School of Production Engineering & Management
Technical University of Crete
Chania, Greece

Diploma Thesis

Modelling of Cooperative Lane Changing in Highways

By PANAGIOTIS STRATIDIS

Supervisor: Dr. Ioannis K. Nikolos, Associate Professor

Chania, June 2016

Abstract

We depend heavily on transport in our everyday lives. Yet continuously increasing road traffic generates serious problems in terms of congestion, safety and environmental impact. Fortunately, information and communication technologies offer new advanced solutions to today's transport problems.

Intelligent Transport Systems (ITS) embrace a wide variety of communications-related applications intended to increase travel safety, minimize environmental impact, improve traffic management and maximize the benefits of transportation to both commercial users and the general public.

This thesis contributes to the development of a microscopic traffic behavior and performance model for fully automated vehicles concerning specifically to the lane changing regime on highways. An algorithm is constructed for cooperational lane changing with a set percentage of vehicles to lane change. This model is then merged with an on-ramp merging algorithm created by I. Dousakis as a relieving mechanism before the on-ramp in order to incorporate the inflow of the ramp into the highway. All lane changes are considered cooperative lane changes since it is assumed that the highway has 100% equipped automated vehicles. The developed model will be integrated in and tested on the Aimsun traffic modeling software.

Thesis Committee

Ioannis K. Nikolos
Associate Professor, Supervisor,
School of Production Engineering and Management,
Technical University of Crete, Greece.

Markos Papageorgiou
Professor,
School of Production Engineering and Management,
Technical University of Crete, Greece.

Ioannis Papamichail
Assistant Professor,
School of Production Engineering and Management,
Technical University of Crete, Greece.

Acknowledgements

First of all I would like to thank Dr Ioannis K. Nikolos for his continuous support and supervision over the course of this graduation project at the Dynamic Systems and Simulation Laboratory (DSSL). Time to time I have found him as a great source of motivation throughout the whole process he has supported this research with his technical expertise and organizational credentials. Overall, it was a pleasure to work with him in the same team. Without his support and guidance this work could not be accomplished.

I would also like to offer sincere gratitude to my colleague and friend Ioannis A. Ntousakis. His guidance and assistance throughout the different obstacles that I would come upon were paramount to the completion of this thesis.

I would like to thank Prof. Ioannis Papamichail and Prof. Markos Papageorgiou for their courteous agreement to become thesis committee members and to spend their time and effort for helping me during my work for my Diploma Thesis.

Special thanks to Prof. Markos Papageorgiou for his offer to join the Dynamic Systems and Simulation Laboratory and carry out this thesis.

Last but not least, I would like to express my dedication to my parents, family members, and friends. Without their support my studies in Technical University of Crete wouldn't have been possible.

Panos Stratidis

Table of Contents

List of Figures

List of Tables

Chapter 1

Introduction

Mobility is a vital good in any modern society which is based on division of labor. However, daily increasing levels of congestion underscore the importance of new technological developments. This is where Intelligent Transport Systems (ITS) come in. The main goal of such systems is to ensure the efficient utilization of the available road capacity by either controlling traffic operations or influencing driver behavior in various ways *[Wahle & Schreckenberg, 2003]* .

Daily recurrent traffic jams reflect the fact that the road networks are not able to cope with the demand for mobility, which will still increase in the near future. Especially in densely populated regions it is physically unattainable to expand the already existing road network, due to high economic and environmental costs. As a result, we need new technologies to improve our worsening traffic conditions. Hence, one of the main objectives of the Intelligent Transport Systems is to place most of the emphasis on using the existing infrastructure more efficiently *[Wahle & Schreckenberg, 2003].*

Research on driver information technologies dates back to the 1950s and has evolved over the past 60 years. Although the technologies have advanced, the primary goals remain the same:

- Improve travel efficiency and mobility,
- enhance safety,
- provide economic benefits,
- conserve energy,
- and protect the environment

Recently, the development of advanced technologies in information processing, sensing and computer control, e.g. Global Positioning Systems (GPS) or the Internet has fostered the development of ITS technologies.

1-1 Objectives of this Thesis

As previously described, roadways are becoming denser and highway throuputs are reaching their limitations in terms of manual driving. Furthermore, the financial and environmental costs of expanding our traffic networks are too high to be considered as an option. In light of these facts technologies need to be developed to optimize the use of the existing networks and roadways. A promising field of interest is that of fully automated vehicles replacing most of the manually driven ones in order to increase efficiency in driving. During the last decade there has been an enormous effort to develop a variety of Vehicle Automation and Communication Systems (VACS) that are expected to revolutionize the features and capabilities of individual vehicles within the next decades.

The main objectives of this work are:

- To give insights into the concepts of Intelligent Transport Systems.
- To review the developed and developing technologies regarding lane changing or merging in general.
- To expand these technologies by developing an algorithm concerning the exact procedure of lane changing of automated vehicles on highways.
- To create a test environment in Aimsun traffic simulation software in order to test the developed algorithm and to process the results to decide if it optimizes the throuput.

1-2 Thesis Outline

The remainder of the thesis is organized as follows:

Chapter 2 is focused on the understanding of what are Intelligent Transportation Systems and what parts they are comprised of. We will analyze what are Automated Highway systems and the importance of them in the concept of ITS. We will then advance on the subject of automated merging, which is the main concern of this thesis. In the 3rd chapter there will be a Literature Review on automated merging, where previous works on the subject of merging throughout the years will be discussed. In chapter 4 there will be a walkthrough of the developed models for lane changing and automated merging and in chapter 5 we will present the test cases used for the simulations and the simulation results. Finally in the last chapter there is an overview of the results and the conclusions we have arrived.

Chapter 2

Intelligent Transportation Systems

Lately there has been major progress in the field of technology and due to that progress many applications for a numerous fields have been developed. Many areas and disciplines have benefitted to this progress of technology, like industry, defense, and consumer satisfaction services. In contrast, surface transportation hasn't benefitted very much from this progress. Due to the nature of the traffic system any disturbances caused either by accidents or driver behavior have a severe impact on the system. The randomness of manual driving and the lack of automatic feedback in the system results to the unpredictable, inefficient, and sluggish traffic flows observed in today's highway systems. The Intelligent Transportation Systems (ITS) projects aim to improve the efficiency of the current transportation systems by using new technologies that allow the implementation of sophisticated decision making techniques *[Ioannou, 1997]*.

2-1 ITS Objectives

Research on driver information technologies dates back to the 1950s and has evolved over the past 50 years. The primary goals though still remain the same:

- **Improve travel efficiency and mobility**

  The main goals of most ITS is the optimization of travel efficiency for existing facilities and resources. Travel efficiency means reducing travel delay and travel time for vehicles. Improvement of travel efficiency can be achieved through increasing the effective capacity of the existing system. Effective capacity is the maximum amount of vehicles per unit of time that a specific part of the system can sustain under specific road conditions *[Wahle & Schreckenberg, 2003]*.

- **Enhance safety**

A very important goal for ITS applications is to assist in ensuring the passenger's safety at all times. Although crashes and fatalities are unavoidable occurrences, ITS services can greatly reduce the probabilities of them. The main objective here is to reduce the amount of crashes and the severity of them. There are ways to quantify these objectives in order to be able to track the progress in the field. For example we can measure them with the use of quantities like the overall crash rate, the fatality crash rate, and injury crash rate *[Wahle & Schreckenberg, 2003].*

- **Provide economic benefits**

A secondary reason to apply ITS services is that it reduces operating costs and boosts productivity. The latter results in a sense that when travel efficiency is optimized people get to their jobs faster and less frustrated, so it improves their efficiency at work. Furthermore ITS can have lower acquisition rates and life cycle costs, compared to traditional transportation improvement techniques. We can quantify the effectiveness of this objective by calculating the cost savings due to the implementation of the ITS service provided *[Wahle & Schreckenberg, 2003].*

- **Conserve energy and protect the environment**

In this objective the environmental factor is taken into consideration. By using ITS technologies we can achieve a reduction in overall emissions and energy consumption in a system. The only way to determine the quantity of this goal is with the help of simulations and analysis. Some of the problems considering the measurement for this objective include difficulty due to small regional applications, extraneous factors, and time evolving nature of ozone pollution. Small scale applications show promising results but the large scale effects are still unknown *[Vanderschuren, 2006].*

- **Customer satisfaction**

Last in the list but an essential goal is customer satisfaction. After all these services are specifically developed to serve the public. Measuring this goal includes the registration of the expectations of the user and their eventual satisfaction or dissatisfaction regarding to a service or product. The pivotal question to be asked is "Does the product deliver sufficient value in return of the investment put into it? For example time or money." In addition to user or customer satisfaction, it is necessary to evaluate the satisfaction of the transportation system provider or manager. One way to measure the performance is to survey transportation providers before and after a project was implemented to see if co-ordination was improved. It may also be possible to bring together providers from each of the stakeholder groups to evaluate their satisfaction with the system before and after the implementation of an ITS project *[Vanderschuren, 2006].*

2-2 ITS Areas of Application

Due to ITS being very broad regarding the applications it can produce, it has been divided into 6 fields of technology *[Vanderschuren, 2006]*:

Advanced Traveler Management Systems (ATMS)

ATMS are managing traffic control and review it to minimize congestion and increase the efficiency of it using various means, like vehicle route diversion, traffic signal altering, variable message signs, etc. *[Vanderschuren, 2006]*.

Advanced Traveler Information Systems (ATIS)

This field consists of giving information to drivers that helps them reach their destination as efficiently as possible. The information can be transferred to them through on-board navigation systems that may accept inputs from ATMS or they can receive the same information from other devices in their home for pre-trip planning. ATIS include a variety of systems that provide real-time, in-vehicle information to drivers, regarding navigation and route guidance, motorist services, roadway signings, and hazard warnings *[Vanderschuren, 2006].*

Advanced Vehicle Control Systems (AVCS)

The AVCS fields is focused on assisting the driver with in-car situations, particularly emergency ones. These systems will assist in controlling the vehicle partly or even assuming full control. For example automatic cruise control (ACC) belongs to this category. In the long term AVCS aspire to fully automated vehicles moving in specially designed lanes in highways, guided by the infrastructure. This long term plan is known as an Automated Highway System (AHS) *[Vanderschuren, 2006].*

Commercial Vehicle Operations (CVO)

Commercial Vehicle Operations refer to the implementation of ITS applications on commercial traffic, such as trucks, buses, vans, taxis, and emergency vehicles. Fleet management operations are a major concern of this field *[Vanderschuren, 2006].*

Advanced Rural Transportation Systems (ARTS)

Advanced Rural Transportation Systems are ITS which are designed for rural areas, since they are quite different from urban areas in many ways *[Vanderschuren, 2006].*

Advanced Public Transportation Systems (APTS)

APTS use ATMS, ATIS, and AVCS technologies to enhance the effectiveness, attractiveness, and efficiency of public transportation and include automated fare collection, public travel security, and especially real-time information systems. However, this information should support the multi-modal aspect, since the availability and accessibility of information is one of the major drawbacks of public transport *[Wahle & Schreckenberg, 2003].*

All the above mentioned fields are expected to improve transport efficiency in the future. However the area that is expected to bring tremendous changes in the current traffic system is AHS (Automated Highway Systems). This area will incorporate the AVCS, ATMS, and ATIS technologies and develop a traffic system where fully automated vehicles are guided to their destinations and the whole flow of traffic is micromanaged by a controller or several controllers. This advancement will lead to greatly increased efficiency and safety. The design of AHS is a challenging one and the issues involved are enormous from the technological, human factors, socioeconomic, legal, institutional, and environmental points of view *[Ioannou, 1997].*

AHS can be the solution to current highway systems that have exhausted the traditional approach to transport optimization by introducing automation into the basic elements of the system, such as the vehicle and the infrastructure decision making tasks *[Ioannou, 1997].*

The consensus in the AHS community is that AHS will evolve over a series of smaller steps in technology. The final step of full automation will not be a leap, but a logical consequence of previous development and deployment efforts. One of the current steps in AHS development is to develop the first system to control lateral movement of vehicles by the use of merging systems *[Ioannou, 1997].*

Table 2-1 Overview of ITS Measures per Objective *[Vanderschuren, 2006].*

	Intelligent Traffic Management Systems	Intelligent Passenger Information Systems	Intelligent Public Transport Systems
Safety	• Variable speed limits • Lane management • Incident management • Warning systems • CCTV cameras • Automatic vehicle identification • Intelligent Speed Adaptation • Weight in motion	• Navigation systems • Parking guidance • Cruise control • Warning systems • Intelligent Speed Adaptation • Black-box systems • Automated vehicle identification • Docking systems • Distance warning	• Fleet management • Navigation systems • Electronic ticketing • CCTV cameras • High-speed ground transportation • Automatic vehicle identification • Intelligent Speed Adaptation • Distance warning
Mobility and Efficiency	• Variable speed limits • Lane management • Incident management • Warning systems • CCTV cameras • Ramp metering • Traffic control • Electronic toll collection • Real-time information • Parking guidance	• Navigation systems • Parking guidance • Cruise control • Warning systems	• Public transport priority • Fleet management • Navigation systems • Electronic ticketing • System integration • High-speed ground transportation • Real-time Information
Customer satisfaction	• CCTV cameras • Lane management • Warning systems • Electronic toll collection • Real-time information • Parking guidance	• Navigation systems • Parking guidance • Real-time information • Electronic toll collection • Docking systems • Warning systems	• Real-time information • System integration • Electronic ticketing • CCTV cameras

2-3 What is an Automated Highway System?

The Automated Highway System (AHS) concept defines a new relationship between vehicles and the highway infrastructure. AHS refers to a set of designated lanes on a limited access roadway where specially equipped vehicles are operated under completely automatic control *[Rilings, 1997]*. AHS uses vehicle and highway control technologies that shift driving functions from the driver/operator to the vehicle. Throttle, steering, and braking are automatically controlled to provide safer and more convenient travel. AHS also uses communication, sensor and obstacle-detection technologies to recognize and react to external infrastructure conditions. The vehicles and highway cooperate to coordinate vehicle movement, avoid obstacles and improve traffic flow, improving safety and reducing congestion. In sum, the AHS concept combines on-board vehicle intelligence with a range of intelligent technologies installed onto the existing highway infrastructure and communication technologies that connect vehicles to highway infrastructure *[Cheon, 2003].*

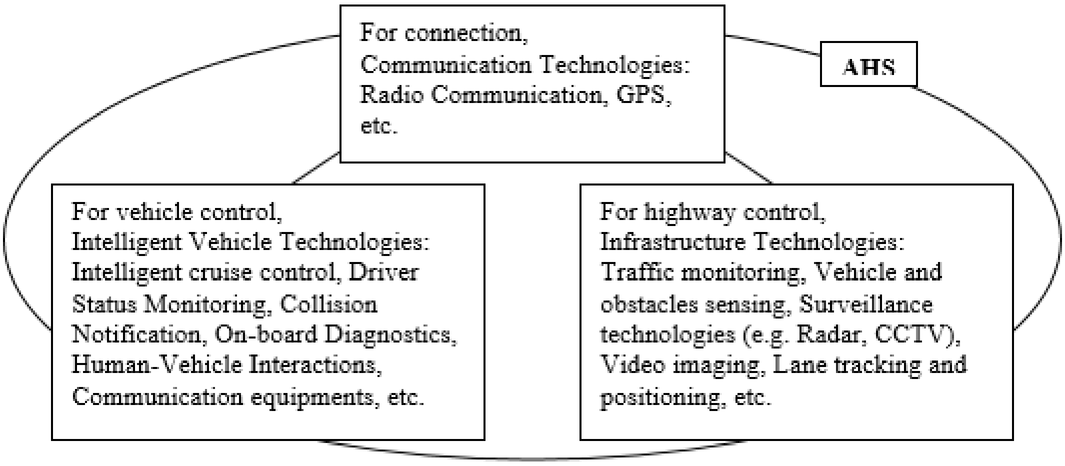

Figure 2-1 AHS Concepts of technologies *[Cheon, 2003].*

2-4 The origin of AHS

The idea of automated driving dates back more than 50 years, when General Motors (GM) presented a vision of “driverless” vehicles moved under automated control at the 1939 World’s Fairs in New York. In the late 1950, research by industrial organizations conceptualized automated vehicles controlled by mechanical systems and radio controls. After the first appearance of computers in the 1960s, researchers began to consider potential uses of computers to provide lateral and longitudinal control and traffic management. The fully automated highway concept was initially examined by GM with sponsorship from U.S. Department of Transportation (DOT) during the late 1970s. In this period, the focus was placed on automated vehicles operating on a highway because the computers were not powerful enough to consider a fully automated highway *[Ioannou, 1997]*.

Advances in computing technologies, microelectronics, and sensors in the 1980s provoked commercial interest in technologies that might enhance driver capabilities and perception, and both public and private sector researchers examined partially automated products and services. Among others, the University of California Partners for Advanced Transit and Highways (PATH) program has carried out significant research and development efforts in highway automation since 1980s. As various advanced transportation technologies emerged that could assist driving, on one hand, and enhance traffic efficiency, on the other, interest in fully automated driving -or integrated automated highway technologies- grew once again *[Ioannou, 1997].*

With the passage of the 1991 Intermodal Surface Transportation Efficiency Act (ISTEA) efforts were focused on early prototype development and testing of fully automated vehicles and highways. The Act prompted the U. S. DOT to establish the National Automated Highway System Research Program (NAHSRP), whose goal was to develop specifications for a fully automated highway system concept, which would support the improvement relevant technologies *[Ioannou, 1997].*

2-5 The current Issues of AHS technologies

Presently, the field of AHS faces some important problems and needs to resolve some important issues. Three of the most important issues that challenge AHS researchers and advocates today are *[Postema, 1998]*:

- Mixed Automated/Manual Traffic or Dedicated AHS Lanes
- Low Level or High Level of Intelligent Highway Infrastructure
- Liability

It is important to find solutions that are technologically feasible, socially acceptable, and that accomplish the appointed program goals. Much research is being done on these three issues as they relate to human factors, economic impact, land use impact, traffic safety and efficiency, and cost to benefit ratios. In this thesis we will focus on the first part of Mixed Automated/Manual traffic. An overview of the subject is presented below.

The mix of automated and manual traffic in highways or in any kind of driving situation is the most challenging task at hand for ITS researchers. Most of the research in automated driving and simulations on the subject are with the assumption that all vehicles are equipped with automatic features and none is manually handled. A different solution to this is dedicated lanes, which are separate lanes built for automated use only.

For the first few years of AHS under the ISTEA (Intermodal Surface Transportation Efficiency Act) legislation, the major thinking among engineers was to plan for dedicated lanes. Many factors influenced that decision; most importantly, they did not know how to deal with the random factor of human drivers. Scientist involved in the research knew that if they could control and coordinate every vehicle on a set of dedicated lanes, traffic accidents and slowdowns could be considerably reduced or even eliminated. This control would eliminate the human error that causes accidents and slows traffic. A reason for dedicated lanes was that proposed systems of that time (1991-95) were very infrastructure dependent. Planners thought that automated lanes would need to be highly specialized, therefore should be reserved for automated vehicles, and not crowded by manual vehicles *[Postema, 1998].*

The largest factor that led scientists to consider a mixed traffic scenario was cost. Many urban areas that could benefit most from AHS simply have no room to add more lanes to existing highways *[Postema, 1998].*

All of these factors have led scientists and planners to more closely consider a mixed traffic scenario. Such a mixed traffic would solve the problems of cost, equity, and the large infrastructure investment, but some of the safety and efficiency benefits would be lost or reduced. Engineers hoped to completely eliminate traffic accidents by using dedicated lanes. However, in a mixed traffic scenario, the most they could hope for is that no automated vehicles would be the cause of an accident. Efficiency would also be reduced, since high speed close-spaced platooning could cause a safety hazard in mixed traffic *[Postema, 1998].*

2-6 Intelligent infrastructure vs. intelligent vehicles

Infrastructure intelligence

This is the extreme case in which the infrastructure assumes full control over the highway vehicles. This means that the vehicles must possess some communication equipment and actuators for throttle, brake, and steering. There would be a need for a communication beacon placed in the infrastructure every 100 meters or so, especially when there are curves in the roadway. Additionally, the infrastructure would control merging lane changing and platooning of each vehicle. Computer systems capable of running such a system would be very expensive and must be 100% reliable. Obviously, this is an extreme scenario, but some things can be learned about the advantages and disadvantages of an intelligent infrastructure from it *[Postema, 1998].*

Vehicle intelligence

On the other side of the spectrum there would be complete vehicle automation with no assist from the infrastructure. In this case the vehicles would need to be able to read lane striping, sense other vehicles and obstacles, and communicate with other AHS equipped vehicles for platooning, merging, and lane changing maneuvers. There are projects that involve objectives such as using video imaging to distinguish lane striping or deliver other actions necessary but the problem in this case is the high processing power that would be needed to be equipped in each vehicle *[Postema, 1998].*

In the case where the most intelligence lies on the vehicles the cost of the system is passed on to the consumers as high buying costs for the vehicles. On the other hand if most of the intelligence is placed on the infrastructure it would cost probably billions of taxpayer money. So the balance must lie somewhere in between and we must always try to reduce the total cost of an AHS system in order to increase its appeal to the wider audience. The advantages of an infrastructure dependent system are safety and efficiency. One single controlling computer is less prone to errors than hundreds of onboard computers trying to make decisions on their own. Also infrastructure facilities have the advantage that they haven't limited space as vehicles do, they have ample amounts of power, and they can be better protected from harsh environments or accidents *[Postema, 1998].*

As for the advantages of vehicle based systems, the main one is that they have a much faster deployment than an infrastructure based system, due to the fact that it could take years to build an intelligent infrastructure when an intelligent vehicle can be produced in a far less time span. A second advantage is that a vehicle based system can be used in many more areas than a specifically chosen intelligent infrastructure. This system can be used on any road, not only the upgraded ones. And as mentioned before infrastructure based systems have a considerably higher cost *[Postema, 1998].*

The best solution should lie somewhere in between, combining infrastructure intelligence with vehicle intelligence in a way that lowers the overall costs and increases the system's safety and integrity. For example, the infrastructure is more suited for maneuver control of the vehicles and vehicle systems are better suited to sense other vehicles and obstacles *[Postema, 1998].*

2-7 Potential benefits of AHS

Researchers have attempted to estimate the benefits that might accrue from the implementation for automated highway systems. The following Table 2-2 summarizes the potential benefits *[Cheon, 2003]*. Many of the benefits shown are fairly speculative, the systems they would depend upon are not yet in existence and there is no clear evidence that the system can produce the following benefits in reality but they can definitely become reality in the next decades *[Cheon, 2003]*.

Table 2-2: Benefits of AHS Technologies *[Cheon, 2003].*

Element	Benefits
Roadway capacity	More vehicles can be accommodated on the highway. The number of vehicles per hour per lane can be significantly increased as traffic speeds are standardized and increased and headway distances are decreased. It is expected that two to three times more vehicles could be accommodated through elimination of inefficiencies caused by inattentiveness, merging, weaving, and lane changing.
Safety	Driving safety will be significantly greater than at present. The human error factor will be removed. Some estimates state that overall 50 percent improvement can be realized with AHS application.
Weather	Weather and environmental conditions will impact little on high performance driving. Fog, haze, blowing dirt, low sun angle, rain, snow, darkness, and other conditions affecting driver visibility and thus, safety and traffic flow will no longer impede progress.
Mobility	All drivers using AHS can be safe, efficient drivers. AHS offers enhanced mobility for people with disabilities, the elderly, and less experienced drivers.
Energy consumption and air quality	Fuel consumption and emissions can be reduced. In the short term, these reductions will be accomplished because started-and-stop driving will be minimized and because on-board sensors will be monitored to ensure that the vehicle is operating at top performance. In the long term, the AHS can support future vehicle propulsion/fuel designs.
Land use	Land can be used more efficiently. Roads will not need to take up as much room, since AHS facilities should allow for more effective use of the right of way.
Commercial and transit efficiency and economic gains	More efficient commercial operations and transit operations. Commercial trucking can realize better trip reliability to support “just-in-time” delivery. And, transit operations can be automated, extending the flexibility and convenience of the transit option to increase ridership and service.
Travel time savings and economic gains	Travel time savings: AHS can restore free-flow travel conditions from congested speeds in urban highway travel, thereby reducing the travel times. In addition, for long-distance intercity travel, it permitted higher cruising speed than today’s driving. Therefore, time that AHS frees up could be used for other purposes.[14]

As the table indicates, it is expected that automated highway and related advanced vehicle control and safety technologies would significantly reduce traffic congestion and enhance safety in highway driving in the near future. This in turn would potentially reduce travel time, and consequently, driving would be more predictable and reliable *[Cheon, 2003]*.

Chapter 3

Literature Review

In this chapter, we will review some of the most popular Lane Changing and Acceleration models.

3-1 Acceleration Models

Acceleration models can be categorized into two groups *[Ahmed, 1999]*:

- Car following models, and
- General acceleration models

The car following models capture acceleration behavior in the car following regime. Under such conditions the drivers are close to their leading cars and follow them. The general acceleration models capture acceleration behavior in both the car following and free flow conditions. In the free flow conditions, drivers are not close to their leaders and have the freedom to attain their desired speed *[Ahmed, 1999].*

Drivers' acceleration behavior, when they are under the car following conditions, has been studied extensively since the 1950s. Simple analysis was used to estimate the models in most of the considered cases. Various researchers started paying attention to the acceleration behavior in the free flow regime in the early 1980s, as microscopic simulation software emerged as an important tool for studying traffic behavior, developing and evaluating various traffic flow control strategies *[Ahmed, 1999]*.

3-1-1 Car Following Models

The general form of the car following models developed in the late 1950s is as follows *[Ahmed, 1999]*:

$$\text{Response}_n(t) = \text{sensitivity}_n(t-\tau_n) \times \text{stimulus}_n(t-\tau_n) \tag{3.1}$$

where,

t = time of observation,

τ_n = reaction time for driver n

$\text{response}_n(t)$ = acceleration applied at time t.

The reaction time τ_n includes the perception time (time from the presentation of the stimulus until there is the appropriate reaction) and the kinetic reaction time. The front relative speed is generally considered as the stimulus, while sensitivity is a proportionality factor, which may be a function of various factors, such as speed or space headway.

[Chandler et al., 1958] developed the first car following model that is a simple linear model. Mathematically, the model can be expressed as

$$a_n(t) = a \times \Delta V_n^{front}(t-\tau_n) \tag{3.2}$$

where,

$a_n(t)$ = acceleration applied by driver n at time t

a = constant

$\Delta V_n^{front}(t-\tau_n)$ = stimulus

$V_n(t-\tau_n)$ = subject speed at time $(t-\tau_n)$

$V_n^{front}(t-\tau_n)$ = leader vehicle speed at time $(t-\tau_n)$

A driver responds to the stimulus at time $(t-\tau_n)$ by applying acceleration at time t. The same sensitivity terms are used for both the acceleration and deceleration conditions. They estimated the model using the correlation analysis method and microscopic car following data.

The car following model developed by *[Gazis et al., 1961]*, known as the *General Motors Nonlinear Model*, is the most general one. The model can be mathematically described as follows:

$$a_n(t) = a \times \frac{V_n(t)^{\beta}}{\Delta X_n(t-\tau_n)^{\gamma}} \Delta V_n^{front}(t-\tau_n) \tag{3.3}$$

Where α, β, and γ are model parameters.

[Leutzbach, 1988] proposed a psycho-physical spacing model, which addresses two limitations of the car following models from a behavioral point of view. The first observation is that drivers do not follow their leaders at large spacings, while the second observation is that drivers cannot perceive small differences in front relative speeds; therefore, drivers do not react to such differences. *[Leutzbach, 1988]* introduced the term “perceptual threshold” in order to define a relative speed threshold, which is a function of space headway. This threshold is smaller at low space headways and gradually increases with larger ones. A driver reacts to the stimulus (the front relative speed) only when the stimulus exceeds the perceptual threshold. At a certain large space headway, the threshold becomes infinity, which means that the driver no longer follows its leader beyond that space headway.

3-1-2 Acceleration Models

The models presented above apply to the car following conditions only. When the headways are large, drivers do not follow their leaders, instead they try to attain their desired speeds. The development of an acceleration model for the free flow regime is very important for microscopic simulation models.

[Gipps, 1981] developed the, well known, first general car following model, which is applicable to both the car following and free flow conditions. The proposed model calculates a maximum acceleration for a driver in order the speed would not exceed a desired speed, and the clear gap would be at least a minimum safe distance. Mechanical limitations of vehicles were captured by introducing the following parameters: maximum acceleration, and most severe deceleration. The motion laws have been used in the above computations.

[Benekohal and Treiterer, 1988] proposed a car following simulation model, called CARSIM, used to simulate traffic in both normal and stop and go conditions. The acceleration for a vehicle is calculated for five different situations and the most binding acceleration is used to update the vehicle's speed and position. These situations are the following:

- The following vehicle is moving but has not reached its desired speed.
- The following vehicle has reached its desired speed.
- The following vehicle was stopped and starts from a standstill position.

- The following vehicle's movement is governed by the car following algorithm, in which a space headway constraint is satisfied.
- The following vehicle is advancing according to the car following algorithm with a non-collision constraint.

A comfortable and a maximum allowable deceleration are assumed to limit the output from the acceleration models within a reasonable boundary.

[Yang and Koutsopoulos, 1996] developed a general acceleration model that is used in MITSIM, a microscopic traffic simulator. Based on headway, a driver is assigned to one of the three following regimes:

- The emergency regime, if the current headway is less than a lower threshold.
- The car following regime, if the current headway is greater than the lower threshold but less than the upper threshold.
- The free flow regime if the current headway is greater than the upper threshold.

In the emergency regime, a driver applies the necessary deceleration to avoid colliding with its leader and increase headway.

3-2 Lane Changing Models

Most of the developed lane changing models use a gap acceptance algorithm in order to decide whether the vehicle is able to change lanes or not.

[Gipps, 1986] presented a lane changing decision model to be used in a microscopic traffic simulator. The model was designed to cover various urban driving situations, where traffic signals, obstructions, and the presence of heavy vehicles affect a driver's lane selection decision. Three major factors have been considered in the lane changing decision process: necessity, desirability, and safety. Various driving conditions have been examined, including the ones where a driver may face conflicting goals *[Ahmed, 1999].*

CORSIM is a microscopic traffic simulator, which uses FREESIM in order to simulate freeways, and NETSIM in order to simulate urban streets. In CORSIM, a lane change is classified as either mandatory (MLC) or discretionary (DLC). A driver performs an MLC when the driver must leave the current lane; it performs a DLC when the driver perceives the driving conditions in the target lane to be better, but, a lane change is not required. A risk factor that is acceptable to the driver is used in order to determine the necessity or desirability of changing lanes, which is a function of a driver’s position relative to the object that gives rise to the need for a lane change. *[Yang and Koutsopoulos, 1996]* developed a rule-based lane changing model, which is applicable only for freeways, implemented in MITSIM. Unlike Gipps’ model *[Gipps, 1986]*, they used a probabilistic framework to model drivers' lane change behavior when they face conflicting goals. A driver considers a discretionary lane change only when the speed of the leader is below a desired value, and checks neighboring lanes for opportunities to increase its speed. Two parameters, impatience factor and speed indifference factor, have been used to determine whether the current speed is low enough and the speeds of the other lanes are high enough to consider a DLC.

Chapter 4

The Lane Changing Model

4-1 Microscopic Traffic Simulator

The traffic simulator used for the lane changing project is Aimsun. Aimsun is a traffic modeling software with numerous functions and capabilities. In this thesis it is used as a microscopic traffic simulator. Aimsun's built-in car following and lane changing behavioral models are based on Gipps car-following and lane changing models.

The Aimsun API module offers the possibility to extend the functionalities of the basic Aimsun simulation environment by including user-defined applications in C++ or Python, which can exchange information dynamically with the Aimsun module. Additionally, the Aimsun microscopic simulator includes the MicroSDK tool, which, among others, allows for the modification or replacement of the incorporated car-following and lane-changing models.

For the purposes of this work, we used all of the above mentioned tools, combined with an external database, to enable the required exchange of information between them. More specifically, the MicroSDK was used to implement the ACC car-following and lane changing model, as well as to store the vehicle speeds and positions in the database. The API was used to determine the Merging Sequence, as described in paragraph 4-6, by using the data stored in the database.

4-2 Objectives

- The first objective of this work is to develop an algorithm for Aimsun that performs Cooperative Lane Changing on Highways.
- The second objective is to combine the former algorithm with the existing one for Cooperative Merging of On-Ramp vehicles described in *[Ntousakis et al., 2014],* which we will describe further on.
- Finally, the goal of this thesis ισ be to develop a microscopic algorithm for Cooperative Merging of On-Ramp vehicles, which includes Cooperative Lane Changing before the on-ramp, in order to "prepare" the right lane for the incoming vehicles and produce a uniform flow between the lanes at the end of the acceleration lane.

4-3 Dual Leader ACC Algorithm

The dual leader sub routine is essentially the part of the code that calculates the acceleration, speed, and position of each lane changing vehicle during the lane changing process. These attributes are calculated in accordance to the Adaptive Cruise Control (ACC) model, which is used for all the vehicles simulated in the road system. Utilizing this algorithm the lane changing vehicle is designated 2 leaders, one natural in the current lane of the vehicle and one virtual in the target lane based on its position. The algorithm then calculates two different accelerationς, one for each leader, and selects the most restrictive (smaller). Afterwards, based on the selected acceleration and the simulation step, it calculates the velocity and the position of the vehicle in the next step of the simulation.

4-4 Cooperative Lane Changing Algorithm

The goal of the development was to create a simulation for cooperative lane changing between the lanes of a highway, which means that the vehicles in the target lane will cooperatively modify their speed in order to accommodate the lane changing vehicle. Two algorithms were developed for this purpose. The differentiating attribute is the selection of the lane changing vehicles. The first one utilizes the Aimsun's decision making for when and where the vehicles will change lane and the other one uses a stochastic substitute to select the vehicles that will change lane and their location. The latter was selected to use in the test case and the simulations so this is the one we will analyze in the current chapter.

The lane changing routine uses a section for the cooperative lane changing to take place. When this section has been selected, we can select a specific percentage of cars that join the section to lane change within its length. Once a car enters the section it is given a random number ranging from 0 to 100. If that number is lower than the set percentage the car joins the queue of cars to lane change. Simultaneously, it is given a random number in the range of the section length to represent the position at which the vehicle will commence the lane changing attempt.

At the time that the lane changing vehicle reaches the lane changing position in the section, the lane changing process starts. The vehicle, its offsets in the target lane (virtual leader-follower), and its current lane before the lane changing are stored in the same line of different matrices as follows (Figure 4-1):

LaneChangingIDs

...
...
....
Id=15
...
...

LaneChangingList

Id of Downstream Vehicle on target lane	Id of Upstream Vehicle on target lane	Current lane
...	...	...
...	...	...
...	...	...
Id=13	Id=20	1
...	...	...
...	...	...

Figure 4-1 A vehicle with Id equal to 15 is registered for lane change.

After the vehicle has been registered in the LaneChanging matrices, the dual leader ACC car-following kicks in. When a vehicle in the car following section of the algorithm is identified as enlisted in the LaneChangingIDs database, it is forced into a dual leader car following mode by using as virtual leader the id stored in the LaneChanging Matrix. In a similar reasoning, when a vehicle with an Id matching the second column of the LaneChanging matrix enters the car following it is forced into a dual leader mode with the vehicle Id that's in the same row in the "LaneChangingIDs" matrix. In this manner the gap for the lane changing vehicle is created. An important thing to notice is that the virtual leader never accelerates in order to accommodate the lane change.

For every simulation step after the lane changing process has started, the gap opposite to the lane changing vehicle in the target lane is checked and, when it reaches acceptable margins, the vehicle completes the lane change. In the first simulation step after the lane change has been completed the subject vehicle is removed from the LaneChangingIDs and LaneChanging matrices and is resuming its default car following mode.

Two flowcharts of the lane changing process are presented in the following page. The first is for a lane changing algorithm in which the lane changes are not controlled, and the second is for a lane changing algorithm that controls which cars will perform a lane changing maneuver.

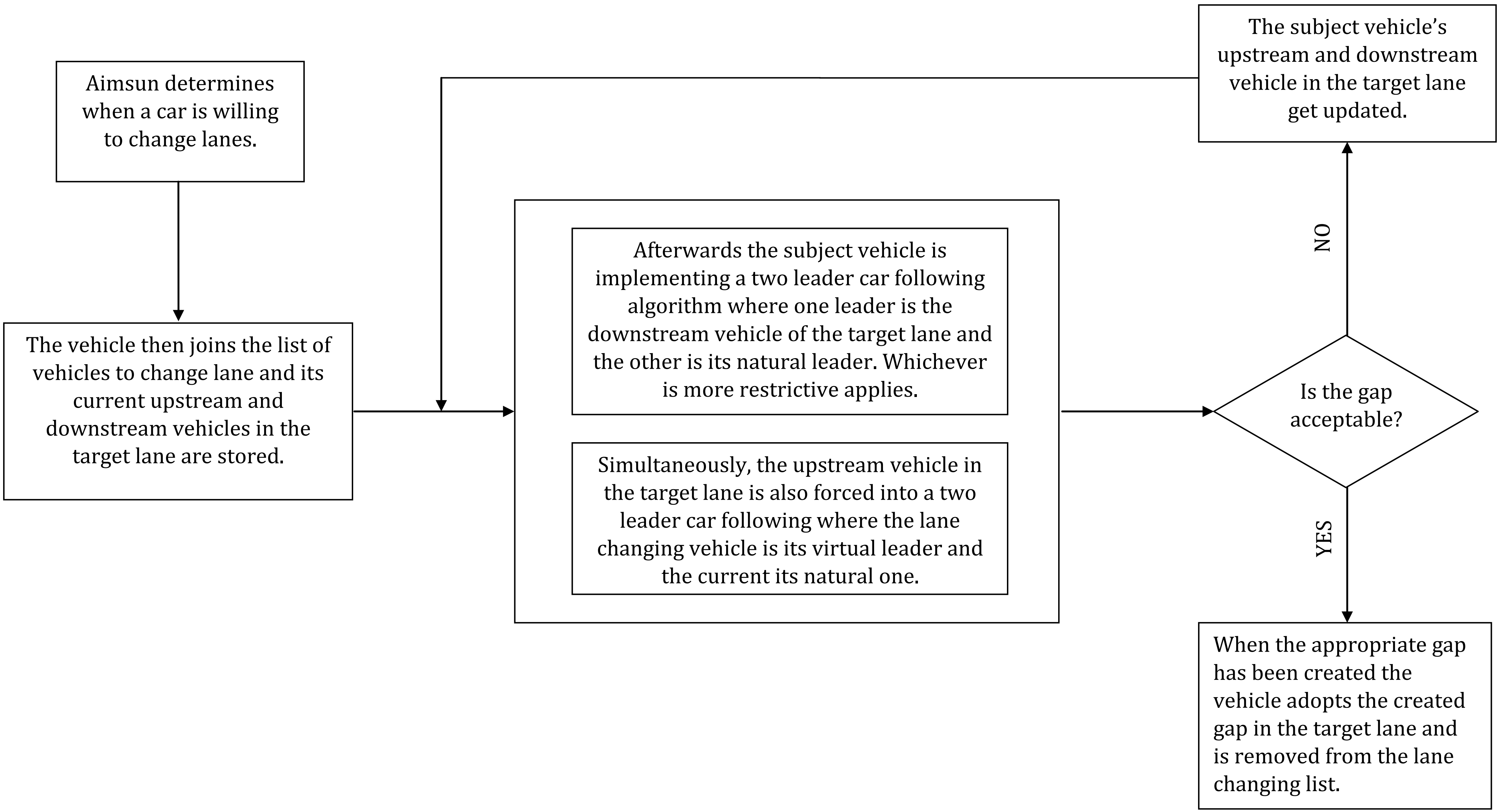

Figure 4-2 Lane Changing Flowchart 1.

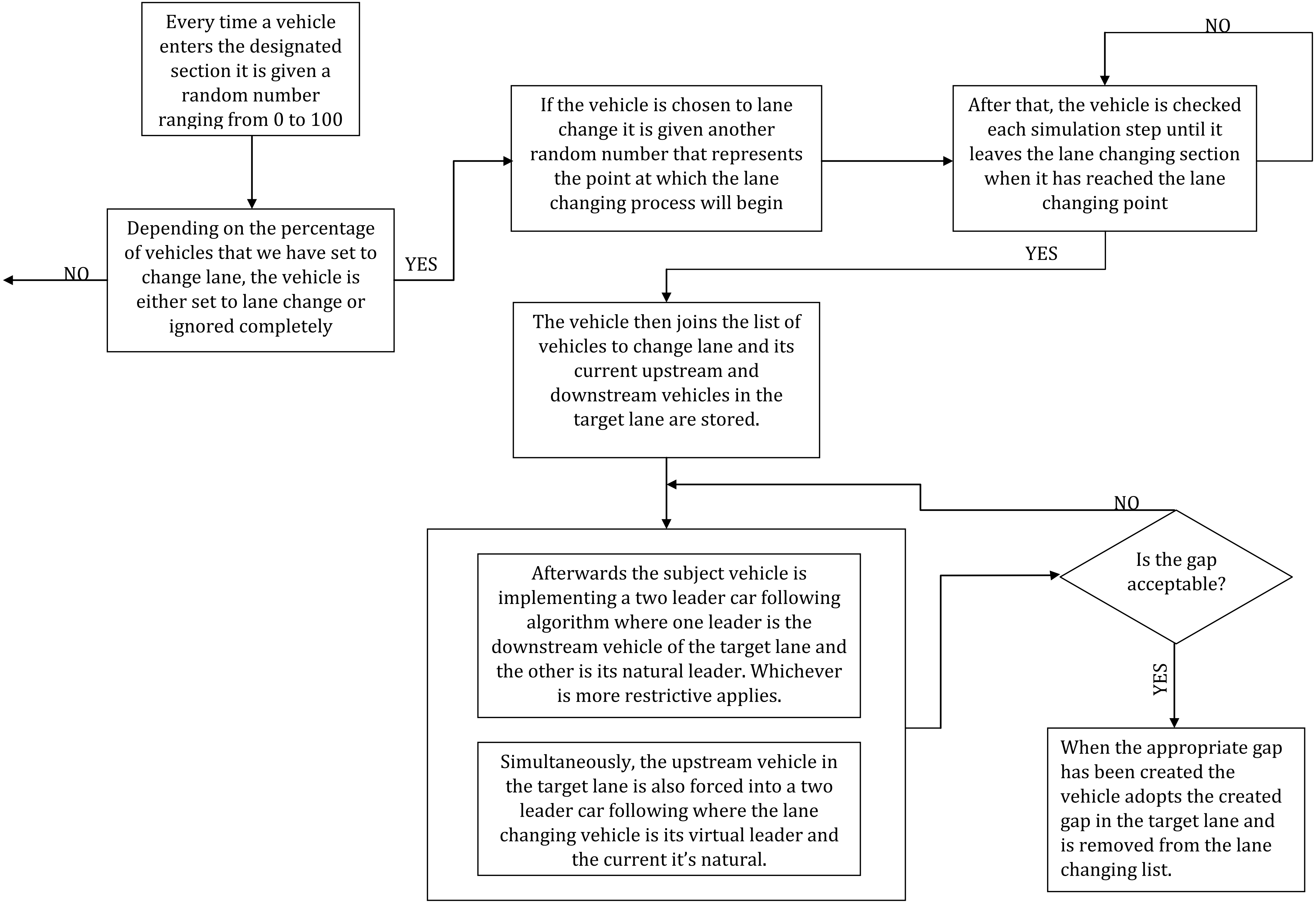

Figure 4-3 Lane Changing Flowchart 2.

4-5 Cooperative Merging of On-Ramp Vehicles

This is the second algorithm that will be used on the unification process. The goal is to create a merging procedure that is as smooth and efficient as possible for both the merging and the highway vehicles. The algorithm was developed by *[Ntousakis et al., 2014].* This merging algorithm tries to determine the merging sequence in such a way that unnecessary decelerations (in the on-ramp and in the mainstream) are mitigated. To this end, the (projected) time to merging point is used to determine the insertion gaps for merging vehicles. The time to merging point is calculated (and updated) according to the current vehicle speed and its distance from the merging point.

More specifically, each new mainstream vehicle entering the cooperation area is placed at the end of the merging sequence since, for physical reasons, its time to MP will be longer than for preceding mainstream vehicles. On the other hand, for each merging vehicle entering the cooperation area, its net time to MP is calculated and is augmented by a typical time-headway to mitigate sharp merging maneuvers; eventually, the merging vehicle is inserted in the MS according to the updated times to MP of all MS vehicles behind the last merging vehicle (whose insertion gap cannot be modified).

In the snapshot of Fig. 4-4, the current merging sequence includes vehicles 3, 2, 4, 5, and 6. Notice that the numbers used in Fig. 4-4 are completely random and serve only as IDs for the corresponding vehicles. A new merging vehicle (ID: 1) is entering the cooperation area and automatically retrieves the speeds and positions of all the vehicles inside this area (through V2V or V2I communication in reality). Then, the previous merging vehicle in the merging sequence is identified (in this case the vehicle with ID: 2).

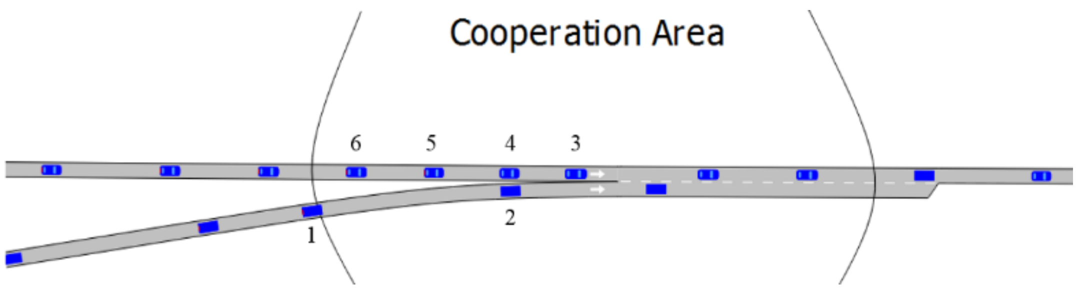

Figure 4-4 Example of gap selection for the 2nd algorithm.

Consequently, the possible gaps to enter are those formed behind this vehicle, namely the gaps between vehicles 2-4, 4-5, 5-6 and the gap behind vehicle 6. For all the vehicles involved in the formation of the previously mentioned gaps (vehicles 2, 4, 5, and 6), the algorithm, running in the entering vehicle (ID: 1), estimates their time to MP, based on their current speeds. These times are subsequently compared to its own (augmented) time to MP, and the new entering vehicle is placed in an accordingly updated MS. In the considered example let us assume that the following sequence of times to MP are computed: $t_2 < t_4 < t_1 < t_5 < t_6$. Therefore, the algorithm decides that vehicle 4 will be the new leader for vehicle 1, which will be the new leader for vehicle 5; the updated merging sequence results as 3, 2, 4, 1, 5, 6.

The outlined algorithmic logic guarantees the merging of vehicles from the on-ramp. However, in case of strong ramp demand, this may be to the detriment of the mainstream traffic, whose flow and mean speed may be accordingly lowered. If this situation is to be mitigated, additional constraints may be employed in the algorithm. For example, the merging vehicle should not be inserted in front of a mainstream vehicle with absolute distance to the merging point shorter than 45 m or speed lower than 10 m/s *[Ntousakis et. al., 2015].*

4-7 The Car Following Model

Regardless which of the two algorithms is used, the separate areas CA_1 or CA_2, we need to define how the appropriate gaps are formed by transforming them into acceleration or deceleration commands for the vehicles. As it was stated earlier in paragraph 4-6, it is assumed that all vehicles in the network are equipped with Adaptive Cruise Control (ACC) systems and are enabled with V2V communication capabilities; the consideration of a penetration rate of equipped vehicles lower than 100% is the subject of on-going research. The control law for this system is a Constant Time Gap control law, described by the following equations *[Ntousakis et. al., 2015].*

$$\ddot{x}_{i,des} = -\frac{1}{h_d}(\dot{\varepsilon}_t + \lambda\delta_i) \tag{4.1}$$

$$\varepsilon_i = x_i - x_{i-1} \tag{4.2}$$

$$\delta_i = x_i - x_{i-1} + h_d\dot{x}_i + L_{i-1} \tag{4.3}$$

with

$$max\_deceleration_i \le \ddot{x}_{i,des} \le max\_acceleration_i \tag{4.4}$$

$$0 \le \dot{x}_i \le max\_speed_i \tag{4.5}$$

where $\ddot{x}_{i,des}$ is the desired acceleration in m/s^2, h_d is the desired constant time gap in seconds, L_i is the length of the vehicle i, $\dot{x}_i$ is the speed of vehicle i, $max\_deceleration_i$ (which is a negative number) is the maximum admissible deceleration of vehicle *i*, $max\_acceleration_i$ is the maximum admissible acceleration of vehicle *i*, max_speed_i is the maximum desired speed of vehicle *i* and λ is a parameter set to 0.2 (Fig. 4-6).

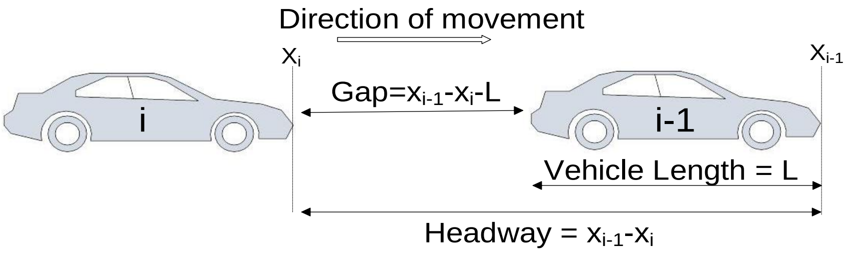

Figure 4-6 Schematic representation of the basic car-following parameters *[Ntousakis et. al., 2015].*

For the vehicles located inside the cooperation areas, we will use the term *"actual leader"* to refer to the next downstream vehicle on the same lane, and the term *"virtual leader"* to refer to the vehicle which is registered ahead the current vehicle *I* in the target lane or merging sequence.

The application of the car-following model calculates a (virtual) position for the virtual leader of each vehicle. Note that the virtual leader is different than the actual leader only if it is located on a different lane. Thus, the virtual leader is virtually moved to the lane of the vehicle in question; at a position in the section equal to its current position on its actual lane. We then have for each vehicle two possible cases:

1. Only one of the two leaders exists. The vehicle applies the equations above according to its actual or virtual leader.
2. Both leaders exist. The equations above are applied for both leaders; the most restrictive of both accelerations is selected.

Once the vehicle is out of the cooperation area, it will return to the standard ACC model, as previously described *[Ntousakis et al., 2015].*

Chapter 5

Simulations and results

In this Chapter we will present the simulations that were performed and their corresponding results.

5-1 The 1st Test case

The first simulation was performed utilizing the Lane Changing Algorithm that was mentioned earlier, on a two lane highway. During the simulation the algorithm was used to make the selection of the lane changing vehicles stochastically and after a vehicle had been selected for lane change, the dual leader sub routine kicked in performing a cooperative lane change at the designated position inside the highway. This algorithm was designed to only perform lane changes from the right lane towards the left lane.

5-1-1 Assumptions

The assumptions for this test case are less demanding than those of the final test case so it's closer to our current technologies and applications. The assumptions of the test case are the following:

- All vehicles have up-to-date access to the exact geometry of the network (lengths of the sections, on ramps and acceleration lanes etc.).
- All vehicles are equipped with Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communication systems with a sufficiently large range.

- Vehicles can exchange information regarding their current speeds, positions and neighboring vehicles (leader and/or follower) at a high sampling rate.
- After the targeted gap is selected, affected vehicles on the target lane are informed about their new virtual leader and adjust their speed to modify their gap or maintain the existing one.
- The whole cooperation process takes place inside pre-defined Cooperation Areas, CA_1.
- Vehicles are equipped with dual-leader ACC systems.
- An Upper-Level controller decides about the number of vehicles to change lane (inside CA_1) from right to left, depending on the on-ramp demand.
- Vehicles are equipped with Adaptive Cruise Control systems (ACC).

5-1-2 Test Case Layout

As we previously mentioned the test case consists of a two lane highway consisting of two sections. The first section is 420 meters long and no lane changes are performed on it. The second section is 700 meters long and is the designated section for the lane changing algorithm.

Once a Vehicle enters the cooperation area (CA1) the algorithm decides if it is a lane changing vehicle or not, and if it is, it is then given a random position inside the section at which the lane changing maneuver will take place.

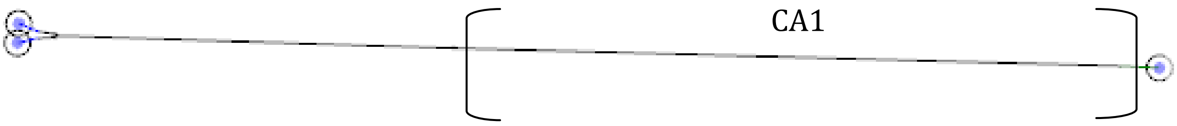

Figure 5-1 First case layout.

Four detectors were placed in total. The first two were placed on the start of CA_1 section each in one lane, and the other two were placed on the end of the CA_2 section in each lane accordingly. The purpose for this setup is to measure the change in flow between the two lanes before and after the cooperation area.

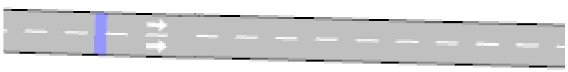

Figure 5-2 Entrance detectors.

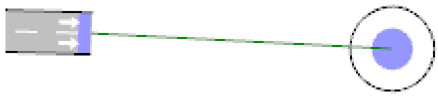

Figure 5-3 Exit detectors.

The input flows for the two lane highway are as follows:

- Right Lane Input 799 veh/h.
- Left Lane Input 877 veh/h.

5-1-3 1st Test Case Results

The simulation was performed 10 consecutive times for a different lane changing percentage of vehicles in Cooperation Area 1, ranging from 0% to 100% (Fig. 5-4).

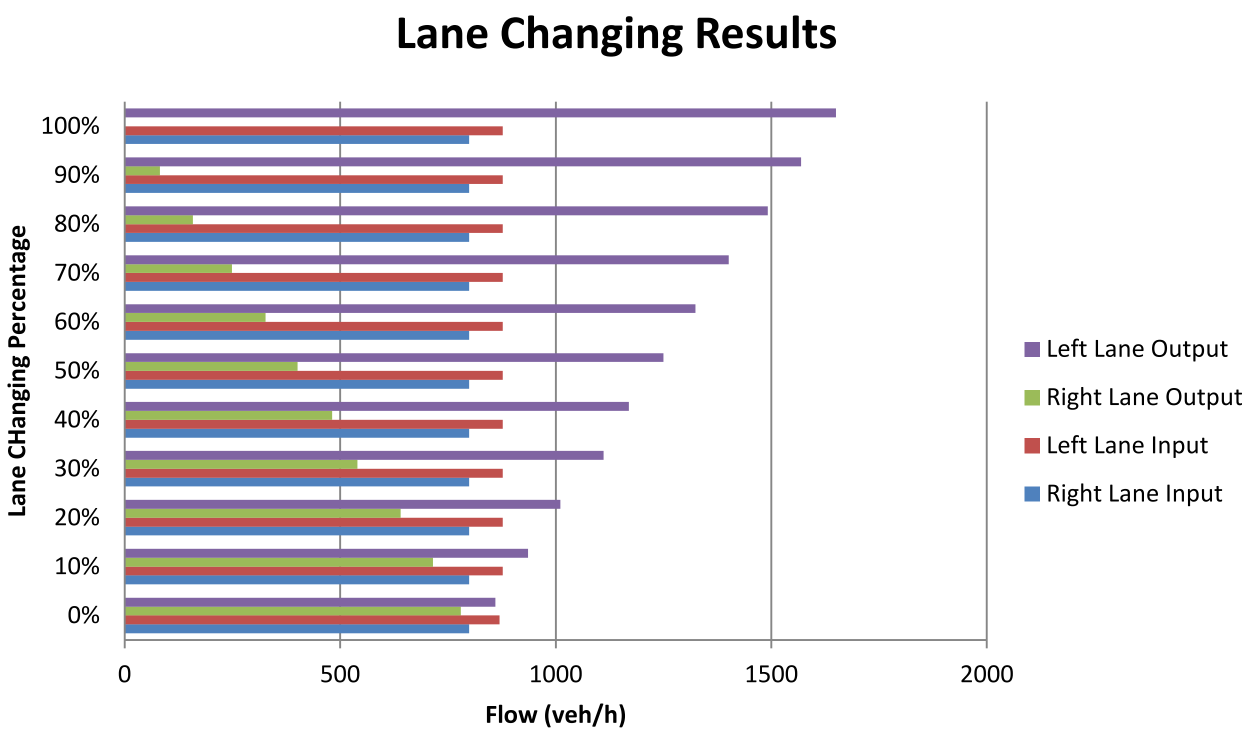

Figure 5-4 Cooperative lane changing simulation results for the 1st Test Case.

As we can see, the algorithm is performing as intended in all the different percentages for lane changing. This algorithm can be used to evenly distribute the flow between the lanes of the highway if necessary in order to smooth the density of each lane.

5-2 2nd Test Case

For this simulation we combined the lane changing algorithm with the Cooperative Merging algorithm. We assume two cooperation areas, the 1st for the Cooperative Lane Changing (CA_1), and the 2nd for the Cooperative merging (CA_2). The CA_1 is for the main highway, starts a few hundred meters before the on-ramp and ends at the on-ramp. The CA_2 ends at the Merging Point (MP). The purpose of this setup is to accommodate the inflow of on-ramp merging vehicles by setting a specific percentage of vehicles to lane change before the on ramp. The percentage of vehicles to lane change is decided by an Upper-Level controller depending on the on-ramp demand.

5-2-1 Assumptions

- All vehicles have up-to-date access to the exact geometry of the network (lengths of the on-ramps and acceleration lanes etc.).
- All vehicles are equipped with Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communication systems with a sufficiently large range.
- Vehicles can exchange information regarding their current speeds, positions and neighboring vehicles (leader and/or follower) at a high sampling rate.
- Vehicles can communicate and exchange data with more than one vehicle quasi-simultaneously.
- After the targeted gap is selected, affected vehicles on the target lane are informed about their new “virtual leader” and adjust their speed to modify their gap or maintain the already existing one.
- The whole cooperation process takes place inside pre-defined Cooperation Areas, **CA_1 for lane change** and **CA_2 for merging**.
- Vehicles are equipped with **dual-leader ACC systems**.
- An **Upper-Level controller** decides about the **number of vehicles to change lane** (inside CA1) from right to left, depending on the on-ramp demand.

- **All on-ramp vehicles are forced to merge** in the right lane of the highway. A ramp metering system upstream is controlling the flow in the on-ramp.

5-2-3 Test Case Layout

The test case layout consists of a two lane highway that expands for 700 meters, an on-ramp with an acceleration lane joins the highway, and then the highway continues for a few hundred meters. The first cooperation area (CA1), where the lane-changing algorithm is used, is located on the main highway. It starts a few hundred meters before the on-ramp and ends at the on-ramp. The second cooperation area is affected by the merging algorithm and it ends at the Merging Point (MP).

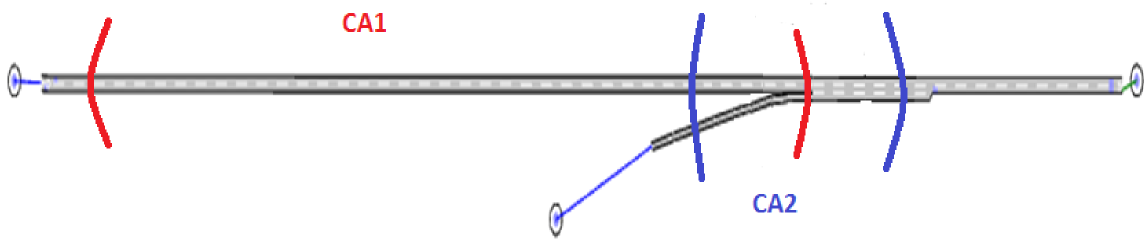

Figure 5-5 Final test case layout.

We can define the percentage of vehicles to lane change from the right to the left lane inside the first cooperation area.

We have placed 6 detectors in total. The first two are located on the entrance of the highway, one in each lane, the next two are located just before the second cooperation area, one in each lane, and the last two are located at the exit of the highway after the on ramp, again one in each lane.

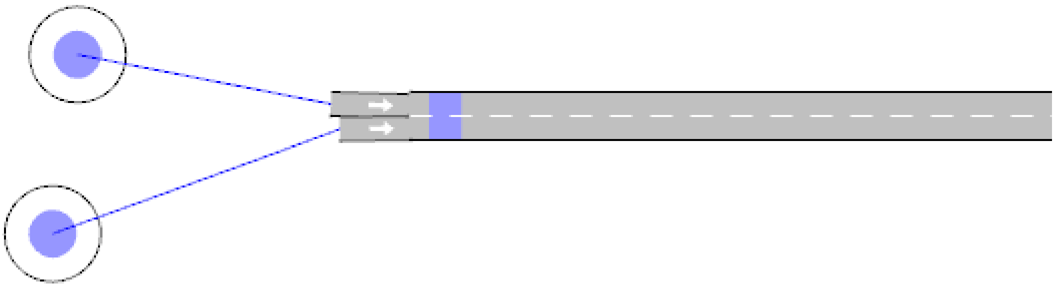

Figure 5-6 Highway entrance detectors.

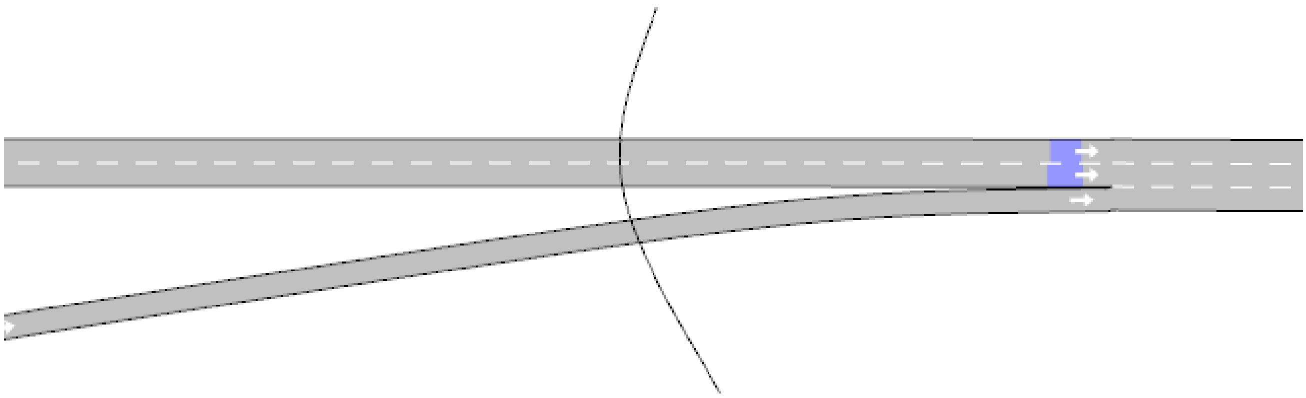

Figure 5-7 Detectors before on ramp.

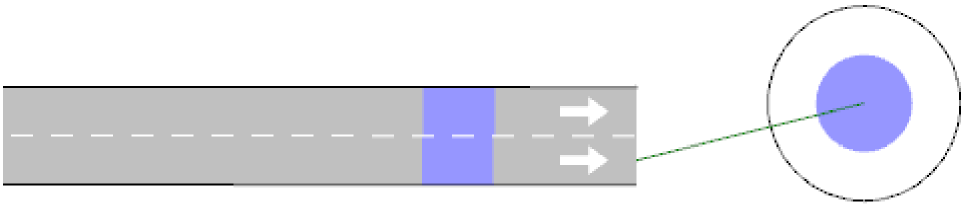

Figure 5-8 Exit detectors.

5-2-3 Medium Traffic Scenario Test Case Results

The Input flows for the simulation are:

- ~1500 veh/h for the left lane.
- ~1790 veh/h for the right lane.
- And ~600 veh/h for the on-ram.

The simulation was performed 10 consecutive times each one for a different lane changing percentage of vehicles in the first cooperation area ranging from 0% to 50% (Fig. 5-9).

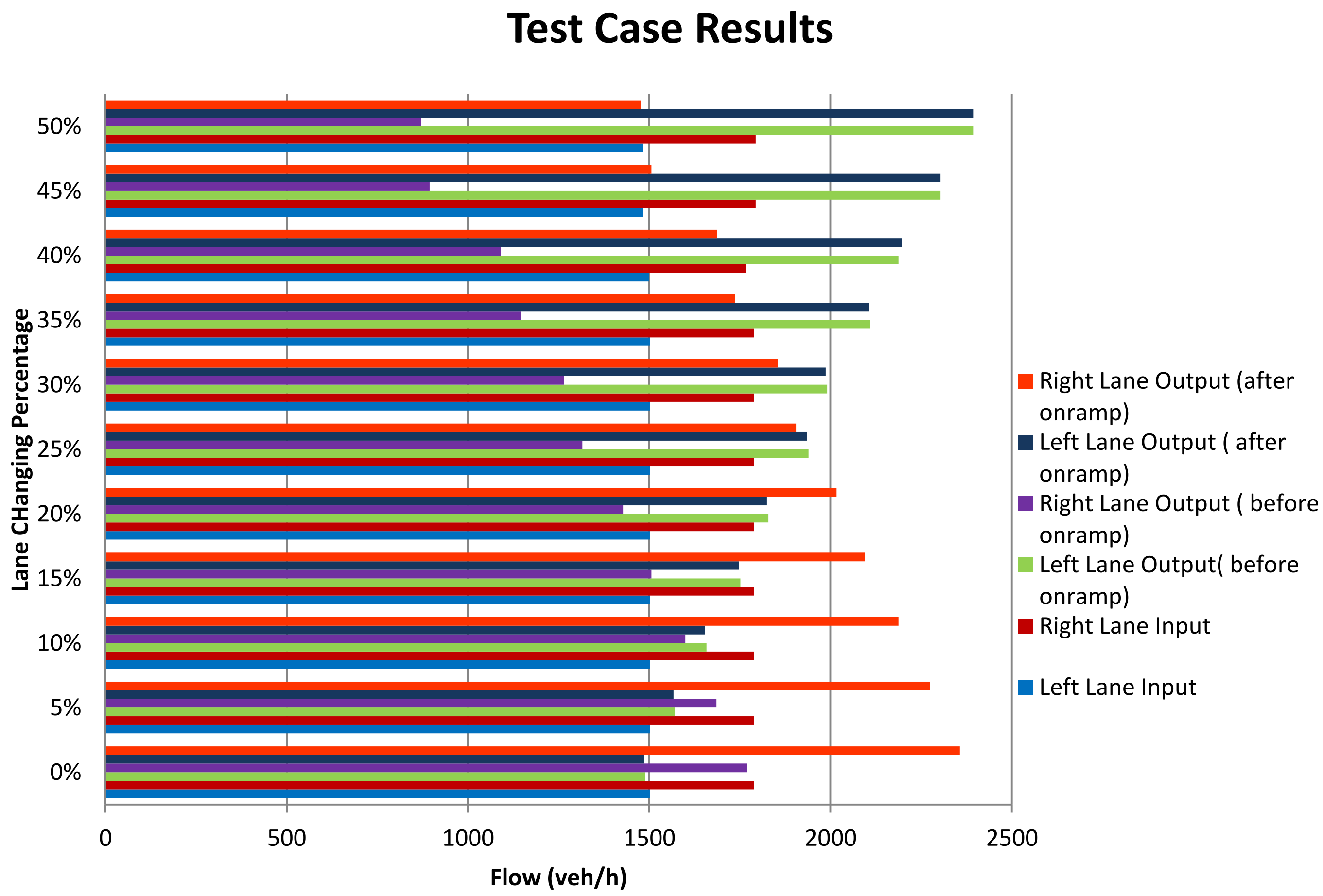

Figure 5-9 Final test case medium traffic simulation results.

As we can observe on the graph, in the case of 0% the right lane output after the on-ramp is really high thanks to the merging vehicles from the on-ramp, but as the percentage is increased we reach an equilibrium in the output of the two lanes in the percentage of 25%. This accommodates the merging vehicles to merge easily into the main highway with a lesser risk of collisions and reduced traffic at the section of the acceleration lane.

5-2-4 High Traffic Scenario Test Case Results

The Input flows for the simulation are:

- ~2000 veh/h for the left lane
- ~1900 veh/h for the right lane
- And ~600 veh/h for the on-ram

The simulation was performed 10 consecutive times as in the previous case each one for a different lane changing percentage of vehicles in the first cooperation area ranging from 0% to 50% (Fig. 5-10).

Figure 5-10 Final test case high traffic simulation results.

We can observe a similar distribution in this high traffic test case with the previous medium traffic test case. There is a very high traffic flow on the right lane when there are no lane changes performed. In this case though there is also a problem at the opposite end of the spectrum where 50% lane changes to the left lane are performed. In this lane changing percentage we can observe a serious congestion problem in the left lane of the first cooperation area where the lane changes are taking place (Figure 5-11). In addition, the same situation arises when there are no lane changes performed on the right lane in the second cooperation area (Figure 5-12). An equilibrium is achieved, which means minimal congestion on both lane ends, when the lane changing percentage is around 15% given the inflow of the on-ramp.

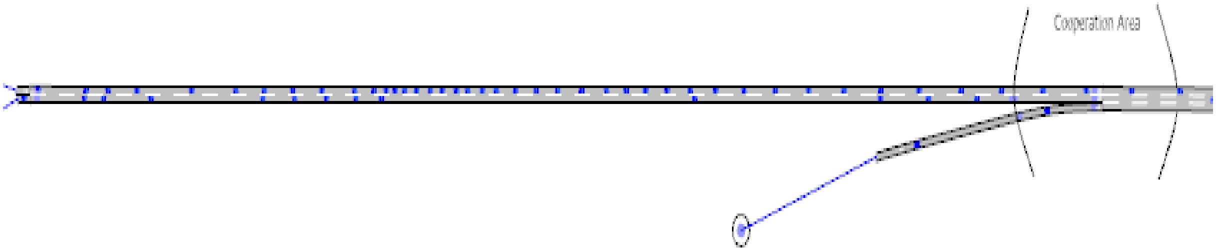

Figure 5-11 50% lane changing percentage simulation.

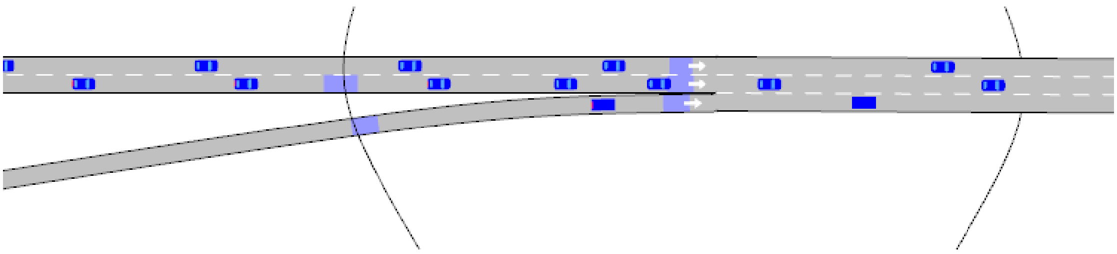

Figure 5-12 0% lane changing percentage simulation.

5-2-5 On-Ramp inflow fluctuation test case.

In this test case we examined the possible congestion situations in cooperation area 2 (on-ramp merging area) when the inflow from the on-ramp rises to a higher output. Each on-ramp inflow setting was tested using a selected percentage of cars to lane change in order to reach an equilibrium in the two lanes after the on-ramp and reduce the congestion in cooperation area 2. Afterwards, the same setting is tested with a 0% lane changing before the on-ramp, to be able to compare the effect of the lane changing.

The inflow settings that were tested for the on-ramp were 400 veh/h, 600veh/h, 800veh/h, and 1000veh/h. The highway inflows remain the same as for the high traffic test case.

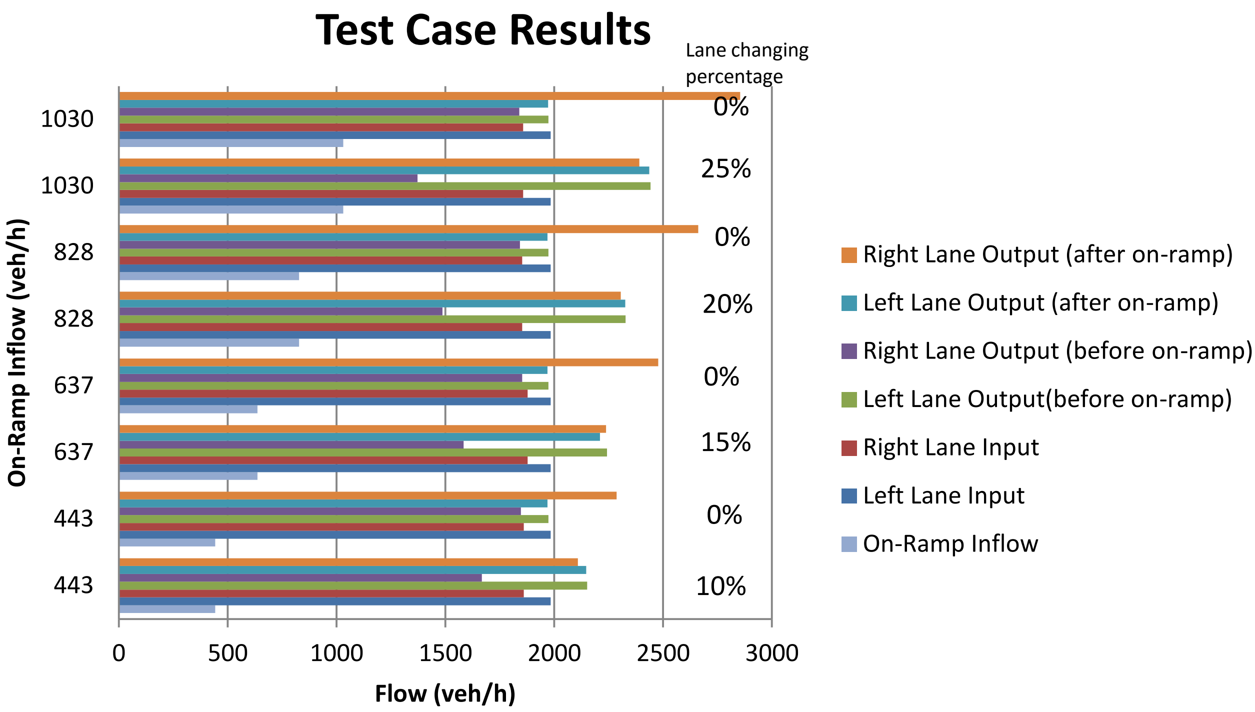

Figure 5-13 On-Ramp inflow fluctuation test case simulation results.

Traffic Setting 1: on-ramp inflow 443 veh/h.

In this scenario the on-ramp inflow is not sufficient for a congestion to manifest in cooperation area 2. An equilibrium is achieved for a lane changing percentage of 10%.

Traffic Setting 2: on-ramp inflow 600 veh/h.

In this scenario the traffic density in the on-ramp merging area is increased significantly at times but it is not at a point where it can be called congestion. An equilibrium is achieved for a lane changing percentage of 15%.

Traffic Setting 3: on-ramp inflow 800 veh/h.

This time cooperational area 2 is populated by heavier traffic and displays a congestion of medium intensity in the section just before the on-ramp. An equilibrium for the two lanes and an alleviation of the congestion is achieved for a lane changing percentage of 20%.

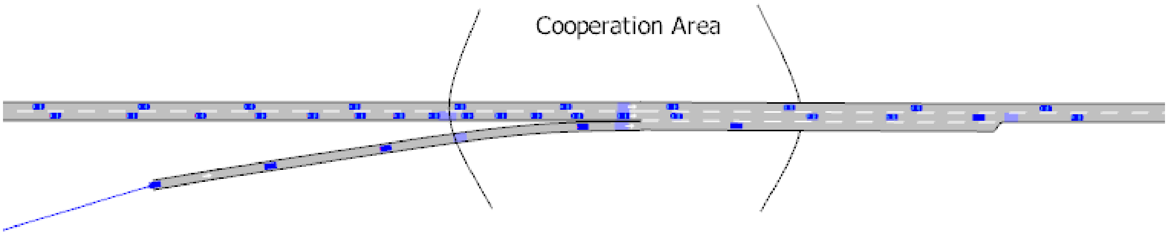

Figure 5-14 0% lane changing percentage simulation.

Traffic Setting 4: on-ramp inflow 1000 veh/h

In this setting the right lane of the highway before the on-ramp gets severely congested as well as the inflow of the on-ramp. An equilibrium for the two lanes and an alleviation of the congestion is achieved for a lane changing percentage of 25%.

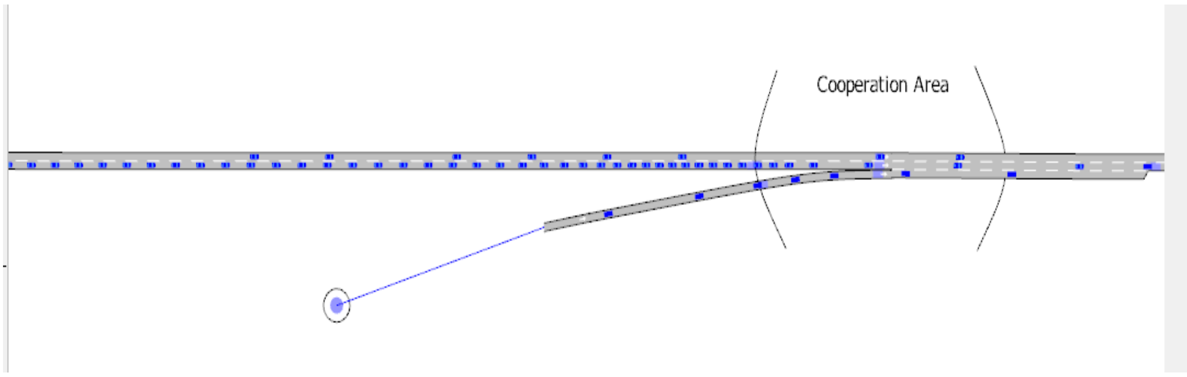

Figure 5-15 0% lane changing percentage simulation.

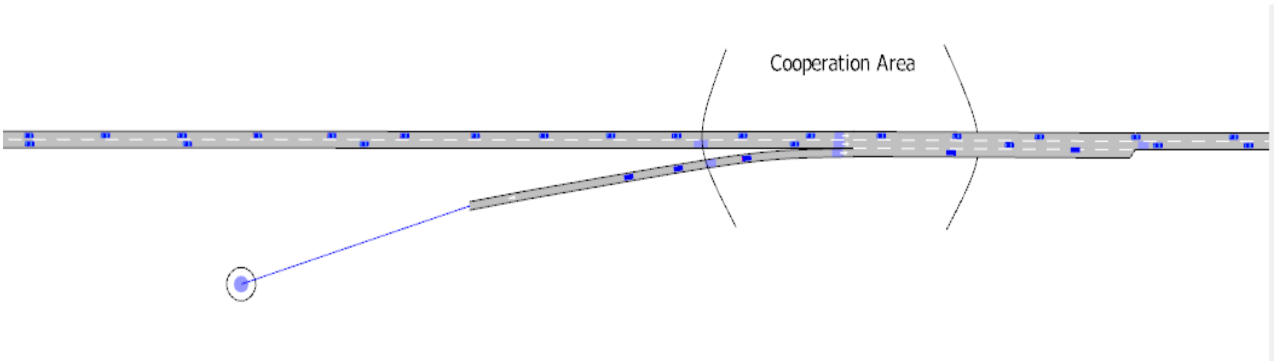

Figure 5-16 25% lane changing percentage simulation.

Chapter 6

Conclusions

In this work a simulation environment was developed in order to test cooperation strategies between vehicles, in order to change their lanes before an on-ramp. The goal is to have equally-distributed flows between the lanes after the on-ramp, more gaps available for the entering vehicles from the on-ramp, and mitigation of congestion. The simulation results demonstrated that the developed algorithms provide rational results. Moreover, the cooperative lane-changing before the on-ramp can be a very useful tool to help the entrance of on-ramp vehicles.

We observed that on high traffic situations there is a lane changing percentage that will decrease the congestion on both ends of the on ramp and in both lanes. However, if the percentage isn't set to the correct amount, serious congestion issues may arise. The lane changing percentage will be set depending on the inflows of the right and left lanes at the entrance of the highway and at the inflow of the on-ramp.

The goal is that it will be possible to regulate the percentage of lane changing vehicles depending on the inflow rate of the on-ramp through an infrastructure controller. In this way we will achieve an efficient traffic distribution. There is already an endeavor to create the rules that this controller will apply in order to mediate the highway traffic accordingly.

Bibliography

Ahmed, K. I. (1999), Modeling drivers' acceleration and lane changing behavior, PhD Thesis, Massachusetts Institute of Technology.

Benekohal, R. F., Treiterer, J. (1988), "CARSIM: Car-following model for simulation of traffic in normal and stop-and-go conditions", Transportation Research Record, 1194.

Chandler, R. E., Herman, R., Montroll, E. W. (1958), "Traffic dynamics: studies in car following", Operations Research 6 (2), pp. 165-184.

Cheon, S. (2003), An overview of automated highway systems (AHS) and the social and institutional challenges they face, University of California Transportation Center (http://escholarship.org/uc/item/8j86h0cj).

Gazis, D. C., Herman, R., Rothery, R. W. (1961), "Nonlinear follow-the-leader models of traffic flow", Operations Research 9 (4), pp.545-567.

Gipps, P. G. (1981), "A behavioural car-following model for computer simulation."Transportation Research Part B: Methodological, 15 (2), pp. 105-111.

Gipps, P. G. (1986), "A model for the structure of lane-changing decisions", Transportation Research Part B: Methodological, 20 (5), pp. 403-414.

Ioannou, P. (Ed.) (1997), Automated highway systems, Springer Science & Business Media.

Leutzbach, W. (1988), Introduction to the Theory of Traffic Flow, Springer Publications.

Ntousakis, I.A., Porfyri, K., Nikolos, I. K., Papageorgiou, M. (2014), "Assessing the impact of a cooperative merging system on highway traffic using a microscopic flow simulator", ASME 2014 International Mechanical Engineering Congress and Exposition, IMECE2014.

Ntousakis, I. A., Nikolos, I. K., Papageorgiou, M. (2015), "On Microscopic Modelling of Adaptive Cruise Control Systems", Transportation Research Procedia, 6, 111-127.

Postema, L. D. (1998), Automated Highway Systems, Incremental Deployment as a Solution for the Future of Transportation, IEEE, WISE.

Vanderschuren, M. J. W. A. (2006), Intelligent transport systems for South Africa: impact assessment through microscopic simulation in the South African context. PhD Thesis, University of Cape Town - University of Twente.

Wahle, J., Schreckenberg, M. (2003), Information in Intelligent Transportation Systems, Interface and Transport Dynamics, Vol. 32 of the series Lecture Notes in Computational Science and Engineering pp. 301-316, Springer Berlin Heidelberg.

Yang, Q., Koutsopoulos, H.N. (1996), "A microscopic traffic simulator for evaluation of dynamic traffic management systems", Transportation Research Part C: Emerging Technologies, 4 (3), pp. 113-129.