. Car following has been realized with the consideration of human factors and overtaking behavior has been researched involving traffic situation. Traffic simulation maneuvers have been shown to verify the correctness and effectiveness of these models in virtual reality traffic simulation system. The corresponding results could be found in (Yu 2013a; Yu 2013b).

Chapter 4 has established Synthetic Natural Environment (SNE) agent model. The interaction between vehicles and environment have researched in detail. GIS has been used in the simulation system to construct SNE agent. With this method, not only the virtual world created in VR-ISSV has been used for the visualization, but also it could supply realistic environment information for the microscopic traffic behaviors analysis and vehicle control algorithms design. Moreover, the simulation fidelity has been enhanced by this method. The vehicle dynamic models involving road and geometry effects have been constructed, including the longitudinal vehicle dynamic models and the lateral dynamic models. With SNE agent in VR-ISSV, the effects of road geometry and wind affecting on intelligent vehicle have been analyzed. The corresponding contributions could be found in (Yu 2012b; Yu 2013d).

Chapter 5 has focused on the intelligent vehicle control. Chapter 4 has analyzed the effect of environment affecting on vehicle. Because researches on the intelligent vehicle control involving environment have magnificent meaning in the traffic safety, the fuzzy logic based intelligent vehicle controllers adapting to complex environment have been designed in this chapter. The steering fuzzy controller for lane keeping, steering fuzzy controller for lane changing and throttle/brake fuzzy controller have been introduced in detail, the road geometry and wind effects have been in the consideration. Based on VR-ISSV, the autonomous road behavior, the car following behavior and the overtaking behavior considering road geometry and wind have been realized with the proposed intelligent fuzzy controllers. Some simulation results have been given to show that the reasonability of fuzzy controllers and the usability of the methods in the improvement of traffic safety. The detailed results can be found in (Yu 2014).

Limits

In general development of MAS, the agent is developed by the agent development platform, and the agent has the ability of communication by itself. The development of MAS based intelligent simulation system is constructed in Visual Studio C++. The service agent for communication is an independent agent, which is more flexible. However, some features of MAS are not reflected in this study. First, in MAS, there are lots of agents normally. Second, MAS could reflect the macroscopic behavior of the system based on the interaction of the individual agents. In this study, the agent number is limited and only microscopic traffic behaviors are researched.

Perspectives

Based on the results given by this thesis, several perspectives should be considered:

In theory

- The capability of the intelligent vehicle agent could be expanded. The agent-based multi-controller architecture is open so that controllers can be easily added, removed or changed. With this method, the intelligent vehicle agent model is openness and scalability, which is useful for large-scale distributed traffic simulation system for future extension.

- The wind model in environment agent could be much more real with the atmosphere environment database considering the real wind movement data and the air density data. The Synthetic Environment Data Representation and Interchange Specification (SEDRIS) could be used in the system to realize the data communication standardization, which is useful for system expansibility and reconfigurability. Some realistic climate database should be studied for the verification of the microscopic behavior affected by climate conditions.

- The mathematical vehicle model and the control model could be enriched because the real transport system is much more complex. Moreover, the behavioral and cognitive properties of the intelligent vehicle agent should be enhanced by considering the driver state, such as fatigue, emotion, *et al.*, which makes the simulation system more real. To enhance the simulation system and improve the simulation fidelity, all the factors should be modeled and simulated. The models of fatigue, motion, *et al.* could be established.

In application

- With respect to the limits mentioned above, the intelligent simulation system developed in this study could be replaced by the existed agent develop platform, because the entity agent, the environment agent and the service agent are designed as independent modules in this study. Considering the standard agent development platform based Foundation for Intelligent Physical Agents (FIPA), show as in Fig. 1. Agent Management System (AMS) realizes the management of the whole platform. Directory Facilitator (DF) provides the yellow page service in the platform. Agent Communication Channel (ACC) supplies commutations among agents. To replace the intelligent simulation system with the existed agent platform, there are two jobs. (1) The service agent and the application management work could be replaced by the existed agent platform. Because each existed agent platform has its own features and concepts, a general agent platform based on the existed agent platforms should be developed. (2) The entity agent and the environment agent are needed to be integrated into the agent platform.

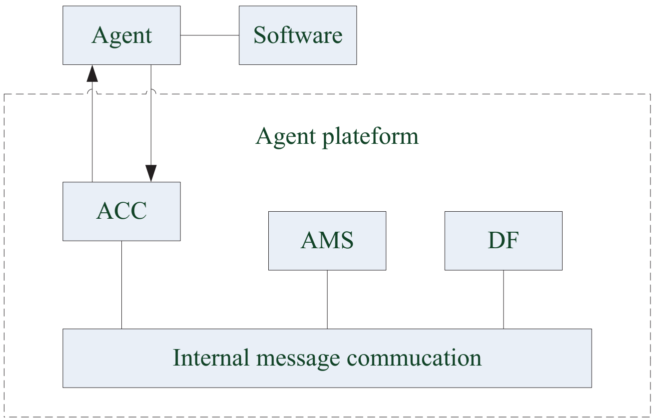


Figure 1: Agent Development Platform based on FIPA

- The application capability of the proposed system should be expanded systematically and the intelligence of the simulation system could be improved. By introducing the mobile agents into simulation system, the flexibility and the ability of system to deal with uncertainty in a dynamic environment could be increased. The simulation system is distributed, mobile agents can help reduce the delay of incident response. New services, operations or control algorithms can be implemented as mobile agents. The simulation performance can be improved by the optimization among these mobile agents.

- The intelligent optimization models could be constructed, including Back Propagation (BP) neutral network, Generic Algorithm (GA), Simulation Annealing (SA) algorithm, Ant Colony Optimization (ACO) algorithm, Partical Swarm Optimization (PSO) algorithm, *et al.* These optimization algorithms can be encapsulated in the Dynamic Link Library (DLLs), which can be flexibly called.

- Augmented reality and mixed reality combining the virtual simulation world and real world play an important role in the improvement of system fidelity. The simulation environment could be the mixed environment: the simulated vehicle runs in a real world or the real vehicle runs in the simulated environment.

- Although the intelligent vehicle control algorithms and microscopic traffic behavior models have been verified in the simulation system. These algorithms and models are still need to be tested by real vehicles. Thus it is better to consider the hardware in loop system (*i.e.* driving simulator) to expend the proposed system. Firstly some reduced scale vehicles can be used in system; secondly the real vehicles could be introduced. After the real vehicle is in the system, the algorithms involving time delay, data loss, *et al.* should be considered.

Résumé Étendu en Français

Motivation de la recherche

Les principales difficultés auxquelles font face le transport terrestre sont la grande augmentation de la congestion, des accidents, des retards, et de la pollution. Pour résoudre ces problèmes, US Department of Transportation a proposé le concept de systèmes de transport intelligents (ITS), et de réseau routier automatisé (AHS). ITS et AHS sont des programmes ambitieux, utilisant des technologies avancées d'informatique, de communications, et de réseau de capteurs, pour transformer le transport routier en un système quasi-autonome, efficacement géré, bien intégré, universellement disponible et abordable.

ITS et AHS sont des systèmes complexes, associant des éléments de nature différent par exemple l'humain, le véhicule et l'environnement... et l'information est abondante, hétérogène et non structurée. L'implémentation de ces systèmes nécessite des véhicules intelligents. Par conséquent, de nombreuses technologies traditionnelles se trouvent d'être très limitées et difficiles à mettre en œuvre. Comme les véhicules intelligents sont chers, la simulation devient la phase primordiale du processus de développement. Modélisation et simulation (M & S) ont été identifiées comme des étapes importantes dans toute réalisation. Grâce aux technologies de M & S, les systèmes complexes du trafic réel, peuvent être analysés dans le monde virtuel avec une base de données du modèle, une plateforme de simulation... comme indiqué dans Fig. 1.

La technologie de réalité virtuelle (VR) est utilisée dans les systèmes de simulation du trafic et les simulateurs de conduite. Le système de simulation du trafic nécessite une masse de calcul importante et la technologie de simulation distribuée. En effet, l'ensemble du système doit être distribué dans des nœuds différents, puis regroupé afin de réaliser la tâche conjointement au travers du réseau informatique. Un système multi-agents (MAS) constitue alors un moyen approprié pour modéliser et simuler des systèmes du trafic, car il offre un moyen intuitif de décrire chaque entité autonome sur le plan individuel. MAS a été utilisé dans la conduite collaborative, la modélisation du comportement du conducteur à base des agents et la simulation du trafic microscopique.

Inspiré par les travaux existants, notre étude combine ITS avec VR et MAS, pour un système de pilotage de véhicules intelligents, par la simulation du com-

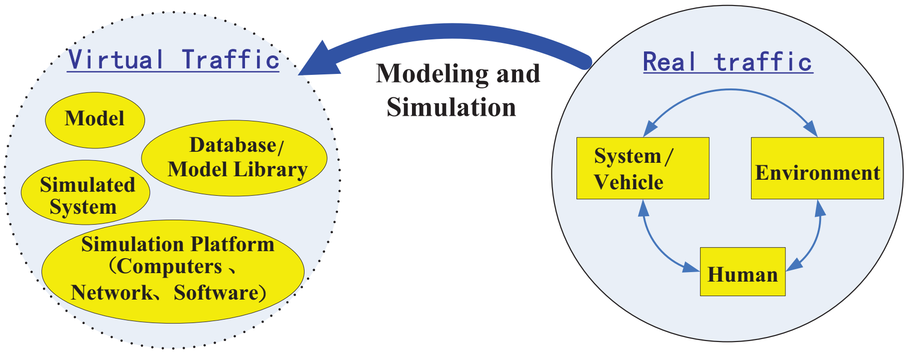


Figure 1: Principe de Simulation du Trafic

portement microscopique du trafic. Elle étudie systématiquement la méthode de modélisation de simulation du véhicule, intègre l'intelligence dans le cadre de simulation de véhicule, et développe les interactions entre les véhicules, les situations du trafic et l'environnement. Avec ces travaux de recherche, une nouvelle approche est proposée pour assurer une meilleure sécurité routière.

Système de simulation intelligent des véhicules en réalité virtuelle

Suite à cette phase d'analyse, un système de simulation intelligent des véhicules en réalité virtuelle (VR-ISSV), basé sur les multi-agents, est proposé. Il assiste l'utilisateur dans la préparation de la simulation pour les situations différentes du trafic, la conception des algorithmes de contrôle dans des environnements différents.

VR-ISSV est créé par l'application de l'approche multi-agent et la technologie de réalité virtuelle. VR-ISSV pourrait améliorer la flexibilité, la réutilisabilité, l'évolutivité et l'interopérabilité des capacités de simulation du trafic dans la théorie, car les composants hétérogènes et les programmes d'application peuvent être intégrés et inter-exploités en étant encapsulés et fournis en tant qu'agents. VR-ISSV permet également d'assurer la réutilisation du modèle, le code héritage et la rapide construction du système dans le niveau d'application. L'objectif est de construire une méthode de modélisation systématique pour VR-ISSV.

Basé sur les multi-agents, VR-ISSV peut être modélisé comme quatre couches hiérarchiques indiquées dans Fig. 2, comprenant une couche matérielle, réseau et système d'exploitation; une couche de gestion de la visualisation; une couche de multi-agents et une couche d'interface homme-machine.

La couche matérielle, réseau et système d'exploitation offre le support de

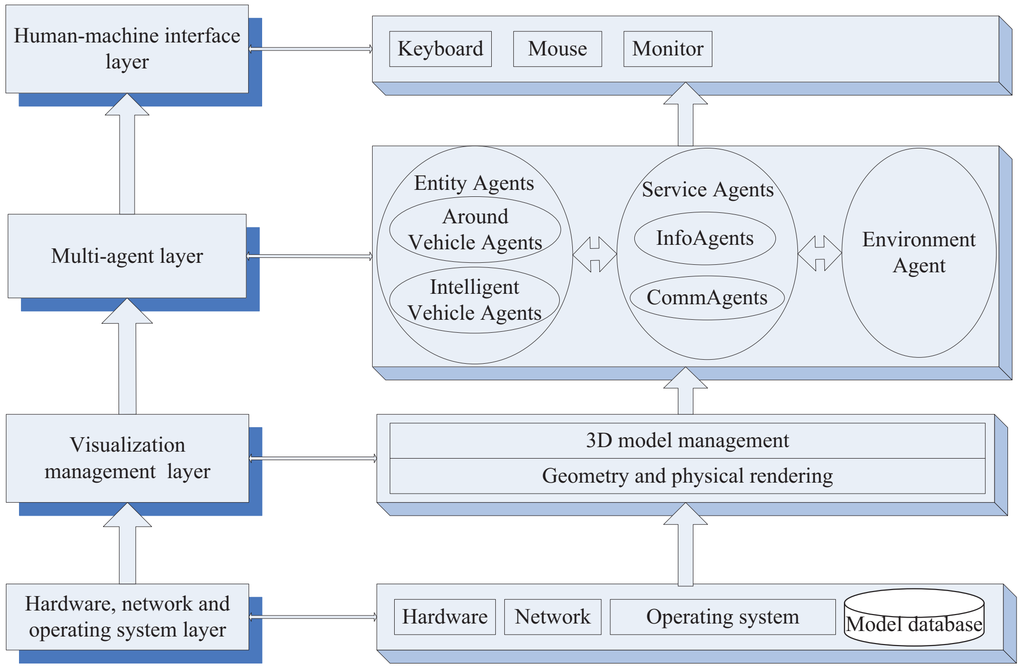


Figure 2: Structure de VR-ISSV basée sur les Multi-agents

fonctionnement du système qui inclut la visualisation, le modèle dynamique du véhicule et le modèle du contrôle, l'environnement distribué du réseau de communication, le système d'exploitation et la base de données de modèle. La couche de gestion de la visualisation est en charge de la gestion du modèle 3D, de l'organisation des scènes 3D et du calcul des propriétés physiques, telles que la détection de collision. La couche de multi-agents inclut agent entité, agent de service et agent de l'environnement. Chaque agent entité correspond à une entité 3D dans la scène et fournit les entités 3D avec les sémantiques spécifiques et des règles de comportement. Agents de service n'ont pas de formes géométriques et leur fonction de base est de fournir un service au système: agent de service de communication (CommAgent) et agent de service d'information (InfoAgent). L'agent de service de communication offre le service de la simulation distribuée, l'agent de service d'information fournit les connaissances nécessaires dans le système de simulation. Agent de l'environnement est l'agent dynamique, qui peut modifier les caractéristiques et peut affecter l'agent entité via les paramètres stockées dans la base de données de modèle. La couche d'interface homme-machine est l'interface pour les utilisateurs qui interagissent directement avec le système de simulation intelligent par les dispositifs, tels que clavier, souris et moniteur.

La structure de multi-agent a 6 avantages. (1) Généralité: en étant encapsulés et fournis en tant qu'agents, les composants hétérogènes et les programmes d'application peuvent être intégrés et inter-exploités. (2) Intelligence: le système de simulation intelligent basé sur les multi-agents reflète la connaissance sémantique et la logique de l'application du système, ce qui permet de soutenir la réutilisabilité et l'interopérabilité dans le niveau de connaissance. (3) Extensibilité: les entités dans la simulation intelligente sont divisées en un certain nombre d'agents faiblement couplés. Chaque agent est relativement indépendant. Il est très facile d'ajouter, de supprimer et de modifier certains agents sans affecter les autres. (4) Réutilisabilité des logiciels: les modèles et les logiciels peuvent être emballés comme l'agent et réutilisés dans le système de simulation. (5) Réconfigurabilité: la simulation intelligente basée sur les multi-agents permet de réaliser rapidement la reconstruction de l'application du système en modifiant les règles de comportement d'un agent individuel ou en modifiant les règles de communication entre les agents. (6) Authenticité. La simulation du trafic pourrait être plus valable en introduisant le système d'information géographique.

Comportement du trafic microscopique

Le modèle de véhicule intelligent virtuel est un modèle 3D combinant le véhicule virtuel avec le module de perception, l'état interne, le module de mouvement, et le module cognitif et de comportement, indiqués Fig. 3. Le module cognitif et de comportement est le cerveau du véhicule intelligent virtuel. La situation du trafic et les comportements du véhicule sont complexes. Donc, le module cognitif et de comportement est modélisé comme un agent multi-contrôleur pour réaliser les comportements microscopiques grâce à la collaboration d'agent à des niveaux différents.

L'organisation de l'agent multi-contrôleur est présentée Fig. 4. Le véhicule intelligent est le contrôleur de haut-agent, qui contient deux contrôleurs: le contrôleur longitudinal et le contrôleur latéral. Et le contrôleur longitudinal est divisé en un contrôleur de vitesse, un contrôleur de suivi et un contrôleur d'urgence. Le contrôleur latéral est divisé en un contrôleur de changement de voie et un contrôleur de suivi de voie. Le comportement du suivi des véhicules et le comportement du dépassement des véhicules sont réalisées par coordination entre multi-contrôleurs.

Le comportement du suivi des véhicules est réalisé par coordination entre le contrôleur de vitesse, le contrôleur de suivi et le contrôleur d'urgence. Ce processus est déterminé par des seuils prédéterminés. Ces seuils sont définis comme une combinaison de vitesse différente et de distance différente.

Les seuils sont définis comme suit:

(1) La distance suivi (l_{FD}):

$$l_{FD} = \gamma \frac{{v_i}^2}{2a_{i\,\max}} + L + \tau v_i,$$

où L est la marge de sécurité qui dénote la séparation entre deux véhicules quand ils arrêtent; $a_{i\,\max}$ est la décélération maximale; τ est le temps de réaction du

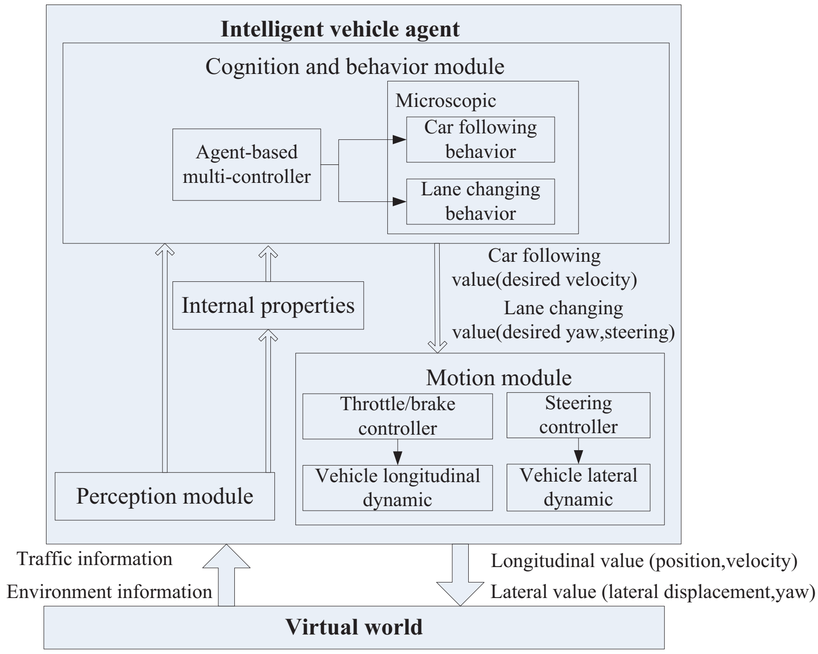


Figure 3: Structure d'Agent du Véhicule Intelligent

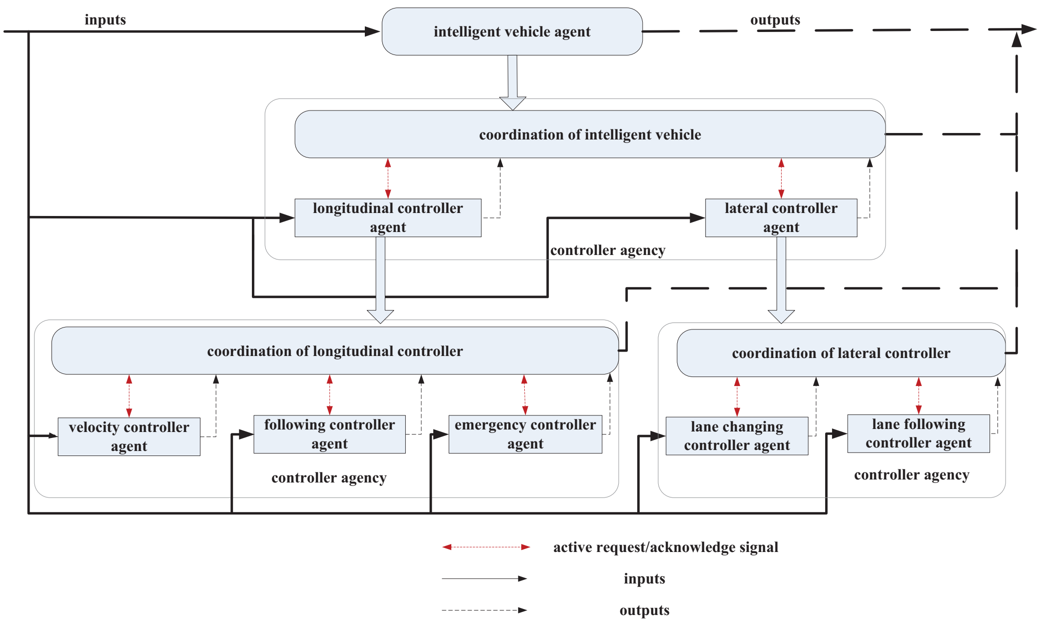


Figure 4: Agent Multi-contrôleur du Véhicule Intelligent

conducteur; γ est le coefficient de sécurité, un paramètre qui peut être sélectionné par l'utilisateur, correspondant à l'état des routes.

(2) La distance de freinage (l_{BD}):

$$l_{BD} = \gamma(\frac{v_i^2}{2a_{i\max}} - \frac{v_{i-1}^2}{2a_{i-1\max}}) + L + \tau v_i.$$

(3) La distance de collision (l_{CD}):

$$l_{CD} = \frac{(v_i - v_{i-1})^2}{2\mu a_{i\max}} + L \ (v_i \geq v_{i-1}).$$

Le mécanisme de coordination entre l'agent contrôleur de vitesse, l'agent contrôleur de suivi et l'agent contrôleur d'urgence est une priorité fixe. L'index de priorité des agents du contrôleur est comme suit: l'agent contrôleur d'urgence > l'agent contrôleur de suivi > l'agent contrôleur de vitesse. Cette coordination est affectée par les seuils entre véhicules:

(1) $S(t) \geq (1.5 \sim 2.5)l_{FD}$, le contrôleur de vitesse est actif, et représente le comportement de maintenir une vitesse optimale lorsque aucun véhicule n'est en vue.

(2) $l_{BD} < S(t) < (1.5 \sim 2.5)l_{FD}$, le contrôleur de suivi est actif, et représente le comportement de maintenir une distance avec tous les véhicules précédents.

(3) $l_{CD} < S(t) < l_{BD}$, le contrôleur d'urgence est actif, et représente le comportement de réagir à une situation d'urgence qui implique généralement un freinage sec.

En considérant l'espace entre les deux véhicules, la différence de la vitesse entre les deux véhicules et l'accélération du véhicule à l'avant, la coordination du contrôleur longitudinal est représentée Fig. 5.

Le comportement du dépassement des véhicules est réalisé par la coordination entre le contrôleur longitudinal et le contrôleur latéral. Dans la simulation de trafic, le contrôleur longitudinal est actif tout le temps, et le contrôleur latéral devient actif quand le changement de voie est actionné. Selon le processus du changement de voie, indiqué Fig. 6, on peut voir que le changement de voie est considéré faisable s'il existe un écart suffisant dans la voie latérale.

Cette faisabilité est divisée en deux cas.

(1) $V_s < V$, pour le véhicule avant dans la voie latérale, le changement de voie se passe si:

$$S_f\,(t) \geq S_f\,(min) = L,$$

pour le véhicule arrière dans la voie latérale, le changement de voie se passe si:

$$S_b\,(t) \geq S_b\,(min) = \frac{V^2 - {V_s}^2}{2j_b} + \tau V + L,$$

(2) $V_s > V$, pour le véhicule arrière dans la voie latérale, le changement de voie se passe si:

$$S_b\,(t) \geq S_b\,(min) = L,$$

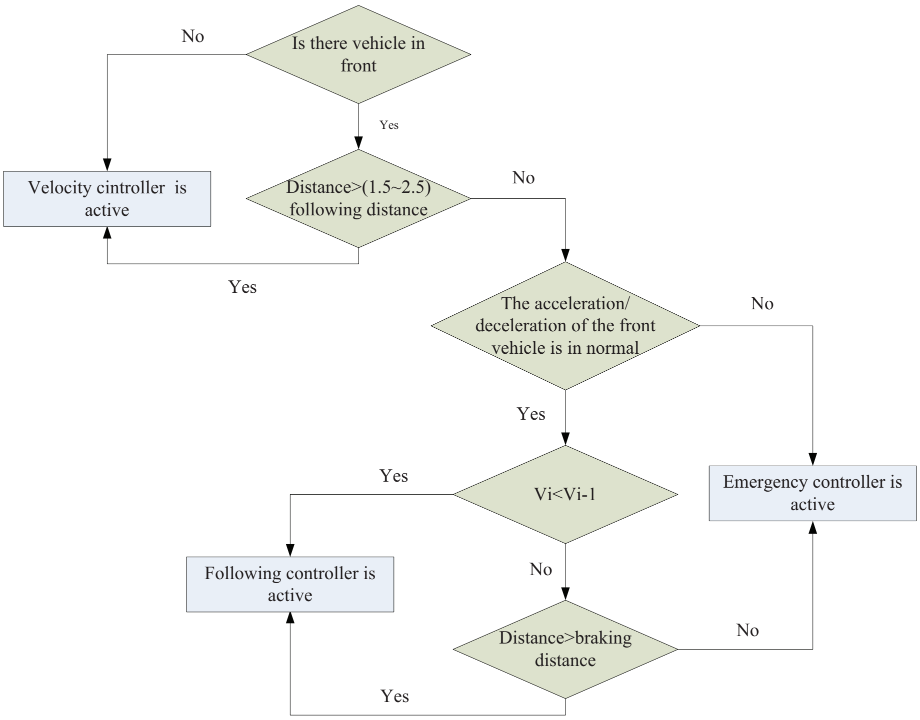


Figure 5: Coordination du Contrôleur Longitudinal

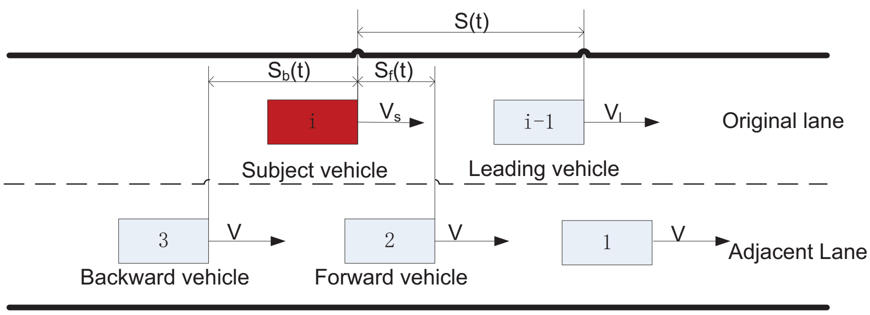


Figure 6: Processus de Changement de Voie

pour le véhicule avant dans la voie latérale, le changement de voie se passe si:

$$S_f\,(t) \geq S_f\,(min) = \frac{{V_s}^2 - V^2}{2j} + \tau V_s + L,$$

où V_s est la vitesse du véhicule sujet; V est la vitesse du véhicule dans la voie latérale; $S_f(min)$ est la distance minimale du véhicule avant dans la voie latérale pour éviter une collision; $S_b(min)$ est la distance minimale du véhicule arrière dans la voie latérale pour éviter une collision; j_b est la décélération maximale du véhicule arrière dans la voie latérale; j est la décélération maximale du véhicule intelligent; τ est le temps de réaction du conducteur; L est une distance constante entre les deux véhicules lorsque'ils s'arrêtent.

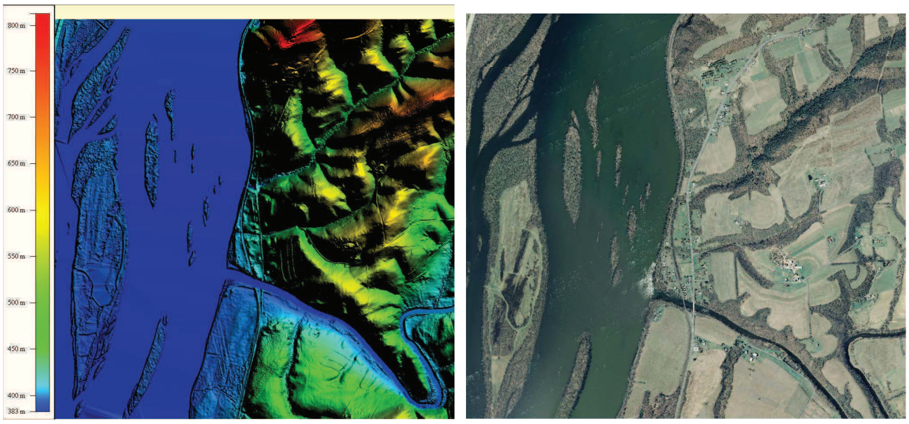
Chaque manœuvre de dépassement des véhicules comprend deux changements de voies et un état de suivi des véhicules. Par conséquent, la vitesse et la direction des véhicules intelligents doivent être gérées. Basé sur le modèle dans cette étude, les contrôleurs sont considérés comme partiellement découplés. La manœuvre de dépassement des véhicules peut être réalisée grâce à la coordination du multi-contrôleur à base d'agents.

Environnement naturel synthétique

La recherche d'un modèle de l'environnement et son impact sur le contrôleur du véhicule joue un rôle important dans la sécurité routière. L'agent d'environnement est construit grâce à la conception de l'environnement naturel synthétique (SNE), l'interaction entre les véhicules et l'environnement naturel synthétique étant alors analysée. Un système d'information géographique (GIS) est utilisé dans le système de simulation, Fig. 7. Avec cette méthode, non seulement le monde virtuel créé en VR-ISSV est utilisé pour la visualisation, mais aussi il permet de fournir des informations d'environnement réalistes pour l'analyse du trafic microscopique et la conception de l'algorithme de commande du véhicule. De plus, la fidélité de la simulation est améliorée.

Le modèle de terrain 3D est construit basé sur les données du modèle de l'élévation digital (DEM) et l'image satellite. L'information de la courbure est obtenue à partir de la carte routière prédéfinie. La pente de la route et l'angle de rang sont obtenues par la détection de collision entre les modèles 3D. L'information d'altitude de route à partir des données DEM est utilisée pour calculer la pente et l'angle de rang comme suit:

$$\begin{cases} \alpha = \sin^{-1}(\dfrac{(z_{fl} + z_{fr}) - (z_{bl} + z_{br})}{2(x_{fl} - x_{bl})}), \\ \beta = \sin^{-1}(\dfrac{(z_{fl} + z_{bl}) - (z_{fr} + z_{br})}{2(y_{fl} - y_{fr})}), \end{cases}$$



(a) Height Map of Terrain (b) Texture Image of Terrain

Figure 7: Visualisation de Terrain

où z_{fl}, z_{fr}, z_{bl}, z_{br} sont les altitudes de la roue avant-gauche, de la roue avant-droite, de la roue arrière-gauche et de la roue arrière-droite. x_{fl}, x_{bl} sont la position de la roue avant-gauche et la position de la roue arrière-gauche le long de l'axe x. y_{fl}, y_{fr} sont la position de la roue avant-gauche et la position de la roue avant-droite le long de l'axe y.

Contrôle du véhicule intelligent

Selon les comportements microscopiques (le comportement du suivi de la route, le comportement du suivi des véhicules et le comportement du dépassement des véhicules), deux contrôleurs différents, basés sur la logique floue, sont utilisés pour les deux modes de conduite: le suivi de voie et le changement de voie. Les deux contrôleurs comprennent les contrôleurs flous de direction (les contrôleurs latéraux) et les contrôleurs flous d'accélérateur et de frein (les contrôleurs longitudinaux). Les contrôleurs flous d'accélérateur et de frein utilisés dans ces deux scénarios sont les mêmes, mais les contrôleurs flous de direction sont différents.

Dans cette étude, trois contrôleurs flous de direction sont définis pour exécuter le suivi de voie selon la courbure de la route, l'angle de rang et le vent latéral, chaque contrôleur flou est sélectionné à partir d'une couche tactique de haut niveau. La structure de base de ces trois contrôleurs flous est le même. Mais les valeurs de la fonction d'appartenance des variables d'entrée et de sortie ne sont pas toujours les mêmes et les règles de logique floue sont différents, ce qui peut refléter le fait que le pilote dirige l'automobile sous les conditions différentes du vent et de la route.

Comme le contrôleur flou de direction pour le suivi de voie, trois contrôleurs flous d'accélérateur et de frein sont définis pour décrire le comportement des conducteurs sous les conditions différentes du vent longitudinal et de la pente. Pour les trois contrôleurs, la structure de base du contrôleur flou et la méthode de défuzzification sont les mêmes. Cependant, les valeurs de la fonction d'appartenance des variables d'entrée et de sortie, et les règles de logique floue sont modifiées.

Conclusions et perspectives

Cette thèse est consacrée à la conception et au développement d'une plateforme multi-agent, en réalité virtuelle, de pilotage de véhicules intelligents pour la simulation du comportement microscopique du trafic. Les résultats de la simulation dans des conditions quasi-réelles ont confirmé l'efficacité de nos approches.

Contributions

Premièrement, un système de simulation intelligent des véhicules en réalité virtuelle (VR-ISSV) est proposé, c'est un système de simulation intelligent basé sur le multi-agent pour les véhicules. VR-ISSV a les caractéristiques de réutilisabilité, de réconfigurabilité et d'extensibilité, ce qui pourrait réaliser la construction rapide de VR-ISSV avec le modèle de reconfiguration et de réutilisabilité du code. Deuxièmement, la modélisation de véhicule intelligent basée sur les agents en considérant la situation du trafic et l'environnement est construite. Troisièmement, la modélisation de l'environnement naturel synthétique et les effets d'environnement sur le véhicule sont étudiés. Enfin, les contrôleurs de véhicules intelligents d'adaptation à un environnement complexe sont considérés.

Perspectives

Théoriquement, la capacité de l'agent du véhicule intelligent pourrait être étendue. Le modèle du vent dans l'agent d'environnement pourrait être plus réel avec une base de données de flux réaliste tenant compte des données réelles de circulation des vents et des données de densité de l'air. La recherche pourrait être faite sur le modèle de véhicule intelligent avec des états conducteurs, tels que la fatigue. En application, le système de simulation intelligente développé dans cette étude pourrait être enrichi en introduisant les agents mobiles dans le système de simulation, la flexibilité et la capacité du système à gérer l'incertitude dans un environnement dynamique voire en considérant la réalité augmentée. Les modèles d'optimisation intelligents pourraient être construits et encapsulés dans la bibliothèque de liens dynamiques (DLL).

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Conception et Développement d'une Plateforme Multi-Agent en Réalité Virtuelle de Pilotage de Véhicules Intelligents

Résumé: Cette thèse est consacrée à la conception et au développement d'une plateforme multi-agent, en réalité virtuelle, de pilotage de véhicules intelligents pour la simulation du comportement microscopique du trafic.

D'abord, un système de simulation intelligent des véhicules en réalité virtuelle (VR-ISSV), basé sur les multi-agents, est proposé: c'est un système modulaire hiérarchique de modélisation et de simulation, comprenant une couche matérielle, réseau et système d'exploitation; une couche de gestion de la visualisation; une couche de multi-agents et une couche d'interface homme-machine. La couche de multi-agents comprend des agents d'entités (agents des véhicules intelligents et agents des véhicules entourés), un agent de service et un agent d'environnement. Ensuite, pour le modèle d'agent du véhicule intelligent, un paradigme de conception décentralisée est utilisé basé sur l'approche multi-contrôleurs, où le comportement du suivi des véhicules et le comportement du dépassement des véhicules sont réalisées par coordination entre multi-contrôleurs. L'agent d'environnement est construit en tenaut compte de l'interaction entre les véhicules et l'environnement naturel synthétique. Un système d'information géographique (GIS) est par ailleurs utilisé afin de définir l'agent d'environnement. Enfin, pour assurer la sécurité dans les manœuvres microscopiques du trafic, plusieurs contrôleurs du véhicule intelligent, adaptés à l'environnement complexe, sont considérés. Les contrôleurs, basée sur la logique floue, sont proposés pour envoyer les commandes appropriées aux actionneurs du véhicule - volant de direction, accélérateur et frein. Les modèles de comportement microscopique du trafic basé sur l'agent de véhicule intelligent sont étudiés sconsidérant différents scénarios et l'environnement.
Mots-clés: Simulation du trafic microscopique, Réalité virtuelle, Multi-agent, Environnement naturel synthétique, Contrôle du véhicule intelligent.

Multiagent-based Virtual Reality Intelligent Vehicles Simulation Platform

Abstract: This PHD thesis is dedicated to the modeling and simulation of microscopic traffic behavior in virtual reality system, with the intent of providing a new approach to effectively ensure traffic safety.

At first, Virtual Reality Intelligent Simulation System of Vehicles (VR-ISSV), based on multi-agent is proposed to simulate the intelligent microscopic traffic, which is a hierarchical modular modeling and simulation system consisting of hardware, network and operating system layer, visualization management layer, multi-agent layer, human-machine interface layer. The multi-agent layer includes entity agents (intelligent vehicle agents and around vehicle agents), service agent and environment agent. Second, for the intelligent vehicle agent model, a decentralized design paradigm is used for developing the multi-controller based intelligent vehicle, whereby the car following behavior and the overtaking behavior could be realized by the coordination of the multi-controller. The environment agent is constructed based on the conception of Synthetic Natural Environment (SNE), taking into account the interaction between the vehicles and the natural environment. Geographic Information System (GIS) is used to establish environment agent. Finally, to ensure the safety in microscopic traffic maneuver, the intelligent vehicle controllers adapting to complex environment are considered. Fuzzy logic based controllers are designed for sending the appropriate outputs to the vehicle's actuators - the steering wheel and the throttle/brake pedals. Microscopic traffic behavior models based on the intelligent vehicle agent involving environment are studied.
Keywords: Microscopic traffic simulation, Virtual reality, Multi-agent, Synthetic natural environment, Intelligent vehicle control.