ROYAUME DU MAROC
Université Mohammed V
- RABAT -
جامعة محمد الخامس
- الرباط -
Faculté des sciences
كلية العلوم

CENTRE D'ETUDES DOCTORALES - SCIENCES ET TECHNOLOGIES

N° d'ordre : 3106

THESE

En vue de l'obtention du : **DOCTORAT**

Structure de Recherche : Laboratoire de Recherche en Informatique et Télécommunications
Discipline : Sciences de l'ingénieur
Spécialité : Informatique et Télécommunications

Présentée et soutenue le : 19 mai 2018 par :

Hajar LAZAR

Modélisation et Simulation de la Mobilité urbaine du trafic routier

JURY

Pr. Ahmed HAMMOUCH	*PES, Ecole Normale Supérieure de L'Enseignement Technique, Rabat*	*Président*
Pr. Moulay Driss RAHMANI	*PES, Université Mohammed V, Faculté des sciences, Rabat*	*Directeur de thèse*
Pr. Salma MOULINE	*PES, Université Mohammed V, Faculté des sciences, Rabat*	*Rapporteur*
Pr. Abderrahim El QADI	*PES, Ecole Supérieure de Technologie, Salé*	*Examinateur*
Pr. Youssef FAKHRI	*PH, Université Ibn Tofail, Faculté des Sciences, Kénitra*	*Rapporteur*
Pr. Khadija RHOULAMI	*PH, Université Mohammed V, Faculté des Lettres et des Sciences Humaines, Rabat.*	*Encadrante*

Années Universitaire : 2017/2018

✉ Faculté des Sciences, avenue Ibn Battouta, BP. 1014 RP, Rabat –Maroc
☎ 00212(0) 37 77 18 76 📠 00212(0) 37 77 42 61 ; http://www.fsr.ac.ma

Modeling and Simulation of Urban Mobility of Traffic Roads

By
Hajar LAZAR

Faculty of Sciences Rabat
GSCM-LRIT Laboratory Associate Unit to CNRST (URAC 29)
Mohammed V University in Rabat
Morocco

Avant Propos

Les travaux présentés dans ce mémoire ont été effectués au Laboratoire de Recherche en Informatique et Télécommunications **(LRIT-CNRST 29)** de la Faculté des Sciences de Rabat(FSR), Université Mohammed V au Maroc, sous la direction du Professeur **Moulay Driss RAHMANI** et avec le co-encadrement du Professeur **Khadija RHOULAMI**.

Je commence par présenter ma plus vive gratitude à mon directeur de thèse Mr. **Moulay Driss RAHMANI**, Professeur de l'enseignement supérieur à la Faculté des Sciences de Rabat. Je tiens à lui exprimer ma reconnaissance pour sa grande disponibilité, sa rigueur scientifique, son enthousiasme et ses précieux conseils qui ont fait progresser ce travail. Qu'il soit assuré de toute mon estime et de mon profond respect.

Je tiens à exprimer mes vifs remerciements à mon co-encadrante Mme. **Khadija RHOULAMI**, Professeur habilité à la Faculté des Lettres et des Sciences Humaines de Rabat. Je vous remercie spécialement pour le temps et la patience que vous m'avez accordés tout au long de ces années en me fournissant d'excellentes conditions logistiques. Je garderai dans mon coeur votre générosité, nombreux conseils, votre soutien sans faille, votre disponibilité, et votre compréhension. Pour tout ce que vous m'avez donné, je vous remercie très sincèrement.

Je tiens également à remercier Mme. **Salma MOULINE**, Professeur de l'enseignement supérieur à la Faculté des Sciences de Rabat, pour l'honneur qu'elle m'a fait pour sa participation à mon jury de thèse en qualité de rapporteur de mon travail, pour le temps consacré à la lecture de cette thèse, et pour les suggestions et les remarques pertinentes qu'elle m'a indiquées.

J'aimerais exprimer toute ma reconnaissance et ma gratitude à Mr. **Ahmed HAMMOUCH**, Professeur de l'enseignement supérieur à l'Ecole Normale de l'Enseignement Technique de Rabat, d'avoir accepté de présider le jury de ma thèse.

Je souhaite remercier également M. **Youssef FAKHRI**, Professeur habilité à la Faculté des Sciences de Kénitra pour sa participation à mon jury de thèse en qualité de rapporteur de mon travail et pour son acceptation de se déplacer pour participer au jury.

Enfin, je voudrais remercier M. **Abderrahim El QADI**, Professeur de l'enseignement supérieur à l'Ecole Supérieure de Technologie de Salé pour avoir accepté d'examiner ce travail.

Je dédie ce mémoire à :

A ma très chère mère, à mon cher père,

Aucun hommage ne pourrait être à la hauteur de

l'amour Dont ils ne cessent de me combler.

Que dieu leur procure bonne santé et longue vie.

A ma soeur Fatima Zahra,

A mes frères Mohammed, Badr

A tous mes amis...

Résumé

La congestion routière devient un problème sérieux qui réduit significativement la mobilité urbaine. Les modèles de simulation microscopiques font partie des différentes techniques qui ont été proposées pour atténuer ce problème. Pour analyser une variété de problèmes de trafic complexes et dynamiques, la simulation microscopique du trafic détermine les mouvements des véhicules individuels circulant sur les réseaux routiers et représente les détails de chaque entité et les relations entre elles dans le flux de trafic. Pour chaque modèle microscopique, les composants les plus importants pour décrire le flux de trafic sont: les modèles d'écoulement ou de poursuite et les modèles de changement de voie . Cette thèse porte sur l'analyse et la compréhension des comportements des conducteurs en traitant les comportements de poursuite et de changement de voie. En outre, nous contribuons au développement de modèles microscopiques du trafic en haute performance qui incluent les modèles d'accélération et de changement de voie. Nous avons revu les modèles microscopiques existants pour les améliorer et en développer de nouveaux. Une autre contribution majeure dans cette thèse est de tenir compte de la sécurité du trafic, les modèles existants sont actuellement inadéquats pour évaluer la sécurité et éviter les collisions. Ceci nécessite d'un examen critique des modèles microscopiques actuels pour déterminer quels composants et paramètres ont un effet en termes de sécurité. Notre objectif final dans cette étude est d'établir de nouveaux modèles de poursuite pour évaluer l'impact de différents scénarios de trafic. D'une part, nous avons proposé d'introduire le facteur de pondération basé sur le temps de collision comme indicateur de sécurité. D'autre part, nous avons combiné les modèles d'écoulement proposés avec le modèle de changement de voie. Les modèles sont validés à l'aide d'un simulateur microscopique de flux de trafic avec différents scénarios: avancer et s'arrêter, s'approcher et s'arrêter au feu de circulation, et perturber la voie en posant des obstacles. Les résultats des tests de simulation indiquent que les modèles proposés produisent de meilleurs résultats et sont plus réactifs au freinage du véhicule. L'approche proposée permet de simuler des mouvements de véhicules plus réalistes et permet d'éviter les accidents par rapport aux modèles existants. Dans l'ensemble, le principal résultat de cette recherche est la conception d'un modèle de simulation microscopique de trafic routier plus réaliste qui sera efficace pour l'étude de la sécurité routière.

Mots clés : Modèles d'écoulements, Modèles de changement de voies, Simulation Microscopique, Mobilité Urbaine, Flux de Trafic.

Abstract

In traffic engineering, traffic congestion problems become a serious problem that reduces significantly urban mobility. Microscopic simulation models are among different techniques which have been proposed to alleviate this problem. To analyze a variety of complex and dynamic traffic problems, microscopic traffic simulation determines the movements of individual vehicles traveling on road networks, and representing details of every entity and the relationships between them within traffic streams. For each microscopic model, the most important component to describe traffic flow are: Car Following (CF) and Lane Changing (LC). Each model has different influencing parameters which are necessary to improve them to ensure more realistic traffic measures. This thesis deals with the analysis and understanding of drivers' behaviors during car-following and lane changing. Furthermore, we contribute to the development of microscopic traffic performance models which includes the acceleration and lane changing models. We reviewed the existing microscopic models to improve the existing models and develop new ones. Another major contribution of this thesis is to consider the traffic safety, the existing models are currently inadequate to assess safety and to avoid collisions. This fact highlights the need for a critical examination of the current microscopic models to determine which components and parameters have an effect on safety term. Our final aim of this study is to establish a new CF model to appraise the impact of different traffic scenarios. In fact, we proposed to introduce the weight factor which is based on time to collision as safety indicator. On the other hand, we combined the proposed car following models with lane change model. The models are validated using a microscopic traffic simulator with different scenarios: go and stop, approaching and stop at traffic light, and close lane by standing obstacles. The simulation test outcomes indicate that the proposed models produce better results and more reactive when the vehicle brakes. The proposed approach has enabled to simulate more realistic vehicle movements and it's can avoid accidents compared to the existing models. Overall, the major outcome of this research is a more realistic microscopic traffic simulation model that will be effective in traffic safety studies.

Keywords: Car-following Model, Lane changes Model, Microscopic Simulation, Urban Mobility, Traffic Flow.

Contents

List of Figures

List of Tables

List of Abbreviations

AASIM	*Autonomous Agent SIMulation*
ACC	*Adaptive Cruise Control*
AFVDM	*Asymmetric Full Velocity Difference Model*
ANN	*Artificial Neural Network*
AOVM	*Asymmetric Optimal Velocity Model*
ARTEMiS	*Analysis of Road Traffic and Evaluation by Micro Simulation*
BM	*Behavioral Mobility*
CCFM	*Cooperative Car-Following Model*
CF	*Car-Following*
CLC	*Cooperative Lane Changes*
CORSIM	*CORridor SIMulation*
COVM	*Comprehensive Optimal Velocity Model*
DLC	*Discretionary Lane Change*
DVO	*Driver-Vehicle Object*
FLC	*Free Lane Changes*
FMLC	*Forced Merging Lane Change*
FVADM	*Full Velocity and Acceleration Difference Model*
FVDM	*Full Velocity Difference Model*
GFM	*Generalized Force Model*
GHR	*Gazis–Herman–Rothery*
IFVDM	*Improved Full Velocity Difference Model*
ITS	*Intelligent Transportation Systems*

KWM	*Kinematic Wave Model*
LC	*Lane-Changing*
LMRS	*Lane changing Model with Relaxation and Synchronization*
LWR	*Lighthill Whitham-Richards*
MFVDM	*Modified Full Velocity Difference Model*
MHVADM	*Multiple Headway, Velocity, and Acceleration Difference Model*
MLC	*Mandatory Lane Change*
MOBIL	*Minimizing Overall Braking Induced by Lane Changes*
MOVM	*Modified Optimal Velocity Model*
MVSDM	*Modified Velocity-Difference Separation Model*
NDA	*Neural Driver Agent*
OVF	*Optimal Velocity Function*
OVM	*Optimal Velocity Model*
PET	*Post-Encroachment Time*
PDE	*Partial Differential Equations*
REC	*Rear-End Collision*
RLC	*Random Lane Change*
SITRAS	*Simulation of Intelligent TRAnsport Systems*
SLC	*Synchronized Lane Changes*
TET	*Time Exposed TTC*
TIT	*Time Integrated TTC*
TTC	*Time-To-Collision*
VDSM	*Velocity-Difference Separation Model*

Chapter 1

Introduction

Sommaire

1.1 Context and motivation

The study of the mobility is a topical subject of which the movements of humans are increasing day by day as well as we use mainly means of transportation requiring infrastructures which are sometimes insufficient. Our displacements are different according to our activities (work, hobbies, etc.). Many researchers have been done to describe human dynamics. Mobility is one of the most used concepts in many fields such as astronomy, sociology, and computer science. For this we need to understand at first its main principles especially with regard to urban travel. What mean the mobility concept? it is a concept whose meaning evolves strongly according to the fields of application which are very varied. Despite these differences, this notion retains a general idea of "change". According to geographers [1], the study of mobility is concerned with the observation of human mobility, and the mobility is divided into four categories: daily mobility, travel, residential mobility and migration. Residential mobility represents local travel with no intention of return, travel represents national and international travel involving the notion of return, migration represents national and international travel without intention of return, and daily mobility is the most interesting in our case, corresponds to the movements that take place in a normal living environment. The individual becomes the actor of his own mobility through the generation of basic needs corresponding to the realization of many trips such as to work, to make domestic activities, etc. In fact, these basic requirements imply the necessity for each individual to move for linking each place of activity using roads network causing traffic jams and congestion that increase the incidence of traffic accidents thus in designing environment in which people can move smoothly, traffic flow analysis is important. Research in traffic engineers is being performed to develop traffic management and strategies to deal with problems associated with congestion. For this purpose, modeling driving behavior is a basic requirement in many transportation applications. The main topics which can particularly benefit from such studies are Accident Analysis and Prevention, Intelligent Transportation Systems (ITS), and Microscopic traffic simulation. Accident analysis and prevention is an interesting research field which refers to measures and methods to minimize the risk of accidents and of injury to road users, such as, drivers, pedestrians, and private and public transport passengers. Many approaches can determine road traffic safety: one is based on statistical and identification considerations named hotspots, which are defined as accident-prone locations on the road, in the sense that a number of crashes higher than in other similar locations is observed there, probably due to local risk factors [2]. Another approach analysed recurrent conditions in observed accidents in order to identify (un)safety factors related to various aspects (vehicle characteristics, road section or geometry, the weather conditions and driving behavior). In addition, there are also other approach which can safely evaluate road traffic using so-called surrogate safety measures. Such methods basically focused on the concept that a surrogate measure should be based on non-crash-event, which in practice correspond to a crash frequency or severity [3]. The concept time-to-Collision in a car-following process is an example of surrogate safety measures involved in this thesis. Intelligent Transportation Systems (ITS) are advanced applications for monitoring and managing increasingly complex transportation infrastructures such as: knowing what is happening and where, from tracking buses and trains on their routes, to locating and addressing stalled vehicles, to connecting drivers with important information about road and traffic conditions. ITS applications can influence drivers' behavior or control the movement of the vehicle. There are many applications of drivers' behavior or control the movement of the vehicle which ITS can influence on [4]:

- Eco-driving advisory systems which can sensitize the drivers who waste energy by accelerating and decelerating.
- To drive more efficiently, there is a vehicle speed control systems that smooth out the maneuvers and give them speed guidance.
- Adaptive cruise control (ACC) and related systems such as intelligent speed adaptation (ISA) can harmonize speed in the stop-and-go traffic.
- The vehicle can save fuel by switching off their engine at red signals and start right before the green light.

Traffic simulation applications are therefore increasingly important to resolve transportation system problems, the number of proposed approaches needed to be tested would be very expensive. For that, traffic simulation modeling is a suitable tool. Traffic simulation models are divided into three types: microscopic; mesoscopic; and macroscopic simulation models. Microscopic models describe explicitly every entity and interaction between them within traffic streams to improve the accuracy and quality of traffic flow studies [5]. Microscopic simulation based on a different traffic behavior, such as, car following and lane changing models which are a fundamental component for all microscopic simulation models and describes the individual movement of each vehicle in terms of spacing with respect to vehicles ahead [6]. Mesoscopic models characterized by the high level of aggregation, low level of detail, and typically based on a gas-kinetic analogy in which driver behavior is explicitly considered [7]. While macroscopic simulation models represent traffic flow as a continuous fluid, which describe entities and their activities and interactions at a relatively low level of detail and established relationships between speed, flow and density. Traffic safety is still an important challenging for transportation. With increasing and the development of automobiles, a lot of researches and effort has been put into understanding traffic phenomena [8]. Among notable safety traffic problems discussed in this thesis, we cited rear-end collision. Rear-end collision problem, particularly, due to drivers following their leaders too closely. In fact, drivers can't decelerate fast enough when their leaders decelerate at unexpectedly high rates [5]. To evaluate safety in car following situations where rear-end collision can appear, a detailed understanding of drivers car following behavior and braking reaction time is required. In summary, and at a microscopic level, there is a need for improving the current understanding of drivers' acceleration and lane changing behavior.

1.2 Statement of the problem

Recently, traffic congestion and traffic safety have been known as a serious problem in all urban areas and it significantly reduces in urban mobility. Different techniques have been suggested to resolve these problems. One of these is a Traffic Simulation Technique. This latter has been used for many reasons, they represent real life, and apply different strategies without the need to make a physical change on site before implementing such strategies. The transport system must supply as much mobility as possible without compromising the user's safety. Traffic safety problems, generally, can be categorized as high severity crashes, such as single and overtaking collisions, or low severity events, such as rear-end collisions [9]. The major cause of these crashes is human behaviour [10]. However, [11] neglect in their crash report the human factors involved. In fact, crashes are multi-factor events in which the majority of traffic injuries are due to interaction between the road, vehicle and road user [12]. Traffic flow is characterized by highly complex interactions between individual traffic participants and the roadway system. These interactions describe the car-following models which represent the basic unit that governs the longitudinal movement for each traffic simulation model. The main of the key questions in this thesis is " how much the previous microscopic models were successful improved for use in traffic safety studies". Answering this query, other questions must be addressed :

- What are the basic components of microscopic simulation models that can affect safety measures?
- Which parameters can describe driver conflict risk in microscopic simulation models, particularly, we interested in car following as the first target in this research?
- What traffic indicators can describe traffic safety in traffic road?
- Which current microscopic simulation models with different car following approaches are able to provide more realistic traffic safety ?

Some of the studies questioned if the car following models embedded in the simulation model platform are reliable and capable to guaranty in a realistic manner the traffic safety based on safety indicators, such as headway's and time to collision. It is anticipated that the main contribution of this research will be a more realistic microscopic traffic simulation, particularly, a proposed CF model which we improve his effective for use in evaluating his impact on traffic safety. As traffic safety research necessitate better accuracy, the proposed CF approach developed in this work will, in turn, reinforce the performance of the CF model. In this perspective, we will propose an approach which demonstrates that is able to perform in every traffic situation such as "steady state following, closing, prior to overtaking, and braking", but here we will focus on the braking situation particularly.

1.3 Thesis objectives

The focus purpose of this thesis is to propose an extended and improved car following model which needs to be more robust than existing car following models in the safety context. The most common approaches ignore the relationships between different levels of vehicle interactions or accident types. In this context, we intend to establish a new approach where traffic analysts can be confident to use microscopic simulation models to evaluate the impact of different traffic scenarios. As has been discussed, the other target of this study is to examine existing microscopic simulation models their strengthen and their ability to be used in safety perspective. In this thesis we aim to study the interactions between drivers moving on the same lane so-called longitudinal driving task and the interaction between drivers moving on the different lanes called lateral driving task. In addition, we improved the mathematical models describing this type of behaviors. We present the main objectives to achieve the major aims of this PhD :

- Reviewing the general structure of existing microscopic simulation models.
- Clarifying the parameters of the microscopic sub-models, particularly the CF model.
- Proposing possible modifications for the chosen existing CF models.
- Proposing a new CF model which is more robust to evaluate safety effects.

1.4 Thesis overview and outline

The approach followed in this thesis is based on the two main steps: modeling and simulation. The outline of the thesis is illustrated in Fig 1.1. The remaining part of this thesis is organized as follows:

Chapter 1: In the remainder of this introductory chapter, we discuss the context of this research. We explain the scope and the motivation of this work. We introduce our main research questions, followed by a presentation of the main objectives.

Chapter 2: The intention of this chapter is to discuss many of the theoretical problems associated with the traffic flow theory. We discuss two fundamental concepts: the urban mobility and the intelligent transport systems. In the first step, we identify the concepts related to the research area to be studied.

Chapter 3: This chapter allowed to realize a state-of-the-art of simulation software tools include two levels of modeling: macroscopic and microscopic models. After a reminder of some basic concepts such as the definition of parameters and their fundamental relationships, we first review the two types of modeling. Then, we highlight the safety indicators that can measure safety in traffic flow and the way in which each criterion could be measured.

Chapter 4: We examine here the existing microscopic simulation models to evaluate the safety dynamically. We show that a lack of appropriate microscopic observations, so far, caused several important questions on longitudinal driving behavior to remain unanswered. Motivated by this consideration, we provide a survey to help readers acquire valuable traffic flow knowledge and emphasized the demand for a new models guarantee the safety perspective. Moreover, we enhance the existing models and develops new ones. In the other hand, we give a survey of several important lane changing models. Another major contribution of this work is the introduction of lane change model with a proposed car following models to evaluate the rear-end collision in emergency braking.

Chapter 5: Concludes the thesis and gives with the suggestions for future research.

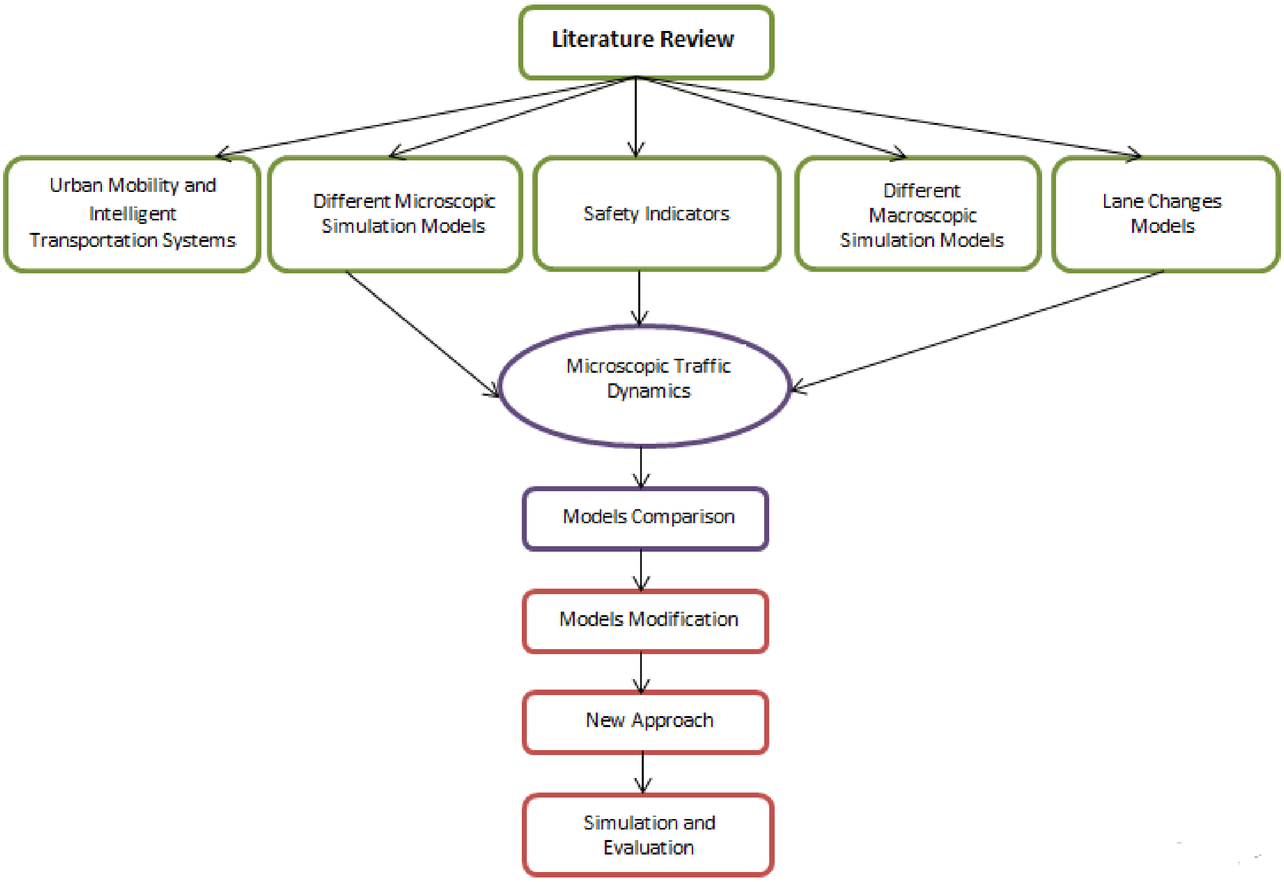


Figure 1.1: Schema of the thesis structure

Publication from this research

- Journals

  Lazar, H., Rhoulami, K., Rahmani, M. D. A Review Analysis of Optimal Velocity Models. Periodica Polytechnica Transportation Engineering, 44(2), pp.123-131, 2016. DOI : 10.3311/pptr.8753.

  Lazar, H., Rhoulami, K., Rahmani, D. Microscopic Evaluation of Extended Carfollowing Model in Multi-lane, Roads. Informatica journal, 42(1), pp. 117–125, 2018.

- Book Chapter

  Lazar H., Rhoulami K., Rahmani M.D., A Novel Velocity-Separation Difference Model for Traffic Flow Theory. In: El Oualkadi A., Choubani F., El Moussati A. (eds) Proceedings of the Mediterranean Conference on Information and Communication Technologies 2015. Lecture Notes in Electrical Engineering, 381. Springer, Cham, 2016. DOI: 10:1007/978-3-319-30298-01.

- Conferences
  Lazar, H., Rhoulami, K., Rahmani, D. A Modified Full Velocity Difference Model Based on Time To Collision as a Safely Indicator for Braking State. In: 2nd IEEE World Symposium on Web Applications and Networking (WSWAN). Sousse, 21-23 March 2015. DOI: 10.1109/wswan.2015.7210342

  Lazar H., Rhoulami K., Rahmani M.D., A Novel Velocity-Separation Difference Model for Traffic Flow Theory. In: El Oualkadi A., Choubani F., El Moussati A. (eds) Proceedings of the Mediterranean Conference on Information and Communication Technologies 2015. Lecture Notes in Electrical Engineering, 381. Springer, Cham, 2016. DOI: 10:1007/978-3-319-30298-01.

- National Publications
  Lazar H., Rhoulami K., Rahmani M.D., Plateforme de simulation de la mobilité quotidienne dans les villes Marocaines, Journées scientifiques URAC du LRIT, CNRST, Rabat, 2013.

  Lazar H., Rhoulami K., Rahmani M.D., Modélisation de la mobilité quotidienne dans les villes Marocaines : Concevoir des agents pour simuler les dynamiques urbaines, Journées Doctorales en Technologies de l'Information et de la Communication, La faculté des Sciences Ibn Tofail, Kénitra, 2013.

  Lazar H., Rhoulami K., Rahmani M.D., Simulation of traffic roads by applying Optimal Velocity Model using multi-agent platform GAMA, Congrès International sur les Sciences et Technologies de l'Information et de la Communication, Ecole Nationale des Sciences Appliquées, Khouribga, 2014.

  Lazar H., Rhoulami K., Rahmani M.D., La modélisation de la mobilité quotidienne dans les villes marocaines : Etude des approches de la mobilité quotidienne, Doctoriales 2014, La faculté des Sciences, Rabat, 2014.

Chapter 2

Urban Mobility and Intelligent Transportation Systems

Sommaire

The accelerated growth of the urban population and the extension of cities, the intensification of economic exchanges have made road traffic and its management one of the major challenges of sustainable development. Recently, there has been a strong focus on improving the efficiency and safety of transportation and this has led to the development of the Intelligent Transportation Systems (ITS). Mobility models have been developed to solve some problems (congestion, energy consumption, accident and safety, etc.) directly related to transport. The main objective of these models is to propose new approaches which lead to making the transport system more intelligent and attractive.

2.1 Urban Mobility : The Daily Mobility

Over the past ten years or so, the notion of mobility has gradually replaced the notion of displacement. Indeed, the latter, too much limited, recovers only the physical aspect while that of the mobility includes the social practices in their cultural, psychological, symbolic dimension, etc. What interests us more exactly here is the daily mobility, formerly known under the term of "pendular travels". This involves travel to work. This mobility requires a set of skills and a set of resources. The first idea contained in the term mobility is the setting in motion. We generally refer to the concept of displacement. Classically, the researchers define a displacement as "an operation that involves going from one place to another, for the purpose of carrying out an activity, using one or more modes of transport". Over the past few decades, daily mobility is growing considerably, highlighted by numerous research studies [13][14]. If mobility has grown, it is not only because it is technically easier, but also because it is socially valued. It has become the condition of a "normal" inscription in social life. This norm is even more important because of the generalization of automobile dependence [15], formatting accessibility to territories and urban amenities. The daily mobility is then the materialization of the movement of the people induced by the interactions between the characteristics of transport networks and the occupation of space. The mode of transport is thus the means of locomotion borrowed to effect the displacement. Walking, two-wheeled vehicles or private cars are the modes of individual transport, unlike public transport. However, in spite of the increase of the level of the urban mobility in the world, the access to places of activities and services are becoming increasingly difficult. Due to the urban sprawl, the distances between the functional destinations such as workplaces, schools, hospitals, administrations, or retail facilities became more important, leading to a growing dependence on the private motorized transport.

2.2 Intelligent Transport Systems

Mobility allows all of us to enjoy a high degree of freedom and quality of life. These achievements must be secured but, at the same time, they present us with major challenges:

now and in the future we must make transport more efficient, more environmentally sound and safer. Better mobility improves quality of life and boosts the ability of individuals and organizations to contribute to the growth of the economy. Here, we refer to "Intelligent Transport Systems" (ITS) term which plays an important role in shaping the future ways of mobility and the transport sector. We expect that through the use of ITS applications in transport will become more efficient, safer and greener. Nowadays, technology plays a quintessential role both for vehicle and infrastructure allowing an upgrade of safety standards and allowing the efficiency performance which lead also to the betterment of the quality of life itself [16]. Intelligent transport systems are a general term for the unified application of communications, control, and information processing technologies to vehicular networks. The subsequent benefits save lives, time, money, energy, and the environment. The acronym ITS is flexible and capable of being understood in a broad or a narrow way. In Europe ITS is called transport telematics, a group of technologies that support ITS. Fundamental attributes of ITS cover all approaches of transport and imitate all features of the transportation system: the vehicle, the infrastructure, and the driver or user, collaborating together dynamically. The universal purpose of ITS is to develop decision making in real time by vehicular network controllers and other users, thereby filtering the operation of the entire transport network. In ref [17], the authors argued that intelligent transport systems help to keep constant driving speed, safety distances between vehicles, and vehicle dynamic route guidance to a pre-defined target and optimize the path between source and destination. Using traffic management within the intelligent transport systems mitigates the formation of congestion, increases safety, and reduces the cost of transportation and emissions in the atmosphere; improves service delivery [18].

2.3 Urban mobility and Road Traffic Study Relationship

Urban mobility is confronted by many challenges and particularly transport systems. The most important transport problems are often related to urban areas and take place when transport systems, for a variety of reasons, cannot satisfy the numerous requirements of urban mobility productivity. In ref [19], the authors observed that among the most notable urban transport problems are:

- Traffic congestion: congestion is one of the most prevalent transport problems. Traffic Congestion occurs when there is an imbalance between transport demand and supply at a specific point in time and in a specific section of the transport system. Urban congestion comes in two categories.

  - Recurrent congestion: the consequence of factors that cause regular demand surges on the transportation system, such as commuting, shopping or weekend trips. However, even recurrent congestion can have unforeseen impacts in terms of its duration and severity. Mandatory trips (workplace-home) are mainly responsible for the peaks in circulation flows, what this means in essence is that most of the congestion in urban areas are recurring at specific times of the day and on specific segments of the transport system.
  - Non-recurrent congestion: the other half of congestion is caused by random events such as accidents and unusual weather conditions (rain, snowstorms, etc.), which are unexpected and unplanned. Non-recurrent congestion is linked to the presence and effectiveness of incident response strategies. As far as accidents are concerned, their randomness is influenced by the level of traffic as the higher the traffic on specific road segments the higher the probability of accidents.

- Environmental impacts and energy consumption: the pollution problem, including noise, generated by circulation has become a serious impediment to the quality of life and even the health of urban populations. Further, energy consumption by urban transportation has dramatically increased. Most vehicles especially diesel trucks generate a lot of CO_2 that is huge enough to impair the vision of the driver of an oncoming vehicle in the opposite direction resulting to accident most times.

- Accidents and safety: growing traffic in urban areas are linked with a growing number of accidents and fatalities, especially in developing countries. Accidents account for a significant share of recurring delays. As traffic increases, people feel less safe to use the roads.

- Difficulties for non-motorized transport: these difficulties are either the outcome of intense traffic, where the mobility of pedestrians, bicycles and vehicles is impaired, but also because of a blatant lack of consideration for pedestrians and bicycles in the physical design of infrastructures and facilities.

2.4 Mobility Models

Vehicular communication is the communication involving vehicles on the road. The ability of a vehicle to communicate with other vehicles and with base stations, can lead to exciting applications for safety, comfort and efficiency of transport [20]. Mobility models in inter-vehicle communications pave the way for novel applications in traffic safety, driver assistance, traffic control, and other advanced services. The most mobility models used in this research area are: the stochastic models, the traffic stream models, the car-following models and the behavioral models. We only list here the widely used models in traffic simulations.

- STOCHASTIC MODELS

  Stochastic models describe all mobility which constrains random movements of nodes on a graph. The graph illustrates a road topology, and the movement is random in a sense that vehicles, individually or with group dynamics, follow casual paths over the graph, usually traveling at randomly chosen speed. Stochastic models are often compared against fully random mobility models, i.e., models that do not constrain the random nodes movement over a graph. Among the stochastic models, we can cite the City Section mobility model introduced by [21] which constrains nodes movement on a grid road topology, where all edges are considered bidirectional, single-lane roads. The vehicles randomly select one of the intersections as their destination over the grid and move towards it with constant speed, with one horizontal and one vertical movement. The speed depends on the road and the vehicle is traveling on two road classes: high-speed and lows speed, and each node sets its speed to a high or low value accordingly. All adjacent vehicles travel at the same speed, and vehicles are allowed to overlap at road junctions. The car to car interactions are ignored. Figure 2.1 an example of vehicle trip over with the City Section model is provided.

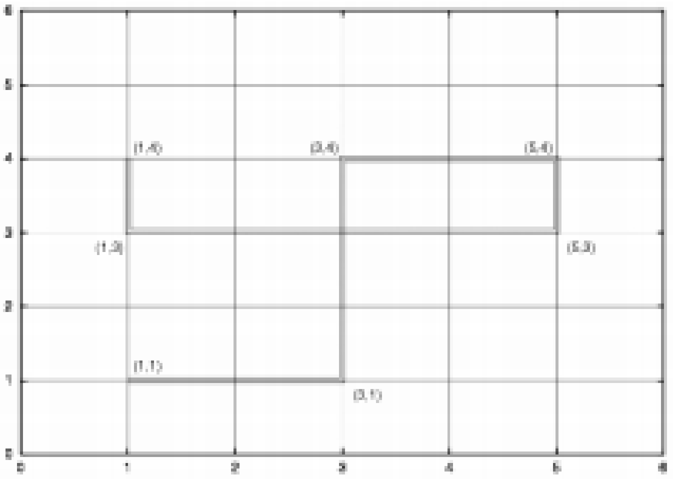
  

  Figure 2.1: Example of vehicle trip over with the City Section model

- TRAFFIC STREAM MODELS

  Macroscopic stream models represent how the behavior of one parameter of traffic flow changes with respect to another. Traffic stream models look at vehicular mobility as a hydrodynamic phenomenon, and try to relate the three fundamental variables velocity $v(x,t)$ (measured in km/h), density $\rho(x,t)$(measured in vehicles/km), and flow $q(x,t)$ (measured in vehicles/h) and all of them are functions of space x and time t. Velocity is an important measure of effectiveness defining levels of service for many types of facilities. Density is a critical parameter for uninterrupted flow facilities because it characterizes the quality of traffic operations. Flow rate is a variable that quantifies demand. It is the number of vehicles that desire to use a given facility during a specific time period [22]. We refer the interested reader to Section 3.4.

- CAR FOLLOWING MODELS

  Car following models describe the behavior of each driver in relation to the vehicle ahead which adapts a following car's mobility according to a set of rules in order to avoid contact with the vehicle ahead. They fall into the category of microscopic level descriptions which represent each car as an independent entity [23]. Figure 2.2 illustrates a general schema for car following models. The most famous car following models used are: GHR Models, Psycho-Physical Models, Linear Models, Optimal Velocity models, Cellular Automata, Fuzzy Logic Models. A description of the differences between those models is detailed in Section 3.2.2.

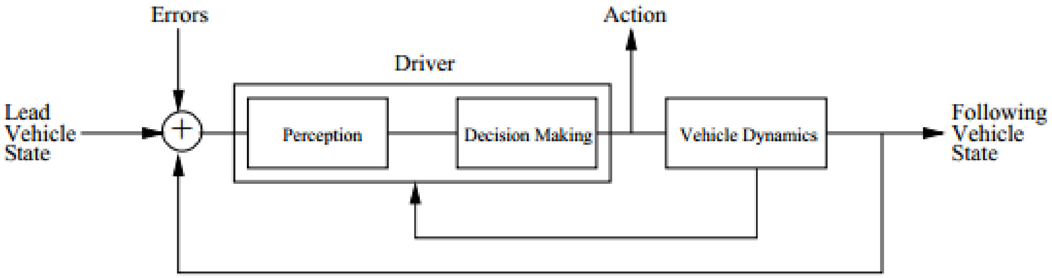


Figure 2.2: General schema for car following models

- BEHAVIORAL MODELS

  Behavioral Mobility modeling (BM) is a novel approach to the problem of modeling human mobility, which can be applied to vehicular traffic as well. The approach introduced by [24] aims to representing realistic mobility patterns based on the paradigm of behavioral rules. Behavioral rules are the main idea which determined every movement which can be modeled as attractive or repulsive forces. In the case of vehicular mobility, the result from the composition of these forces determines the acceleration vector which drives the car movement. An example of force-composing model is illustrated in Figure 2.3. However, under the computational point of view, this model is especially expensive as every movement requires the elaboration and composition of multiple inter-object forces.

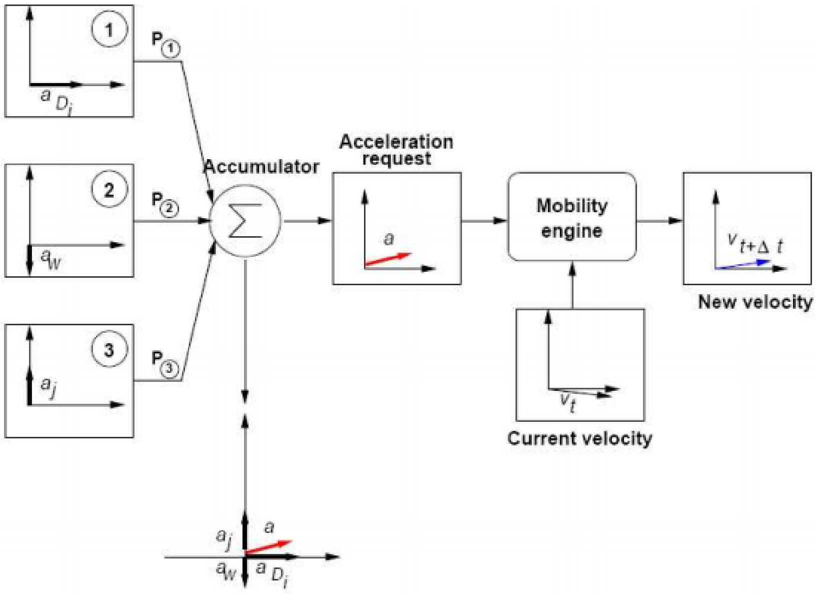


Figure 2.3: Mobility engine for vehicle i: independent acceleration vectors, modeling different behavioral rules, are combined and result in an acceleration request

2.5 Chapter summary

This chapter allowed to realize a state of the art of two great concepts: the urban mobility, particularly, daily mobility and the intelligent transport systems. This first step was very important in order to identify the concepts related to the research area to be studied. Then, we discussed their relationship and the most notable problems related to urban transport. Finally, we describe the most widely mobility models applied to vehicular traffic, especially, microscopic and macroscopic mobility models which will be the subject to be detailed in the next chapter.

Chapter 3

Traffic modeling: studies and literature reviews

Sommaire

With the rapid development of information and communication technologies in recent decades, the future of the automobile seems to be closely linked to the use of innovative systems that can, among other things, act on behavior driving. We are talking about intelligent transport systems. Traffic flow models are divided into two major types, macroscopic and microscopic models. Macroscopic models characterize the global behavior of the traffic, in a scale of relatively important study, while microscopic models study the motion of individual vehicles. In this chapter, we interest to finest scale, namely the microscopic scale, which road traffic is modeled by the individual evolution of each vehicle. In this model, the speed of a vehicle is directly according to the distance that separates it from the preceding vehicle (leader vehicle), modulo a delay time. This delay time is generally assimilated to the reaction time of the driver in order to take into account the variations in behavior of his leading vehicle. This is a car-following process also known as longitudinal driving behavior. The modeling of traffic in the broader sense proposes to describe more finely the flow of vehicles on a road. In this case, it is necessary to understand two behavioral sub-models which are responsible for vehicle movement inside the network: Car Following (CF) and Lane Changing (LC) models. These models are schematized in Fig 3.1.

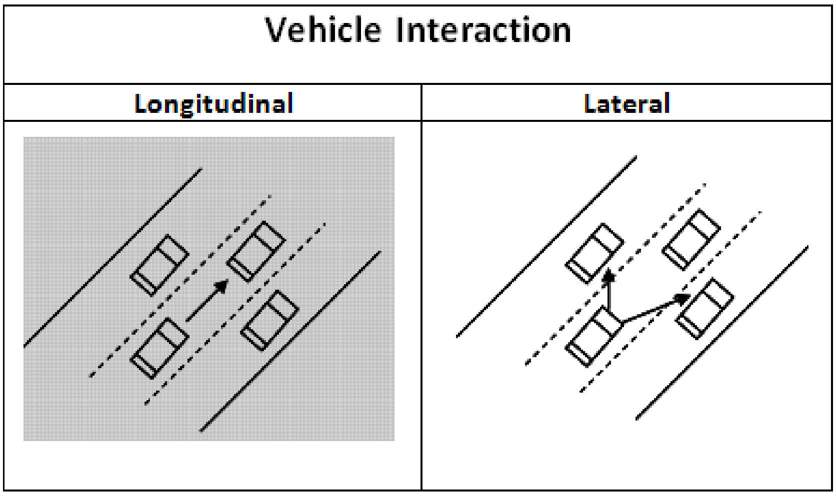


Figure 3.1: Vehicle interaction classification

3.1 Heterogeneous modeling traffic flow

3.1.1 Traffic road concept

The road network has been developed to respond to displacement demands. The roads have been designed throughout history to answer in particular commercial demand. For several decades this demand has been supplemented by those related to commuting place of residence - work and in the migrations of population. Two major components establish the traffic:

- The fixed component (infrastructure): it is composed of roadways, signs and markings. The set of infrastructures, known as the road network, can be classified as a network of urban roads and interurban roads.
- The mobile component: it is composed of individuals who use the infrastructure (vehicles and pedestrians)

A peculiarity of traffic road is essentially related to the design of the infrastructure which is designed, according to a projected demand, to respond to a collective optimum but that each individual realizes his displacement by seeking to reach his individual optimum, which is often antagonistic with the collective optimum. The two definitions below clearly show the dual individual and collective aspect of the traffic, the individual aspect being represented by the fact that the traffic is formed by different vehicles and the collective aspect by the fact that the traffic is interpreted as a fluid (i.e a flow of vehicles)[25].

3.1.2 Modeling traffic flow

The traffic flow problem started some 40 years ago, when Lighthill and Whitham [26] presented a model based on the analogy of vehicles in traffic flow. Then, mathematical description of traffic flow has been an interesting subject of research and debate for traffic engineers. Research in this field of road traffic has attracted scientists on all sides, as its social, economic and environmental impacts are enormous. Heterogeneous traffic is defined as a traffic comprising of motorised two-wheelers and three-wheelers along with several other vehicles with no lane discipline. While, traffic composed of identical vehicles and following the lane discipline is termed as homogeneous [27]. To understand traffic behavior, we require a thorough knowledge of traffic stream parameters and their mutual relationships. This relationship between the traffic parameters results many researches yielded many mathematical models named Traffic Flow Models. In order to classify road traffic models, four criteria can be distinguished:

3.1.2.1 Granularity level

We distinguish two levels of granularity: microscopic, and macroscopic. These levels of granularity define the level of detail at which the system to be studied is represented. Microscopic simulation, for example, offers a higher level of detail than macroscopic simulation. Macroscopic models correspond to a continuous vision of the flow. They are based on an analogy with fluid mechanics: we represent the flow of vehicles in the form of a flow. The aim is not to describe the individual behavior of vehicles but to give a description of the overall behavior, through aggregated variables [28]. In contrast, microscopic simulation models approach the traffic more finely. We try to reproduce the behavior of each vehicle-driver pair. This type of model aims to get as close as possible to the actual behavior of the drivers (vehicle-driver). To do this, these models attempt to reproduce the way a vehicle responds to its environment, that is, the infrastructure on which it travels and the vehicles around it. These models describe both the behavior of each system entity (i.e the vehicle / driver pair) and the interactions between these entities Fig 3.2.

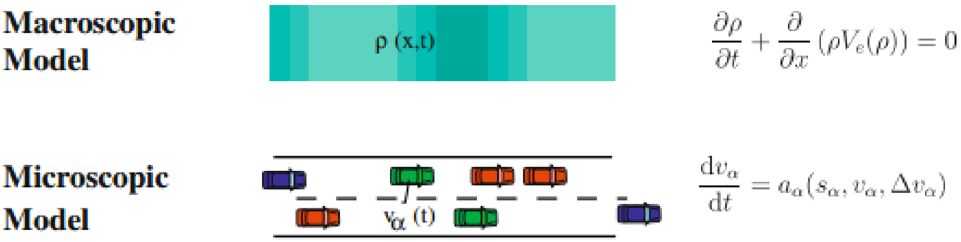


Figure 3.2: Illustration of traffic modeling approaches including typical model equations

3.1.2.2 Representation of time

The majority of traffic models describe dynamic systems, so the time management is an important component of the simulation system. There are two states of the model (continuous / discrete). In continuous models, the elements of system continually change state over time in response to discrete or continuous stimuli. The discrete models consider that system states change only on certain dates.

3.1.2.3 Deterministic or stochastic processes

Deterministic models do not use any random variables or probabilistic functions. The interactions are defined through exact logical or mathematical relationships. Conversely, stochastic models use probability functions or variables that can be randomly defined, which makes it possible to introduce a certain dispersion around the simulated phenomena.

3.1.2.4 Mathematical structure

Traffic flow models can also be categorized by their mathematical structure.

Partial differential equations (PDE) : the models of this class used location x and time t as a continuous independent variable of continuous fields such as the local speed $V(x, t)$ or density $\rho(x, t)$. The model equations contain these fields and their derivatives with respect to either of the two variables. This is the distinctive feature of PDEs [29]. The main advantage of most PDE traffic flow is suited to express macroscopic models and allowed for a fast numerical solution.

Coupled ordinary differential equations: the models of this class used the continuous state variables: location $x_i(t)$ or speed $V_i(t)$ of vehicle i, depend on only one variable, the time t. The model equations contain the state variables and their time derivatives and are coupled with the equations of the leading vehicle. This mathematical form is the most natural form to describe time-continuous microscopic models called car-following models.

Coupled iterated maps served to describe the model which uses discrete time steps Δt instead of continuous time while the state variables remain continuous. Iterated maps are used for both microscopic and macroscopic models. In microscopic models, the continuous state variables are the position, lane and speed of all vehicles. In macroscopic iterated maps, space is discretized into cells and the continuous state variables are traffic density and local speed. The term "coupled" means that the new state of the vehicles of microscopic models or the cells of macroscopic models depends not only on the old state but on the old state of the neighboring vehicles or cells, respectively.

3.2 Transport models classes

There is a wide variety of modeling approaches which they are grouped into four classes (land-use models, travel demand models, traffic flow models, and network management models)(see Table 3.1). In transportation and network planning, the static and dynamic models are distinguished. The static models can have traffic forecasts to size at best very expensive infrastructure for the long term. They simulate the demand for traffic at certain points in the network, hence the term planning. The dynamic models describe the traffic flow. Some have been built on analogies between the traffic flow and the flow of a fluid or the kinetics of gases. Other models view the network as a succession of cells exchanging information in the form of vehicles. Others seek to describe the movement of a vehicle based on the characteristics of the vehicle in front of it [30]. The traffic flow models are subdivided into two large scales: macroscopic and microscopic. We gives details of both scales. Here, we are particularly interested in the microscopic traffic flow models.

Table 3.1: Transport models classes

Category of models	Objective	Time scale	Spatial scale
Land-use	Planning, management	Very long term	Global
Travel demand	Planning	long term	Global
Traffic flow	Evaluation, planning or management	Short term	Local or global
Network management	Control, regulation	Very short term	Local

3.2.1 Microscopic traffic flow models

Microscopic models attempt to analyze the flow of traffic by modeling driver-driver and driver-road interactions within a traffic stream which respectively analyzes the interaction between a driver and another driver on the road and of a single driver on the different features of a road. The main purpose of microscopic models is to be able to describe the individual behaviors of users for two driving situations:

- Car-following behavior, where a microscopic model can be subdivided into longitudinal components that intervene in the choice of a desired speed and an acceleration or braking law to reach this speed.
- Lane change behavior, this includes overtaking maneuvers in the current section as well as insertion maneuvers.

To understand traffic behavior, we require a thorough knowledge of traffic stream parameters and their mutual relationships. This relationship between the traffic parameters results many researches yielded many mathematical models. For this purpose, we present the microscopic parameters used in microscopic models and the main models proposed in the literature.

- Microscopic parameters

When describing a stream of traffic microscopically, we examine each vehicle separately. Two characteristics at an instant t are of importance, location and speed. The position taken by vehicle i on a road can be indicated by $x_i(t)$ and the position taken by vehicle ahead can be indicated by $x_{i+1}(t)$. The speed of vehicles i and $i+1$ is given by the derivative of a position denoted by $v_i(t)$ and $v_{i+1}(t)$ respectively. A vehicle occupies a certain space on road: the relative spacing represent the front bumper to back bumper distance between i and $i+1$ is identified as $S_i(t) = \triangle x_i = x_{i+1} - x_i$ and the space S_i consists of the physical length l_i of the vehicle and the distance gap d_i that a driver maintains between himself and the vehicle ahead which is expressed as $S_i = l_i + d_i$. Analogous to space there is a vehicle's time headway h_i is the ratio of the relative spacing by the speed of the follower vehicle. The relative speed is given by $\dot{S_i}(t) = v_{i+1}(t) - v_i(t)$ (Fig 3.3).

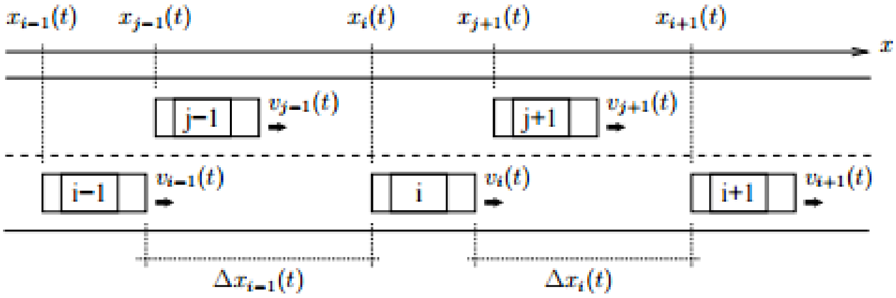


Figure 3.3: Car following process

- <u>Car-following models</u>

The car-following (CF) models form an underlying component of microscopic traffic simulations, which enable transport engineers to replicate the dynamic behavior of travelers at small discrete intervals. The CF model plays an important role to describe the drivers individual behavior. Car-following process examines the manner in which individual vehicles follow one another in the same lane where the driver adjusts his or her acceleration according to the conditions in front and each vehicle is governed by an ordinary differential equation (ODE) that depends on speed and distance of the car in front [31]. The most CF models have a significant impact on the ability of traffic micro-simulations to replicate real-world traffic behavior [32]. Various models were formulated to represent how a driver reacts to the changes in the relative positions of the vehicle ahead. The car-following models have been designed for single-lane roads, based essentially on the following ordinary differential equation:

$$a_i(t) = \frac{v_{i+1}(t) - v_i(t)}{T} \tag{3.1}$$

This model is based on the idea that the acceleration $a_i(t)$ of the vehicle i at time t depends on the relative speed of the vehicle i and its leader $i+1$ by means of a certain relaxation time T. However the previous equation describes a phenomenon is not stable enough in the case of road traffic. Hence the appearance of several variants of this model includes safe-distance models, stimulus-response models, and optimal velocity models.

- Safe-distance or avoidance collision models

Safe-distance or collision avoidance models try to describe simply the dynamics of the only vehicle in relation with his predecessor, so as to respect a certain safe distance. The earliest safety distance car-following model is proposed by Pipes [33] which find a safe following distance within which a collision would occur if the lead vehicle driver behaves unpredictably; unless the subject vehicle drive keeps a longer space in front of the vehicle compared with the safe-distance when following another vehicle [32]. This model assumed the following minimum inter-distance rule.

A good rule for following another vehicle at a safe distance is to allow yourself at least the length of a car between you and the vehicle ahead for every ten miles an hour (16.1 km/h) of speed at which you are traveling.

Kometani and Sasaki [34] proposed the first model of avoidance collision. This model aims to transcribing the trajectory of a vehicle according to a minimal safe distance. A following driver keeps a safe distance to avoid a collision. The safe distance is related to vehicle velocity at time t and its leader velocity at time $t-T$ which T is the driver's reaction time. The safe distance can be calculated as follows.

$$S(t-T) = \alpha v_{i+1}^2(t-T) + \beta_1 v_i^2(t) + \beta v_i(t) + b_0 \tag{3.2}$$

The coefficients α and β_1 represent the inverse of the maximum deceleration capacity respectively of the leading vehicle and of the follower vehicle. The coefficient β is homogeneous in the inverse of a time and b_0 is homogeneous at a distance. These are the parameters of the model to be calibrated. The works of Gipps [35] aimed at completing this initial approach by incorporating a safe speed to keep safe distance related to distance between two successive cars and their accelerations and speeds. The vehicles accelerate to reach the desired speed and decelerate to avoid a collision when they try to maintain the desired speed [36] . The maximum speed depends on the acceleration is also influenced by the vehicle characteristics and limitations imposed by the leading vehicle expressed as follows:

$$v_i(t+T) = \min \begin{cases} v_i(t) + 2.5a_{max}T(1 - \frac{v_i(t)}{v_{max}})\sqrt{0.25\frac{v_i(t)}{v_{max}}} \\ a_{min}T + \sqrt{a_{min}^2 T^2 - a_{min}(2(x_{i+1}(t) - x_i(t) - s_{jam}) - v_i(t)T - \frac{v_{i+1}^2(t)}{b}} \end{cases} \tag{3.3}$$

with a_{max} maximum acceleration, a_{min} maximum deceleration (minimum acceleration), v_{max} the desired (maximum) velocity and s_{jam} jam spacing front-to-front distance between two vehicles at standstill.

- Stimulus-response models

The first CF models developed to replicate CF behaviors of drivers are the stimulus-response models. This type of models consists of stimulus–response concept based on the assumption that the driver of the following vehicle perceives and reacts appropriately to the spacing and the speed difference between the following and the lead vehicles [37]. In general, the response is a deceleration or acceleration of the subject vehicle is delayed by an overall reaction time T. The stimulus may include the relative speed and/or spacing between the subject vehicle and its leader [32]. Here, we reviewed the major subgroups of stimulus–response models.

Gazis–Herman–Rothery model

From 1950s and early 1960s, there was a rapid development of stimulus-response models [38] [39] and they made their efforts to develop a famous GHR model, named after [40]. The general formulation of this model is:

$$a_i(t) = \gamma \frac{(v_{i+1}(t))^m}{(S_i(t-T))^n} \dot{S}_i(t-T) \tag{3.4}$$

where γ is the sensitivity parameter, m and n are parameters that are used to fit the model to data. The rate $\dot{S}_i(t-T)$ is considered as the stimulus, the acceleration a_i as the response, hence the name "stimulus–response" model. This model allows taking into account the inter-distance between both vehicles. Numerous studies were led to determine the optimal combination of parameters (m, n). Among them [40] [41][42][43]. For more details, see Table 3.2.

Table 3.2: Proposed value of (m, n) parameters for GHR model

Models	**Value of m**	**Value of n**
Gazis et al., 1961	[0;2]	[1;2]
Edie, 1963	1	2
May and Keller, 1967	0.8	2.8
Heyes and Ashworth, 1972	-0.8	1.2
Ceder and May, 1976	0.6	2.4

Linear model

Based on the GHR model [39] proposed a linear model by adding some terms in the first GHR model to adapt the acceleration of the subject vehicle with consideration of its leading vehicle braking. A simplified version of this model is:

$$a_i(t) = k_1 \dot{S}_i(t - T) + k_2(S_i(t - T) - D_i(t)) \tag{3.5}$$

This approach is based on different parameters for the driver to develop the acceleration to be applied to his own vehicle. The parameter $D_i(t)$ describe a desired following distance formulated by:

$$D_i(t) = \alpha + \beta v_i(t - T) + \delta a_i(t - T)$$

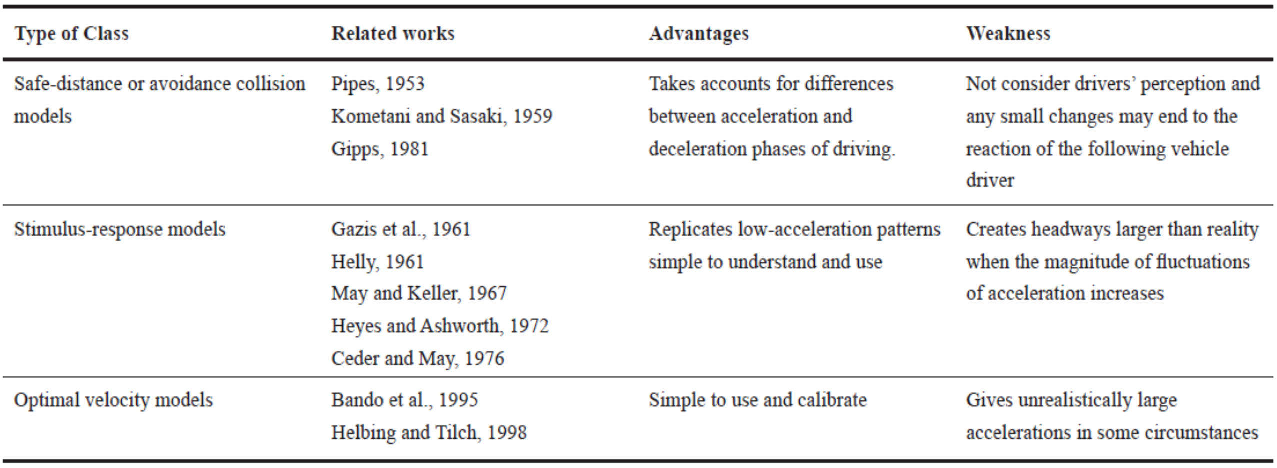
where k_1, k_2, α, β, and δ are model calibration parameters.

- Optimal velocity models

Optimal velocity models are another approach generally based on the difference between the driver's desired velocity and the current velocity of the vehicle as a stimulus for the driver's actions. The optimal velocity models obtain more attention and it has become one of important researches of a traffic flow model, because of its good traffic physical and mathematical characteristics [44], which will be discussed emphatically in Chap 4.

Table 3.3 summarizes three types of the microscopic model with his advantages and his inconvenient.

Table 3.3: Summary of some existing car-following models



Type of Class	Related works	Advantages	Weakness
Safe-distance or avoidance collision models	Pipes, 1953 Kometani and Sasaki, 1959 Gipps, 1981	Takes accounts for differences between acceleration and deceleration phases of driving.	Not consider drivers' perception and any small changes may end to the reaction of the following vehicle driver
Stimulus-response models	Gazis et al., 1961 Helly, 1961 May and Keller, 1967 Heyes and Ashworth, 1972 Ceder and May, 1976	Replicates low-acceleration patterns simple to understand and use	Creates headways larger than reality when the magnitude of fluctuations of acceleration increases
Optimal velocity models	Bando et al., 1995 Helbing and Tilch, 1998	Simple to use and calibrate	Gives unrealistically large accelerations in some circumstances

3.2.2 Macroscopic traffic flow models

The macroscopic models arise from a hydrodynamic analogy of the flow of vehicles. The goal of these models is to be able to characterize the global behavior of the traffic, in a scale of relatively important study. Their current applications cover the simulation of the traffic with the aim of the planning and of the conception of infrastructures, but also the dynamic management of the traffic and the evaluation of these measures of management. Mathematical models describe the evolution of the above variables using systems of partial differential equations [45]. Since then, the research in the field of the traffic flow has not stopped attracting the scientists of any edge; so much its social, economic and environmental impacts are considerable. Traffic models answer this need by translating the application of the scientific approach in the problems posed by the transport. The first macroscopic models were derived from the work of[46] [47]. They led to the so-called first order models of type LWR. Nevertheless, this type of models has several disadvantages [48] [49] which are summarized in a number of unrealistic assumptions. Later, Payne models, called second order models, eliminate the main defects of the LWR model [50].

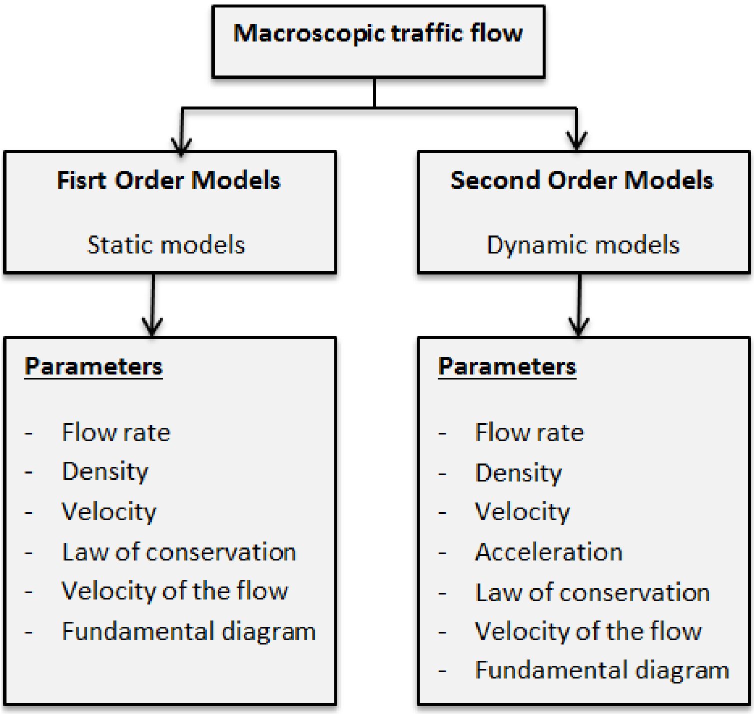


Figure 3.4: Macroscopic traffic flow models classification

- First order models

The most commonly used model is also one of the pioneer models in road traffic modeling. This is the model developed simultaneously by [46] [47], based on an analogy with fluid dynamics. This model , Known under several names, among others the LWR (LighthillWhitham-Richards) model, the hydrodynamic model or the kinematic wave model (KWM) is based on the assumption that traffic is always in equilibrium, that it evolves from one state of equilibrium to another and assumes the existence of a relationship between two of the three variables. In the case of the macroscopic models, the individual behavior of the vehicles is no longer described, only the displacement of all the vehicles is represented. Before developing macroscopic models further, it is important to define the set of variables and concepts on which they were established.

- The number of vehicles is $N(x,t)$.
- The flow rate conventionally denoted $Q(x,t)$ corresponding to the number of vehicles flowing at a point of abscissa x and time t per unit of time.

$$Q(x,t) = \frac{N(x, t \longrightarrow t+dt)}{dt}$$

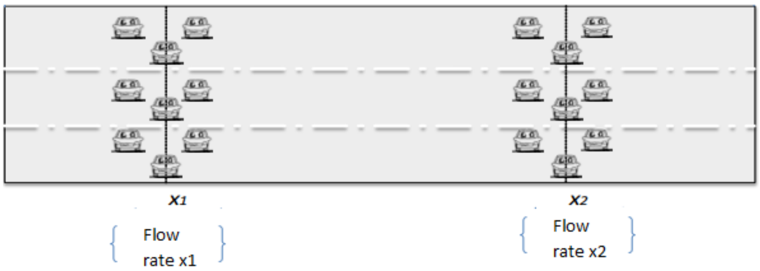


Figure 3.5: Flow rate

- Instantaneous spatial density $K(x,t)$ corresponding to the number of vehicles per unit length lying on a section close to the abscissa point x, at time t.

$$K(x,t) = \frac{N(x \longrightarrow dx,t)}{dx}$$

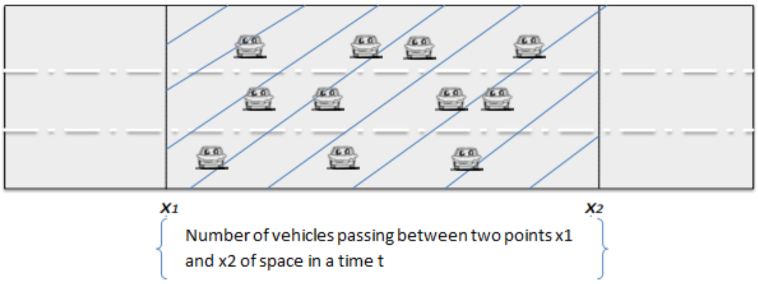


Figure 3.6: Spatial density

- The velocity $V(x,t)$ corresponding to the average space velocity of the vehicles located in the section $[x, x - dx]$ at time t.

$$V(x,t) = \frac{Q(x,t)}{K(x,t)}$$

The basic elements that represent first order road traffic flows are related to the following three relationships:

- The law of conservation: the number of vehicles entering at any given time on a section must be equal to the number of vehicles leaving the section in the same time interval.

$$\frac{\partial Q(x,t)}{\partial x} + \frac{\partial K(x,t)}{\partial t} = 0 \tag{3.6}$$

- The velocity of the flow: corresponding to the velocity of equilibrium at which the vehicles move over a given section in a time interval.

$$V = V_{eq}(K(x,t)) \tag{3.7}$$

- The fundamental diagram: The three basic variables presented above (velocity, density and flow rate), on which the macroscopic models are based, are linked by a fundamental relation such that the flow rate is equal to the product of the density by the velocity Eq (3.8). This fundamental relationship is described by a fundamental diagram obtained from an experimental study of a section of road, corresponding to a succession of points of equilibrium between all these variables.

$$Q(x,t) = K * V(K(x,t)) \tag{3.8}$$

Several authors have proposed numerous representations of the fundamental diagram. Among the most commonly encountered relationships are those proposed by [51][52][54][55]. The first scientific studies on the traffic flow go back to the works Greenshield's model [51]. This model represents how the behavior of one parameter of traffic flow changes with respect to another. The most simple relation between speed and density is proposed by Greenshield and scaled the fundamental relation or fundamental diagram later. The fundamental diagram family and its most important relations is shown in Fig 3.7.

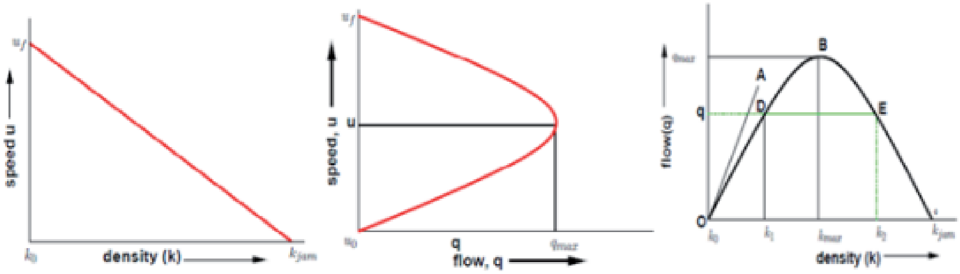


Figure 3.7: Fundamental traffic flow diagram

Many other models came up, prominent among them, we found Greenberg's model. Greenberg used a fluid-flow analogy concept and proposed a logarithmic speed-density relationship. This model shows better goodness of fit compared to Greenshield's model. The main disadvantage of this model is its inability to predict speed at lower densities. That is due when a density approaches zero, speed tends to increase to infinity (Fig 3.7). In 1961,

[56] suggested an exponential speed-density relationship and derived an exponential model that attempted to overcome the limitation of the Greenberg model. The most advantage of this model is shows better than Greenshield and Greenberg Models for uncongested condition but not good in congested condition. The main drawback of the model is speed becomes zero only when density reaches infinity. Hence this cannot be used for predicting speeds at high densities [57] (Fig 3.8).

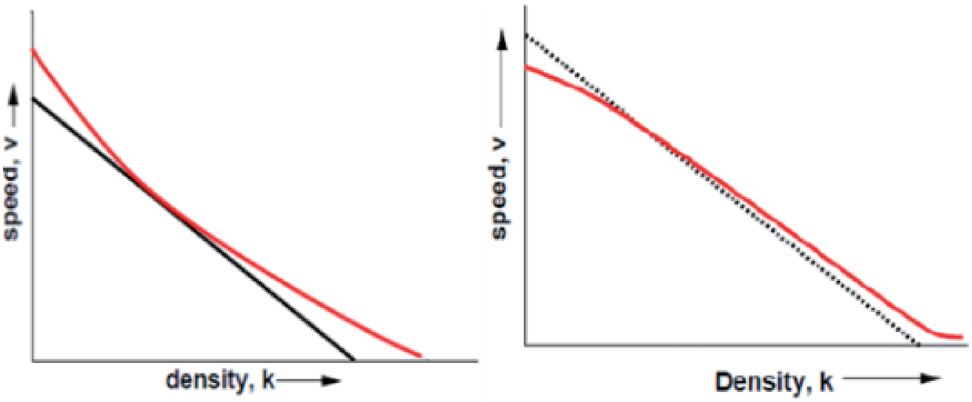


Figure 3.8: Speed density relationship by [51] and [56]

Fundamental Diagrams can be presented by the following formula [58]. The table 3.4 below summarizes the fundamental diagrams proposed in the literature.

Table 3.4: Fundamental diagrams proposed in the literature

Auteurs	Fundamental diagram
Greenshields, 1935	$Q_e(K) = K.V_{max}[1 - (\frac{K}{K_{max}})]$
Chandler, 1958	$Q_e(K) = Q_{max}[1 - (\frac{K}{K_{max}})]$
Greenberg, 1959	$Q_e(K) = K.V_{critique} \ln(\frac{K}{K_{max}})$
Edie, 1960	$Q_e(K) = K.V_{max} \exp(-(\frac{K}{K_{max}}))$
May, 1990	$Q_e(K) = K.V_{max} \exp(-\frac{1}{a}(\frac{K}{K_{critique}})^a)$

- Second order models

The second order models allow to take into account the states of non-equilibrium as well as the situations of convergence towards a state of equilibrium. In order to study the non-equilibrium states (accelerations and deceleration), many authors have proposed to complete the LWR model with an independent dynamic equation expressing the behavior of the acceleration a of the flux [50] [59] [48] [60]. The general form of this equation, which reflects the behavior of the acceleration of the flow is presented by a relaxation term (towards the state of equilibrium) and by a term which expresses at least one individual behavior of the vehicles Eq (3.9).

$$\begin{aligned} a &= \frac{\partial V(x,t)}{\partial t} + V(x,t)\frac{\partial V(x,t)}{\partial x} \\ &= \frac{V_{eq}(K) - V}{T}(Relaxation) + B \end{aligned} \tag{3.9}$$

The term B allows to distinguish the various models of the second order. The first work in this direction was proposed by [50]. Other models were introduced then, in order to correct the main faults of Payne's model, including the isotropic nature of the model. There are some gaps in higher order models (i.e. models involving more than two equations) as outlined in the paper [48]. In ref, the authors [61] and [62] proposed a new models which have been able to correct several problems by deducing a common formalism of the second order models.

$$\begin{cases} \dfrac{\partial K}{\partial t} + \dfrac{\partial VK}{\partial x} \\ \dfrac{\partial V}{\partial t} + V\dfrac{\partial V}{\partial x} = \frac{1}{T}(V_{eq}(K) - V) - \frac{1}{K}C^2(K)\dfrac{\partial K}{\partial x} \end{cases} \tag{3.10}$$

Where T is the reaction time and C corresponds to the speed characteristic of the traffic. The term $\dfrac{\partial V}{\partial t} + V\dfrac{\partial V}{\partial x}$ designates the acceleration, the expression $\frac{1}{T}(V_{eq}(K) - V)$ indicates the relaxation term, and $\frac{1}{K}C^2(K)\dfrac{\partial K}{\partial x}$ is anticipation term. Different expressions of this celerity have been proposed and presented in Table 3.5.

Table 3.5: Different models of the second order developed since the model of Payne [73]

Model	$C(K)$
Payne, 1971	$C(K) = \sqrt{\dfrac{-V_e'(K)}{2T}}$
Aw et Rascle, 2000	$C(K) = -K.P'(K), withP'(K) = aK'$
Zhang, 2002	$C(K) = K.V_e'(K)$
Jiang et al., 2002	$C(K) = -c_0$

3.3 Safety related indicators

Safety in the traffic system is most usually measured in terms of the number of traffic accidents and the consequences of accidents in terms of fatalities and injuries of varying severity. This is a traditional approach that has established the use of accident data as an accepted measure of safety. Proximal safety indicators have been suggested as an alternative to the use of accident data. These are defined as measures of accident proximity, based on the temporal and/or spatial measures that reflect the closeness of road-users (or their vehicles), in relation to the projected point of collision. The actual measure of accident proximity depends on the safety indicator concept or technique used. Furthermore, the use of surrogate safety indicators is also a more resource efficient and ethically appealing alternative for fast, reliable and effective safety assessment [63].

Despite the many advantages related to the use of proximal safety indicators, a number of fundamental problems have been identified. These concern the lack of a consistent definition, their validity as a measure of traffic safety, and the reliability of their associated measurement technique. The intention of this section is to discuss many of the theoretical and practical problems associated with different safety indicators and their associated measurement techniques. Particular attention is given to the Time-to-Collision measure and various derivatives including Post-Encroachment Time. These concepts are widely recognized as established proximal safety indicator measures by researchers and safety analysts.

3.3.1 Time-to-Collision measure

One of the most well known proximal indicators of traffic safety is Time-to-Collision initially introduced by [64] as a time based surrogate safety measure for evaluating collision risk [65][66][67]. This indicator has been used as an alternative for other traffic conflict techniques. This particular indicator was originally suggested by [64] who described a TTC event as: *"...the time that remains until a collision between two vehicles would have occurred if the collision course and speed difference are maintained."*

The general TTC definition implies that the reaction time of the road-user is also considered, which in some cases may be important with regard to the intention and purpose of safety study [68]. In car following situations the TTC indicator is only defined when the speed of the following vehicle is higher than the speed of the lead vehicle [67]. Rear end collision risk is defined as the time for the collision of two vehicles if they continue at their present speed and on the same lane and at the same speed (Fig 3.9). The time to collision of a vehicle driver combination i at instant t with respect to a leading vehicle $i+1$ can be calculated with:

$$TTC = \frac{S_i(t)}{\dot{S}_i(t)} \forall S_i(t) > 0 \tag{3.11}$$

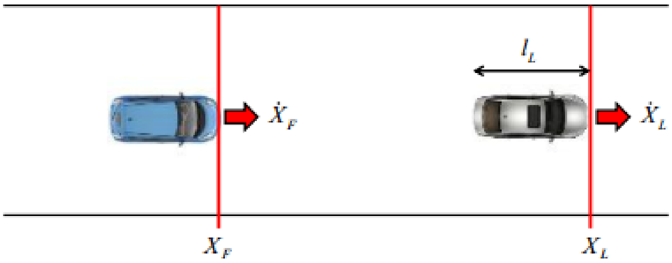


Figure 3.9: TTC for rear end collision

Since head-on conflicts are the same as rear-end ones except that the leading vehicles velocity is in the opposite direction. So TTC is [69]:

$$TTC = \frac{x_1 - x_2}{v_1 + v_2} \tag{3.12}$$

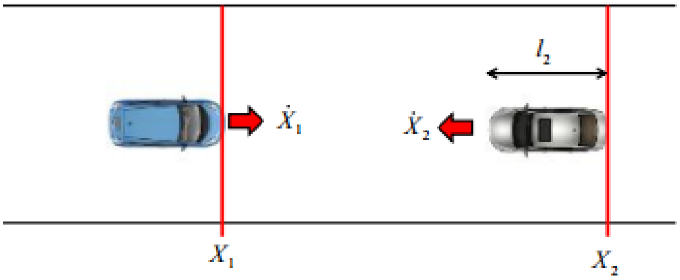


Figure 3.10: TTC for head-on collision

For right-angle conflicts the following equation can be applied [70]:

$$TTC = \begin{cases} \frac{d_2}{v_2}, if \frac{d_1}{v_1} < \frac{d_2}{v_2} < \frac{d_1+l_1+w_2}{v_1} \\ \frac{d_1}{v_1}, if \frac{d_2}{v_2} < \frac{d_1}{v_1} < \frac{d_2+l_2+w_1}{v_2} \end{cases} \tag{3.13}$$

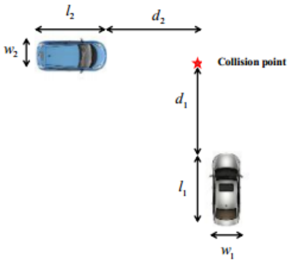


Figure 3.11: TTC for right-angle conflicts

An example representing a typical conflict situation and the calculation of Time-to-Collision is illustrated below in Fig 3.12. The figures show the calculation of TTC on two separate occasions, although it should be remembered that these calculations are made continually at regular time-intervals during the course of a safety critical event for the purposes of determining a "minimum" TTC-value.

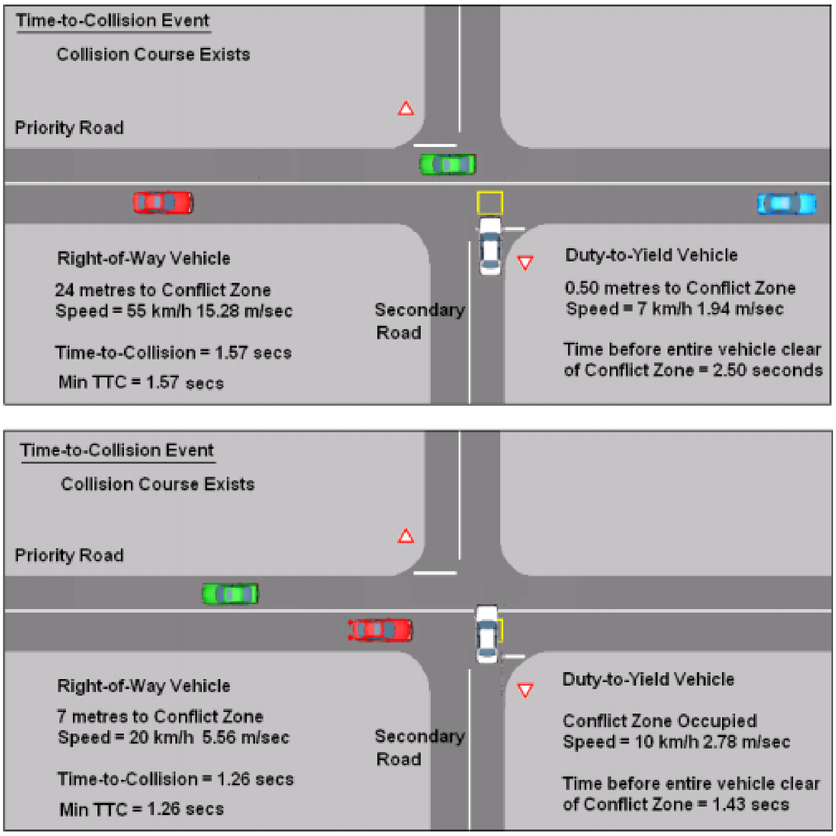


Figure 3.12: Example of a conflict situation and the calculation of Time-to-Collision

3.3.2 Extended Time-to-Collision (TET, TIT)

The researchers [70] have proposed two alternative proximal safety indicators that are based on general principles of the Time-to-Collision concept. The first of these is referred to as Time Exposed TTC (TET) and represents a summation of all moments that a driver approaches a front vehicle with a TTC-value below the threshold value TTC^*, the latter is considered to be the boundary between safe and safety-critical approaches. The TET indicator for a subject i can be expressed by:

$$\begin{aligned} TET_i &= \sum_{t=0}^{T} \delta i(t) \tau \\ \delta i(t) &= \begin{cases} 0, else \\ 1, \forall 0 \leq TTC_i(t) \leq TTC^* \end{cases} \end{aligned} \tag{3.14}$$

In which δ is a switching variable, H is a time period, τ is a small time step, and $T = \frac{H}{\tau}$ is the time instants t taken into account in the calculation ($t = 0...T$). Its value is 1 in case a driver i at instant t experiences a TTC value between 0 and the specified threshold value TTC^*, otherwise, its value is 0.

The second indicator, referred to as Time Integrated TTC (TIT), is similar to the first but represents a measure of the integral of the TTC profile during the time it is below the threshold. In continuous time expressed as:

$$TIT_i = \sum_{i=1}^{N} \int_0^T [TTC^* - TTC_i(t)]dt, \forall 0 \leq TTC_i(t) \leq TTC^* \tag{3.15}$$

Both measures are illustrated in Fig 3.13 below.

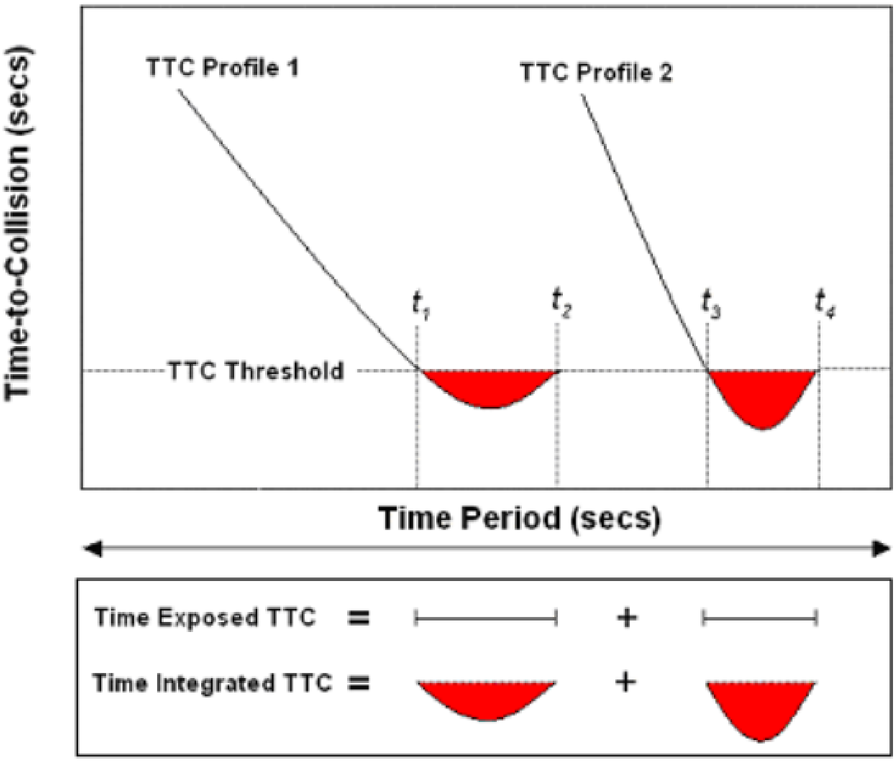


Figure 3.13: The Time Exposed and Time Integrated TTC proximal safety indicator measures proposed by [70]

3.3.3 Post-Encroachment Time (PET)

A further variation of the Time-to-Collision concept is Post-Encroachment Time (PET). This measure is used to measure situations in which two roads-users that are not on a collision course, pass over a common spatial point or area with a temporal difference that is below a predetermined threshold. PET is the difference between times that a vehicle enters a conflict point until another vehicle arrives to this point [71]. PET can be applied for intersections and highways. The measure represents the difference in time between the passage of the "offended" and "conflicted" road-users over a common conflict zone (i.e. area of potential collision) [72]. An example representing the calculation of Post-Encroachment Time is illustrated below in Fig 3.14. The example shown below indicates the position of the two vehicles involved in the safety critical event at the start and end of the PET-measurement.

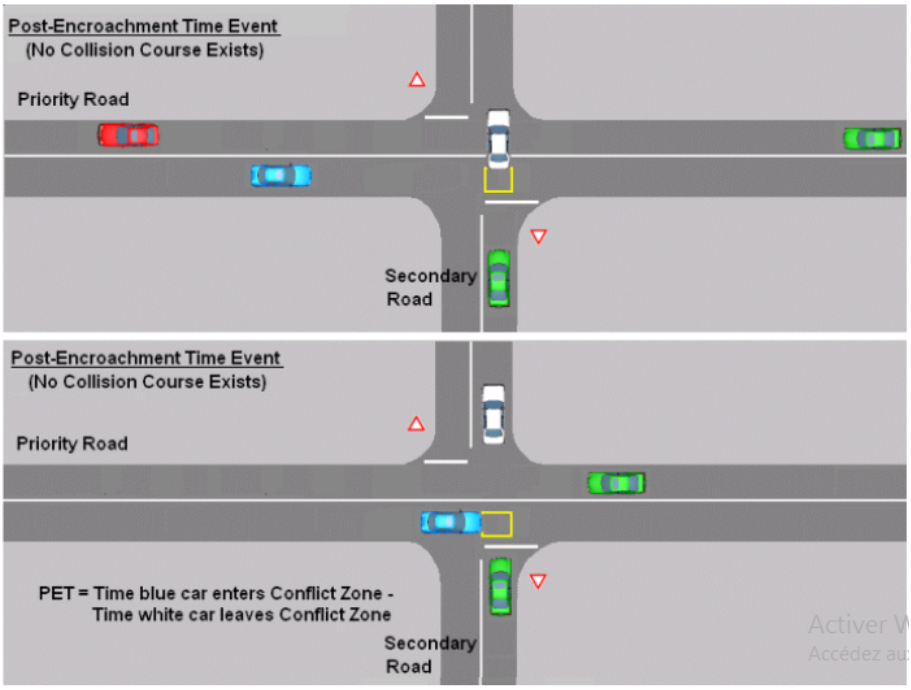


Figure 3.14: Example of the calculation of a Post-Encroachment Time event

3.4 Chapter summary

The intention of this chapter is to discuss many of the theoretical problems associated with the traffic flow theory. The majority of simulation software tools include two levels of modeling: macroscopic models (low fidelity), which describe entities and their activities and interactions at a relatively low level of detail and established relationships between speed, flow and density. Microscopic models (high fidelity) are better adapted to the description of more punctual elements of the network, while macroscopic models are adapted to the representation of networks of large sizes. The existing microscopic and macroscopic car-following models are investigated. Then, we highlight the safety indicators that can measure safety in traffic flow and the way in which each criterion could be measured. In the next chapter, we examine existing microscopic simulation models to evaluate the safety dynamically, and emphasized the demand for a new models guarantee the safety perspective.

Chapter 4

Microscopic Modeling and simulation of traffic flow

Sommaire

The intention of this chapter is to provide a survey of microscopic car following models. We interest specially to review the most car-following model well-known the optimal velocity model, which has successfully revealed the dynamical evolution process of traffic congestion in a simple way. Furthermore, we aim to criticize and give the advantages and weaknesses of each model, which constitutes a strong perspective to develop a better one [73].

4.1 Optimal velocity models

Newell Model

One of the first models learning on an analysis of the trajectories of vehicles and firstly defined the optimal velocity function is Newell [74]. The acceleration of a vehicle represents the driver's response and is determined by the following equation:

$$\begin{aligned} v_i(t+T) &= V_{opt}(S_i(t)) \\ &= V_{opt}(x_{i+1}-x_i) \end{aligned} \tag{4.1}$$

With $V_{opt}(S(t))$ is the optimal velocity under the headway $S(t)$. This model has directly given the speed of $n-th$ car by the optimal velocity function.

OV Model

In the mid-1990s, Bando introduced the notion of desired velocity, chosen as a function of relative spacing or headway [75]. They introduced two major types of theories for car-following regulations. The first type called follow-the leader theory which was used by [74], based on the idea that each vehicle must maintain the legal safe distance of the preceding vehicle, which depends on the relative velocity of these two successive vehicles. The other type for regulation is that each vehicle has the legal velocity, which depends on the following distance from the preceding vehicle. Based on the latter assumption, [75] investigated the equation of traffic dynamics and found a realistic model of traffic flow. The mathematical form is given as:

$$a_i(t) = \kappa(V_{opt}(S_i(t)) - v_i(t)) \tag{4.2}$$

The stimulus here was a function of the relative spacing and the sensitivity κ was a constant which did not introduce the time lag of response. The optimal velocity function proposed by [75], generally, must satisfy the following properties: It is a monotonically increasing function and it has an upper bound (maximal velocity). The optimal velocity function as that used by [75] expressed as:

$$V_{opt}(S_i(t)) = \frac{v_{max}}{2}\{\tanh(S(t) - h_c) + \tanh(h_c)\} \tag{4.3}$$

where h_c is the safety distance. When $S(t) \to \infty$, the optimal velocity reaches the maximal velocity $V(\infty) = \frac{v_{max}}{2}\{1 + \tanh h_c\}$. Furthermore, when $h_c \gg 0$, $V(\infty) \cong v_{max}$: the maximal value of the optimal velocity is v_{max} for $S(t) \gg h_c \gg 0$.

GF Model

Helbing and Tilch [76] proposed an extended model considering the headway and the velocity of the following car and the relative velocity between the preceding vehicle and the following vehicle when the following vehicle was faster than the preceding vehicle. They added a new term to the right of Eq (4.2). This new term represents the impact of the negative difference in velocity on condition that the velocity of the front vehicle is lower than that of the follower. The GFM formula is:

$$a_i(t) = \kappa(V_{opt}(S_i(t)) - v_i(t)) + \lambda\Theta(-\dot{S}_i(t))\dot{S}_i(t) \tag{4.4}$$

They carried out a calibration of the OV model with the empirical follow-the-leader data and given the function of OVM model as follows:

$$V_{opt}(S_i(t)) = V_1 + V_2 \tanh[C_1(S_i(t) - l) - C_2] \tag{4.5}$$

With V_1 , V_2 , C_1 , C_2 parameters calibrated.

Multi-following Model

The Multi-following model proposed by [77] is an extension of the OV model which take into consideration the multi-vehicle interactions. They suppose that drivers do not only react on the dynamics of their leading vehicle, but also take into consideration up to m cars ahead with a sensitivity κ_j. Their equation is presented as follows:

$$a_i(t) = \sum_{j=1}^{m} a_j V_{opt}(\frac{x_{i+j} - x_i}{j}) - v_i, i = 1, 2, ..., N \tag{4.6}$$

N is the total number of vehicles.

FVD Model

Jiang et al.[78] proposed an extended model considering the headway and the velocity of the following car and the relative velocity between the following vehicle and the preceding vehicle, and takes both positive and negative velocity differences into account, which was called full velocity difference (FVD) model. They obtained a more systematic model, one whose dynamics equation is as:

$$a_i(t) = \kappa(V_{opt}(S_i(t)) - v_i(t)) + \lambda \dot{S}_i(t) \tag{4.7}$$

λ is another sensitivity parameter.

MOV Model

In[79] model, the introduction of a weighting term makes it possible to reactivity of the model to braking. This weighting is a function of the collision time. The modified optimal velocity function expressed as:

$$V_{opt}^{new}(S_i(t), \dot{S}_i(t)) = V_{opt}(S_i(t)) * W(S_i(t), \dot{S}_i(t)) \tag{4.8}$$

Where the weighting factor is as follows:

$$W(S_i(t), \dot{S}_i(t)) \quad = \quad \frac{1}{2} + \frac{1}{2}\tanh B(\frac{\dot{S}_i(t)}{S_i(t)} + C) \tag{4.9}$$

The dynamic equation of the system is obtained as:

$$a_i(t) \quad = \quad \kappa(V_{opt}^{new}(S_i(t), \dot{S}_i(t)) - v_i(t)) \tag{4.10}$$

FVAD Model

Zhao and Gao [80] developed the new car- following model based on FVD model. They found out that the velocity difference is not enough to avoid an accident under an urgent case where they defined as:

"A situation that the preceding car decelerates strongly, if two successive cars move forward with much small headway distance, e.g. a freely moving car decelerates drastically for an accident in front or the red traffic light at an intersection, the following car is freely moving and the distance between the two cars is quite small"

For these reasons, they extend the FVDM by incorporating the acceleration difference, and then get a new model called the full velocity and acceleration difference model (FVADM) as follows:

$$a_i(t) \quad = \quad \kappa(V_{opt}(S_i(t)) - v_i(t)) + \lambda\dot{S}_i(t) + \beta g(\ddot{S}_i(t-1), a_{i+1}(t))\ddot{S}_i(t-1) \tag{4.11}$$

With $\ddot{S}_i(t) = a_{i+1}(t) - a_i(t)$ is the acceleration difference between the preceding vehicle $i+1$ and the following vehicle i. The function $g(.)$ is to determine the sign of the acceleration difference term.

$$g(\ddot{S}_i(t-1), a_{i+1}(t)) = \begin{cases} -1, \ddot{S}_i(t-1) > 0 and a_{i+1}(t) \\ \\ \hfill 1, others \end{cases} \tag{4.12}$$

VSD Model

In 2006, the authors [81] conducted a detailed analysis of FVDM and found out that second term in the right side of Eq (4.7) makes no allowance of the effect of the inter-car spacing independently of the relative velocity. For that, they proposed a velocity-difference-separation model (VDSM) which takes the separation between cars into account and the dynamics equation becomes:

$$\begin{aligned} a_i(t) &= \kappa(V_{opt}(S_i(t)) - v_i(t)) \\ &+ \lambda\Theta(\dot{S}_i(t))\dot{S}_i(t)(1 + \tanh(C_1(S_i(t) - l) - C_2)^3 \\ &+ \lambda\Theta(-\dot{S}_i(t))\dot{S}_i(t)(1 - \tanh(C_1(S_i(t) - l) - C_2)^3 \end{aligned} \tag{4.13}$$

Lijuan and Ning Model

Lijuan and Ning [82] suggested a new car following model based on FVDM with acceleration of the front car considered. With detailed study, they observed than when FVDM simulate the car motion all the vehicle accelerate until the maximal velocity and when the velocity reach maximal velocity the acceleration and deceleration appeared repeatedly. For that, they modified the Eq (4.7) to take into account the influencing factor of the following car by adding up to Eq (4.7) the leading acceleration. The dynamic equation of the system is obtained as:

$$a_i(t) = \kappa(V_{opt}(S_i(t)) - v_i(t)) + \lambda\dot{S}_i(t) + \gamma a_{i+1}(t) \tag{4.14}$$

Where γ is the sensitivity, expressing the response intensity of the follow car to leading acceleration.

MHVAD Model

The authors introduced all the three types of ITS information either headway, velocity, or acceleration difference to stabilize the traffic flow. Based on this idea, [83] proposed a new car-following model takes into account the effects of the acceleration difference of the multiple preceding vehicles which affects to the behavior of the following vehicle just as the headway and the velocity difference, called multiple headway, velocity, and acceleration difference (MHVAD). Its mathematical description is following:

$$\begin{aligned} a_i(t) &= \kappa(V_{opt}(\sum_{j=1}^{q} \beta_j S_{i+j-1}(t)) - v_i) \\ &+ \lambda \sum_{j=1}^{q} \xi_j \dot{S_{i+j-1}}(t) \\ &+ \gamma \sum_{j=1}^{q} \zeta_j \ddot{S_{i+j-1}}(t) \end{aligned} \tag{4.15}$$

Taking q preceding vehicles and β_j, ξ_j, $\zeta_j \in \Re$, and $\beta_j \geq 0$, $\xi_j \geq 0$, $\zeta_j \geq 0$ are different weighting value coefficients, respectively. The β_j satisfies two conditions:

1. β_j is a monotone decreasing function with $\beta_j \leqslant \beta_{j-1}$, because the effect of the preceding vehicle to the current car reduces with the increase of the headway distance.
2. $\sum_{j=1}^{q} \beta_j = 1$, $\beta_j = 1$ for $q = 1$ so as to ξ_j, and ζ_j

And β_j is defined as follows:

$$\begin{aligned} \beta_j &= \frac{q-1}{q^j} for j \neq q \\ &+ \lambda \sum_{j=1}^{q} \xi_j \dot{S_{i+j-1}}(t) \\ &+ \gamma \sum_{j=1}^{q} \zeta_j \ddot{S_{i+j-1}}(t) \end{aligned} \tag{4.16}$$

$$\beta_j = \begin{cases} \frac{q-1}{q^j} for j \neq q \\ \\ \frac{1}{q^{j-1}} for j = q, j = 1, 2, ...q \end{cases} \tag{4.17}$$

The optimal velocity function $V_{opt}(.)$ used here is the Eq (4.3).

MFVDM I and MFVDM II

Jing et al. [84] modified a FVD model to get two extended car- following models MFVDM I and II. In the first time, they proposed the modified full velocity difference model (MFVDM I) taking into account the following optimal velocity function (Helbing and Tilch, 1998) Eq (4.5).

$$V_{opt}(S_i(t), v_i(t)) = v_i^0(1 - \exp(-\frac{S_i(t) - S(v_i(t))}{R_n})) \tag{4.18}$$

The proposed MFVDM I mathematical form expressed as

$$a_i(t) = \kappa(V_{opt}(S_i(t), v_i(t)) - v_i(t)) + \lambda \dot{S}_i(t) \tag{4.19}$$

where R_n is the range of the acceleration interaction and $S(v_i(t))$ is a certain velocity-dependent safe distance. The authors have improved that optimal velocity $V_{opt}(S_i(t), v_i(t))$ is a function of the vehicle distances and the velocity of the following vehicle which must satisfy three conditions:

1. $V_{opt}(S_i(t), v_i(t))$ is monotonically increasing to$S_i(t)$ and $v_i(t)$.
2. The larger values of $V_{opt}(S_i(t), v_i(t))$, will be beneficial to make FVDM fit with the field data better.
3. $\lim S_i \to +\infty V_{opt}(S_i(t), v_i(t)) \cong v_i^0$ and $\lim v_i \to v_i^0 V_{opt}(S_i(t), v_i(t)) \cong v_i^0$ where v_i^0 is the desired velocity of the following vehicle.

For above analysis, they proposed a new optimal velocity function satisfies the above three conditions defined as forms:

$$V_{opt}(S_i(t), v_i(t)) = v_i^0 \tanh(\frac{S_i(t) - S(v_i(t))}{R_n}) \tag{4.20}$$

In second time, substituting the Eq (4.20) into Eq (4.19), and they get the second modified full velocity difference model(MFVDM II). Finally, they introduced a new optimal velocity function Eq (4.20) and modified the additional term of Eq (4.7) to get a new model called the improved full velocity difference model (IFVDM) defined as follows:

$$a_i(t) \quad = \quad \kappa(V_{opt}(S_i(t), v_i(t)) - v_i(t)) + \alpha \dot{S}_i(t) \tag{4.21}$$

The additional term α defined as a form:

$$\alpha \quad = \quad \frac{1 - \frac{S_i(t) - S(v_i(t))}{R_n}}{\mu_i} \tag{4.22}$$

where μ_i is the reaction time of the addition term.

COV Model

Another car-following model proposed by [85] incorporating a new optimal velocity model in Eq (4.2), whose not only depends on the following distance of the preceding vehicle, but also depends on the velocity difference with preceding vehicle. they proposed a new model called Comprehensive Optimal Velocity Model (COVM), its mathematical expression:

$$a_i(t) \quad = \quad \kappa(V_{opt}(S_i(t), \dot{S}_i(t)) - v_i(t)) \tag{4.23}$$

They suggested a new optimal velocity function $V_{opt}(S_i(t), \dot{S}_i(t)$ as:

$$V_{opt}(S_i(t), \dot{S}_i(t)) \quad = \quad V_1(S_i(t)) + \sigma V_2(\dot{S}_i(t)) \tag{4.24}$$

with σ is the reaction coefficient to the relative velocity and $0 < \sigma < 1$. They replaced their new function of Eq (4.24) in Eq (4.23), they get a new model expressed as follows:

$$a_i(t) = \kappa(V_1(S_i(t)) - v_i(t)V_1(S_i(t)) - v_i(t)) + \lambda V_2(\dot{S}_i(t)) \tag{4.25}$$

Taking $\lambda = \kappa\sigma$, $V_1(S_i(t))$, is the same with that of the OVM Eq (4.5) and $V_2(\dot{S}_i(t)) = L\tanh(C_3(\dot{S}_i(t)))$. Where L, and C_3 are constants.

CCF Model

In real driving behaviors, keeping a safe distance reflects the drivers' driving intention and accordingly affects vehicle maneuvers. Based on this study, [86] targeted at developing a new car-following model that takes the impact of a desired following speed and safe distance as part of driving behavior modeling. According to the safe space headway theory, the safe distance $S_i^{safe}(t)$ can be defined as follows:

$$\begin{aligned} S_i^{safe}(t) &= (d_i + S_0 + L_{i+1}) - d_{i+1} \\ &= S_0 + L_{i+1} + v_i(t)T_i + \frac{\dot{S}_i(t)(v_i(t) + v_{i+1}(t))}{2\alpha} \end{aligned} \tag{4.26}$$

where d_{i+1} denotes the braking distances of the leading vehicle, d_i is the braking distance of the following vehicle, S_0 is the minimum distance kept in static traffic, L_{i+1} is the length of the leading vehicle, and α is the acceleration. They are modeled two effects by using force, $f_i^{(+)}(t)$ and $f_i^{(-)}(t)$ which represents the attractive force of acceleration and the retardant force of deceleration respectively. Then, they get a new car-following model as a form:

$$m_i a_i(t) = f_i^{(+)}(t) + f_i^{(-)}(t) \tag{4.27}$$

With $f_i^{(+)} = m_i\kappa(V_{opt}(S_i(t)) - v_i(t))$, and $f_i^{(-)} = m_i\lambda(1 - \frac{S_i^{safe}(t)}{S_i(t)})$. Taking both the desired following speed of positive correlation and the safe distance of negative correlation, they name their model the cooperative car-following model (CCFM), replace the forces into Eq (4.27) to get the CCFM expression.

$$a_i(t) = \kappa(V_{opt}(S_i(t)) - v_i(t)) + \lambda(1 - \frac{S_i^{safe}(t)}{S_i(t)}) \tag{4.28}$$

AFVD Model

Xu et al. [87] presented an asymmetric full velocity difference approach, in which take into account the effect of asymmetric acceleration and deceleration in a car-following. The most existing car-following models have not sufficiently taken the asymmetry of acceleration and deceleration behaviours into consideration. The authors modified the GFM Eq (4.4) by extended to an asymmetric full velocity difference (AFVD) approach in which two sensitivity coefficients are defined to separate the model to positive and negative velocity. The AFVD model can be expressed as:

$$\begin{aligned} a_i(t) &= \kappa(V_{opt}(S_i(t)) - v_i(t)) \\ &+ \lambda_1 H(-\dot{S}_i(t))\dot{S}_i(t) \\ &+ \lambda_2 H(\dot{S}_i(t))\dot{S}_i(t) \end{aligned} \tag{4.29}$$

where H is the Heaviside function. They dedicated their efforts to calibrate λ_1 and λ_2 and they get the mathematical presentation.

$$\lambda_1 = \tfrac{1}{\tau_i^{\prime}} \exp - \tfrac{(S_i - S(v_i))}{R_i^{\prime}} \ ; \ \lambda_2 = \tfrac{1}{\tau_i^{"\prime}} \exp - \tfrac{(S_i - S(v_i))}{R_i^{"}}$$

with τ_i and R are two new parameters obtained during the mathematical derivation which need to be determined by field data.

AOV model

In 2015, the authors [88] interested in taking the asymmetric characteristic of the velocity differences of vehicles and they proposed an asymmetric optimal velocity model for a car-following theory (AOV). They based on the assumption that the relationship between relative velocity and acceleration (deceleration) is in general nonlinear as demonstrated by actual experiments (Shamoto et al., 2011). They formulated FVDM to get an asymmetric optimal velocity (AOV) car-following model as follows:

$$a_i(t) = \kappa(V_{opt}(S_i(t)) - v_i(t) + \dot{S}_i(t)\exp(-\mu\dot{S}_i(t))) \tag{4.30}$$

Yi-Rong et al. model

Recently, Yi-Rong et al. [89] proposed a new car- following model with consideration of individual anticipation behaviour. However, the effect of anticipation behaviour of drivers has not been explored in existing car-following models. In fact, they suggested a new model including two kinds of typical behaviour, the forecasting of the future traffic situation and the reaction-time delay of drivers in response to traffic stimulus. The main idea of this model is that a driver adjusts his driving behaviour, not only according the observed velocity $v_i(t)$ but also the comprehensive anticipation information of headway and velocity difference. The dynamics equation is as follows:

$$a_i(t) \;=\; \kappa(V_{opt}(S_i(t+p_1T)) - v_i(t)) + \lambda \dot{S}_i(t+p_2T) \tag{4.31}$$

Where $S_i(t+p_1T)$ denotes the driver's anticipation information of headway at time $t+p_1T$. $\dot{S}_i(t+p_2T)$ represents the anticipation information of the velocity difference at time $t+p_2T$. The variables p_1T and p_2T denote the time interval during which the headway and velocity difference information are anticipated, and variables p_1, p_2 are the anticipation coefficient corresponding to individual behavior in headway and velocity difference, respectively. Making the Taylor expansion of the variables $S_i(t+p_1T)$ and $\dot{S}_i(t+p_2T)$ and neglecting the non linear terms yields the following equation:

$$S_i(t+p_1T) = S_i(t) + \dot{S}_i(t)p_1T$$
$$\dot{S}_i(t+p_2T) = \dot{S}_i(t) + \ddot{S}_i(t)p_2T$$

Then, they calculate the optimal velocity $V_{opt}(S_i(t+p_1T))$ and they get it as a form $V_{opt}(S_i(t+p_1T)) = V_{opt}(S_i(t) + \dot{S}_i(t)p_1T)$

4.2 Review and synthesis

Several models are inspired by the dynamical model (OVM) proposed by [75] to describe many properties of real traffic flows such as the instability of traffic flow, the evolution of traffic congestion, and the formation of stop-and-go waves. We follow a tree model to show the historical development of the optimal velocity models (Fig 4.1). In 1988, due to the problems encountered the OVM such as high acceleration and unrealistic deceleration, [76] proposed GFM that takes into account the impact of the negative difference in velocity on condition that the velocity of the front vehicle is lower than that of the follower.

The main drawback of GFM doesn't take the effect of positive velocity difference on traffic dynamics into account and only considers the case where the velocity of the following vehicle is larger than that of the leading vehicle. Then, [78] pointed out that when the preceding car is much faster, the following vehicle may not break even though the spacing is smaller than the safe distance. The basis of GFM and takes both positive and negative velocity differences into account, they proposed FVD model. The main advantage of FVDM is eliminating unrealistically high acceleration and predicts a correct delay time of car motion and kinematic wave speed at jam density. In fact, [80] argued that previous models OVM, GFM and FVDM does not describe the driver's behavior under an urgent case that the preceding car decelerates strongly, if two successive cars move forward with much small headway distance. They found out that the velocity difference is not enough to avoid an accident under such urgent case in previous models for that, they extend the FVDM to get the FVADM. The main advantage of FVADM compared to previous models that can describe the driver's behavior under an urgent case, where no collision occurs and no unrealistic deceleration appears while vehicles determined by the previous car-following models collide after only a few seconds.

In 2006, [81] conducted a detailed analysis of FVDM and found out that makes no allowance of the effect of the inter-car spacing independently of the relative velocity. For that, they proposed the VDSM which takes the separation between cars into account. The strong point of VSDM that the model can perform more realistically in predicting the dynamical evolution of congestion induced by a small perturbation, as well as predicting the correct delay time of car motion and kinematic wave speed at jam density. Lijuan and Ning [82] suggested a new car following model based on FVDM with acceleration of the front car considered. With detailed study, they observed than when FVDM simulate the car motion all the vehicle accelerate until the maximal velocity and when the velocity reach maximal velocity the acceleration and deceleration appeared repeatedly. For that, they modified the FVDM to take into account the influencing factor of the following car by adding the leading acceleration. They proved that their new model has certain enlightenment significance for traffic control, and is useful for establishment of Intelligent Transport Systems (ITS).

Previous models used only one type of ITS information, either headway, velocity, or acceleration difference of other cars to stabilize the traffic flow. However, traffic flow can be more stable by introducing all the three types of ITS information. Based on this idea, [83] proposed a new car-following model MHVAD takes into account the effects of the acceleration difference of the multiple preceding vehicles which affects to the behavior of the following vehicle just as the headway and the velocity difference. The main advantage of MHVAD Compared with the other existing models is that the proposed model does not only take the headway, velocity, and acceleration difference information into account, but also considers more than one vehicle in front of the following vehicle. The model improved the stability of the traffic flow and restrains the traffic jams.

Others category of car-following models inspired their idea to modify or to propose a new model via optimal velocity function. Among them,[84] introduced a new optimal velocity function. They pointed out that the new model can perform more realistically in predicting the correct delay time of vehicle motion and kinematic wave speed at jam density, as well as predicting the dynamical evolution of congestion induced by a small disturbance. Another car-following model COVM proposed by [85] incorporating a new optimal velocity model depends on the following distance of the preceding vehicle and the velocity difference with preceding vehicle. As discussed above, all of the previous models could not avoid collisions in the urgent braking situation. They improved that the unrealistically high deceleration will not appear in COVM, and the accidents in the urgent braking case can be avoid in COVM. Almost works has been reported the mechanisms of velocity difference, however, the relationship between space headway and safe distance in avoiding a collision is neglected. Based on this study, [81] targeted at developing a new car-following model CCFM. The main results of CCFM indicate that unrealistic deceleration and collisions can be prevented. Moreover, the CCFM averts negative velocity appearing in the COVM. In car-following approach, the efforts are more and more dedicated to the development of models with a high performance. In this regard, Xu et al. [87] presented AFVD model based on the effect of asymmetric acceleration and deceleration in a car-following. The purpose of the analysis of AFVDM pointed out that the positive velocity difference term is significantly higher than the negative velocity difference term, which agrees well with the results from studies on vehicle mechanics. Based on an asymmetric theory and OV model, in 2015, they suggested another car-following theory AOV. The main advantages of AOV model are avoiding the unrealistically high acceleration appearing in previous models when the velocity difference becomes large, however, the asymmetry of AOV model between acceleration and deceleration depends non linearly on the velocity difference with the asymmetrical factor. The author [89] investigated in car following theory and they proposed a new model. The authors improved that the effect of individual anticipation behavior has an important influence on the stability of the model and this effect should be considered in the modeling of traffic flow. In fact, they suggested including other factors which have a great effect on individual anticipation behavior, such as the size of vehicles, the age, the experience, and the physical fitness level of drivers, as well as the environment of the road and so on.

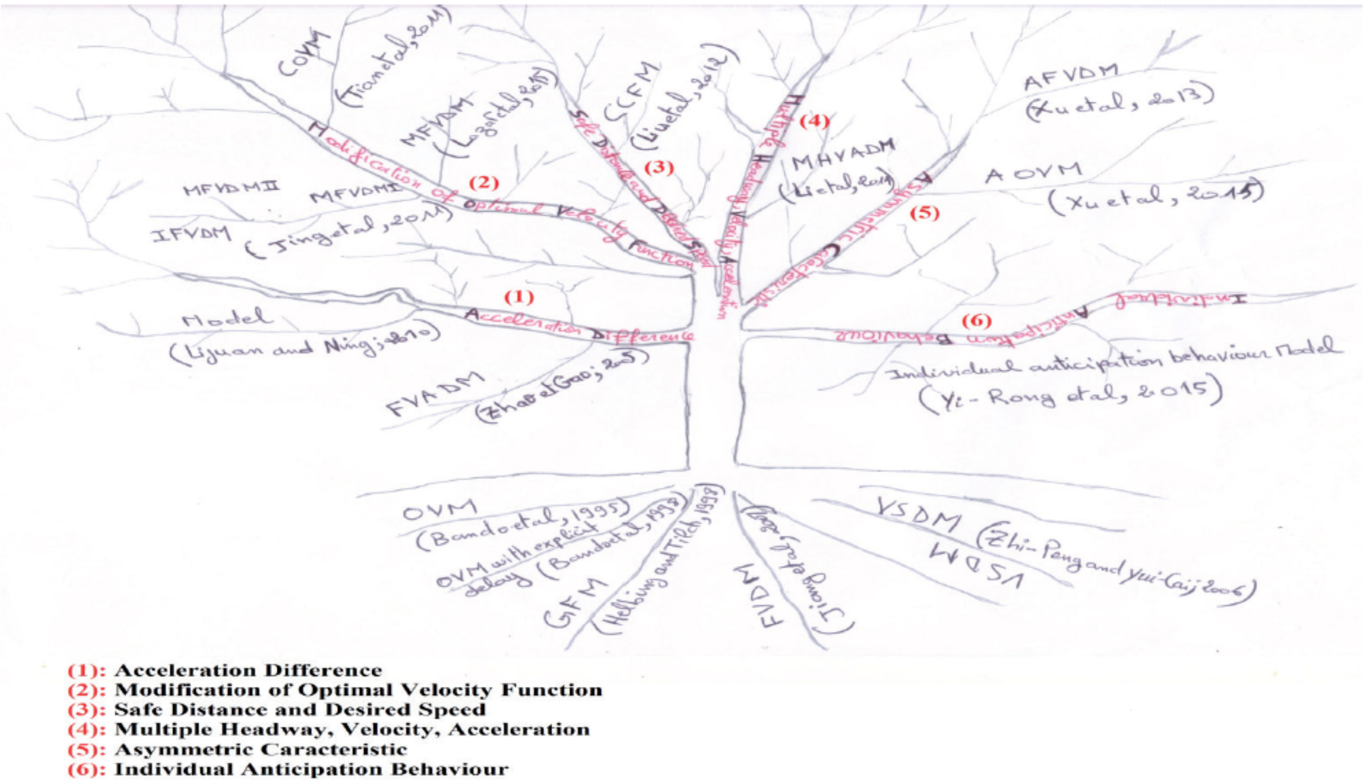


Figure 4.1: Model tree of optimal velocity Models

4.3 Proposed car following models

As presented above, thereafter, and inspired by the OV model, some new car-following models were successively put forward to describe the nature of traffic more realistically. Some were extended by incorporating a new optimal velocity function or introducing multiple information of headway or velocity difference, or acceleration difference, whereas others considered the individual anticipation behaviour. In this work, we also invested in car-following approach by introducing a new OV function. The selection of the OVF thus depends on a user's choice. However, this choice cannot be completely arbitrary since the OVF must satisfy several analytical conditions to describe the observed relation between spacing and velocity. The OVF should be a continuous non-negative function defined for $S_i > 0$ and must be a monotone function [90]. We used a new OVF introducing a weighting factor that depends on the ratio of the relative speed to spacing, that is the opposite of the inverse of time to collision (TTC) Eq (4.9). The goal of the weighting factor is to obtain model more reactive on braking state. This reactivity is based on the excess of follower speed in comparison to that of the leader. The weighting factor must satisfy some proprieties:

- When the relative speed is positive $\dot{S}_i(t) > 0$, the weighting must maintain the reference OV function Eq (4.5) unchanged.
- For negative decreasing relative speed $\dot{S}_i(t) < 0$, it has to be decreasing and has to go toward zero when $\dot{S}_i(t) -> infini$.

There are several functions which behave similarly with varying only the headway stimulus. Therefore, Here the new OV function modulates the reactivity of the car following model according to the actual headway and the relative speed between the follower and ahead car. The new optimal velocity function $V_{opt}^{new}(S_i(t), \dot{S_i(t)})$ is expressed as the combination of the optimal velocity function proposed by [75] based only on headway stimulus and the weighting factor established the inverse of time to collision to make the model more reactive in braking case.

$$V_{opt}^{new}(S_i(t), \dot{S_i(t)}) = V_{opt}(S_i(t)) * W(S_i(t), \dot{S_i(t)}) \tag{4.32}$$

The motivation for our contribution comes from the key idea behind the new optimal velocity function Eq (4.32). We also invested in car-following approach and we proposed two car-followings models named modified FVD model (MFVDM) [91] and modified VSD model (MVSDM) [92]. We inspired by [47] to get a MFVD model by incorporating the new OVF Eq (4.32) in FVDM Eq (4.7). Its mathematical description as follows:

$$a_i(t) \quad = \quad \kappa((V_{opt}^{new}(S_i(t), \dot{S}_i(t)) - v_i(t)) + \lambda \dot{S}_i(t) \tag{4.33}$$

According to the above analysis, the FVD model has a drawback that makes no allowance of the effect of the inter-car spacing independently of the relative velocity. In fact, they modified the FVDM by taking the separation between cars into account. Since this model takes velocity difference dependent on separation into account, they call it a velocity-difference-separation model (VDSM) Eq (4.13). Based on this latter, we proposed to extend the VSDM by introducing the new OVF Eq (4.32) to get a new model, named, Modified Velocity Separation Difference model (MVSDM). Figure 4.2 showed a proposed car-following algorithm. The dynamic equation becomes as follows:

$$
\begin{aligned}
a_i(t) &= \kappa(V_{opt}^{new}(S_i(t), \dot{S}_i(t)) - v_i(t)) \\
&+ \lambda\Theta(\dot{S}_i(t))\dot{S}_i(t)(1 + \tanh(C_1(S_i(t) - l) - C_2)^3 \\
&+ \lambda\Theta(-\dot{S}_i(t))\dot{S}_i(t)(1 - \tanh(C_1(S_i(t) - l) - C_2)^3 \qquad (4.34)
\end{aligned}
$$

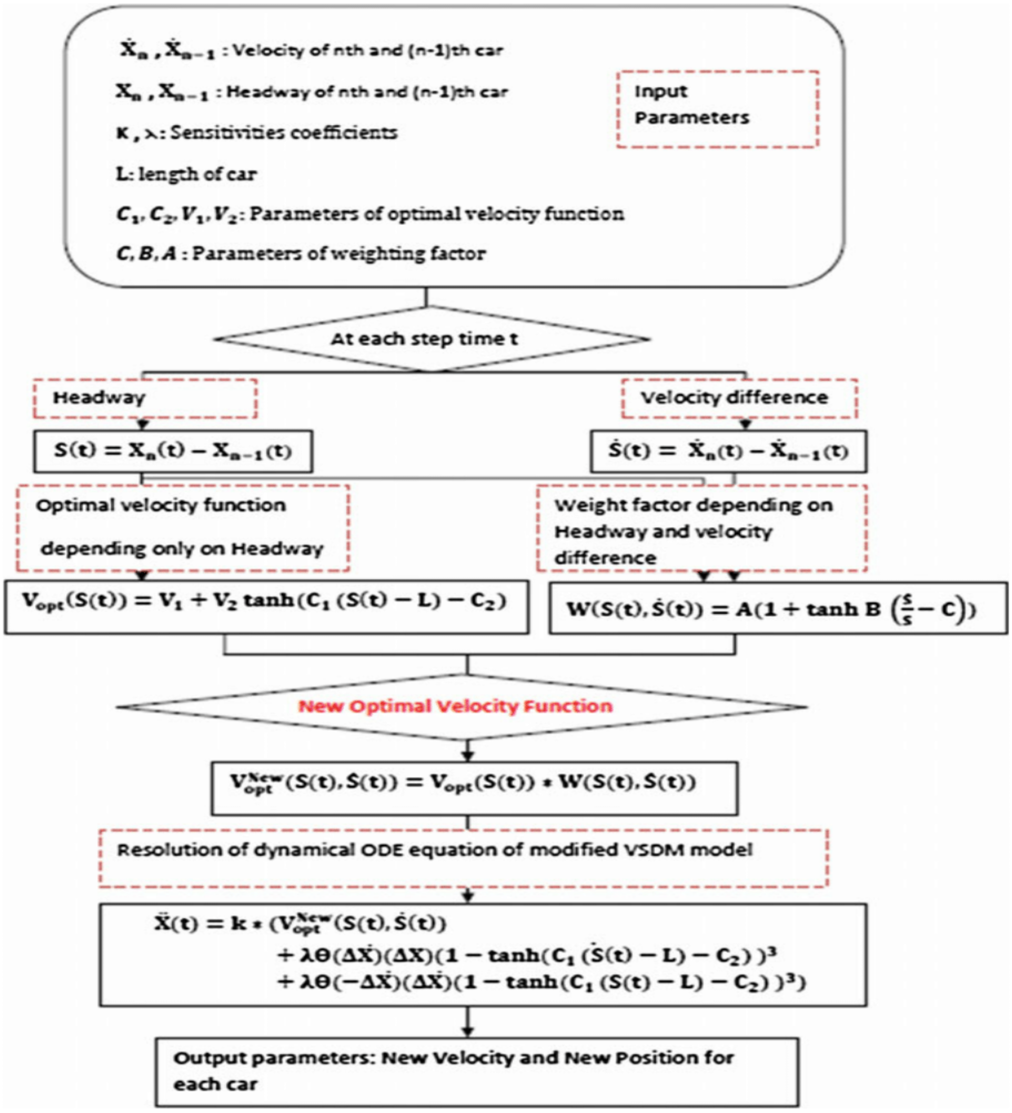


Figure 4.2: The MVSDM car following algorithm

4.4 Microscopic traffic flow approach

For an ideal flow of a dynamic traffic simulation study, we proposed the basic algorithm presented in Fig 4.3 which based on three major steps given as:

- Preparation of the traffic flow simulation: in this step, we must define the road environment and also we must specify the initial parameters and variables, including initialization of position, velocity, and so on.
- Implementation of the model and validation of its different scenarios: in this stage, we adopt our car following model to compute acceleration for each car and then compute the new speed and position on both lanes for the next time step. At the same time, we start lane changes rules, we determine which car change whereto and add these cars to the correct position on the lane and removed changed cars from their old lane.
- Analysis of results: for the next time step, we update the network and information state to get a new velocity and position state; then we jump to step 2, and we begin an another cycle.

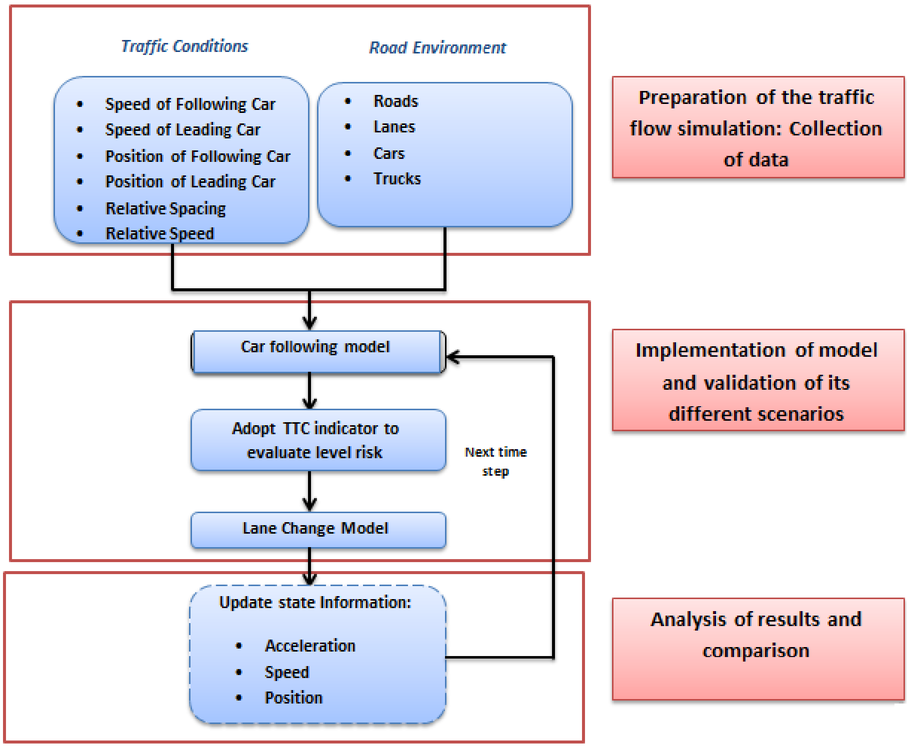


Figure 4.3: Flowchart of the proposed approach

4.4.1 State of art of lane changing models

The transfer of a vehicle from one lane to adjacent lane is defined as lane change. Lane change, as one of the basic driver behaviors, can never be avoided in the real traffic environment. Lane changing models are therefore an important component in microscopic traffic simulation Modeling the behavior of a vehicle within its present lane is relatively straightforward, as the only considerations of any importance are the speed and location of the preceding vehicle. Therefore the understanding of lane changing behavior is important in several application fields such as capacity analysis and safety studies. A number of lane changing models have been proposed and implemented in recent years [93] [94] [95].

The applications of lane changing models can be broadly classified into two groups: Driving Assistance models (i.e. adaptive cruise control) and Driving Decision models (computer simulation) as shown in Fig 4.4. Lane changing models for adaptive cruise control are mainly focused on developing driving assistance models, which can be further classified into collision avoidance models and automation models. Both of these model types consider the steering wheel angle and lateral motions to control the lane changing performance of vehicles [93]. Collision avoidance models are developed to control drivers lane changing manoeuvres and assist them to execute a safe lane change. Automation models are applied to perform the driving tasks either partially or entirely. Many studies have been focused on the scope for driving assistance systems to enhance road capacity and road safety [96][97][98][99][100][101][102][103].

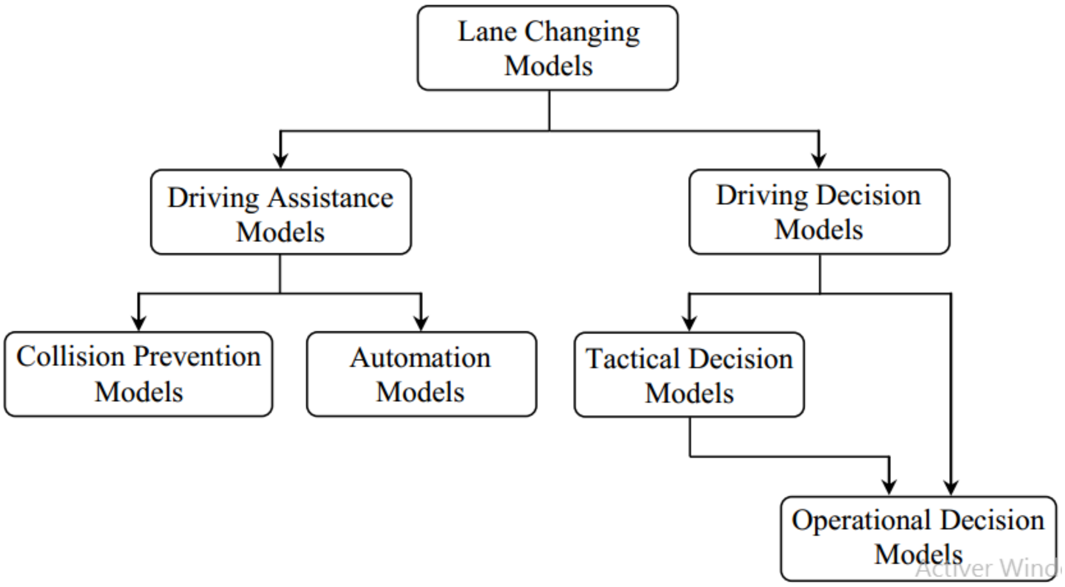


Figure 4.4: Classification of available approaches in lane changing studies

Lane changing models for computer simulation are focused on drivers lane changing decisions under different traffic conditions and under different situation and environmental characteristics. While responding to the surrounding environment, drivers' decisions can be classified as either strategic, tactical and operational [104]. The strategic level is the highest decision level and deals with drivers' decisions which require over 30 seconds making and executing. Strategic level decisions are usually made before the start of the trip and include the goal or purpose of the trip and choice of route [93]. A driver's destination choice, mode choice and route choice are examples of strategic driving decisions [105]. While executing the strategic level decisions, a series of tactical decisions are made by the drivers.

The tactical level includes anticipatory measures to enable or facilitate operative actions such as changing lanes or entering a priority road. At the tactical level, manoeuvres are selected to achieve short term objectives such as a decision to pass a slow moving vehicle or maintaining the desired speed. At the tactical, or intermediate, decision level, the time required for making and executing the decisions is between 5 and 30 seconds.

At the lowest decision level or the operational level, the manoeuvres are converted to control operations. Here, the drivers decide about the manoeuvres to control their vehicles. These take place on a time scale of less than five seconds and include decisions such as whether or not to accept a gap [98]. However, The authors [106] defined another level, namely, the post-decision phase which the actions pertaining to this decision are simulated, e.g. performing the lane change or keeping to one's lane, waiting or entering a priority road, or cruising versus stopping at the traffic light. The main focus of this section is to review microscopic lane changing models for computer simulation (see Fig 4.5). Since the 1980s, lane changing decision models underpin the microscopic traffic simulation packages being applied increasingly in research and practice. These lane changing models are categorized into four groups: rule-based model, discrete-choice-based model, artificial intelligence model, and incentive-based model. These models are the primary focus of this thesis and are considered in greater detail in the following section.

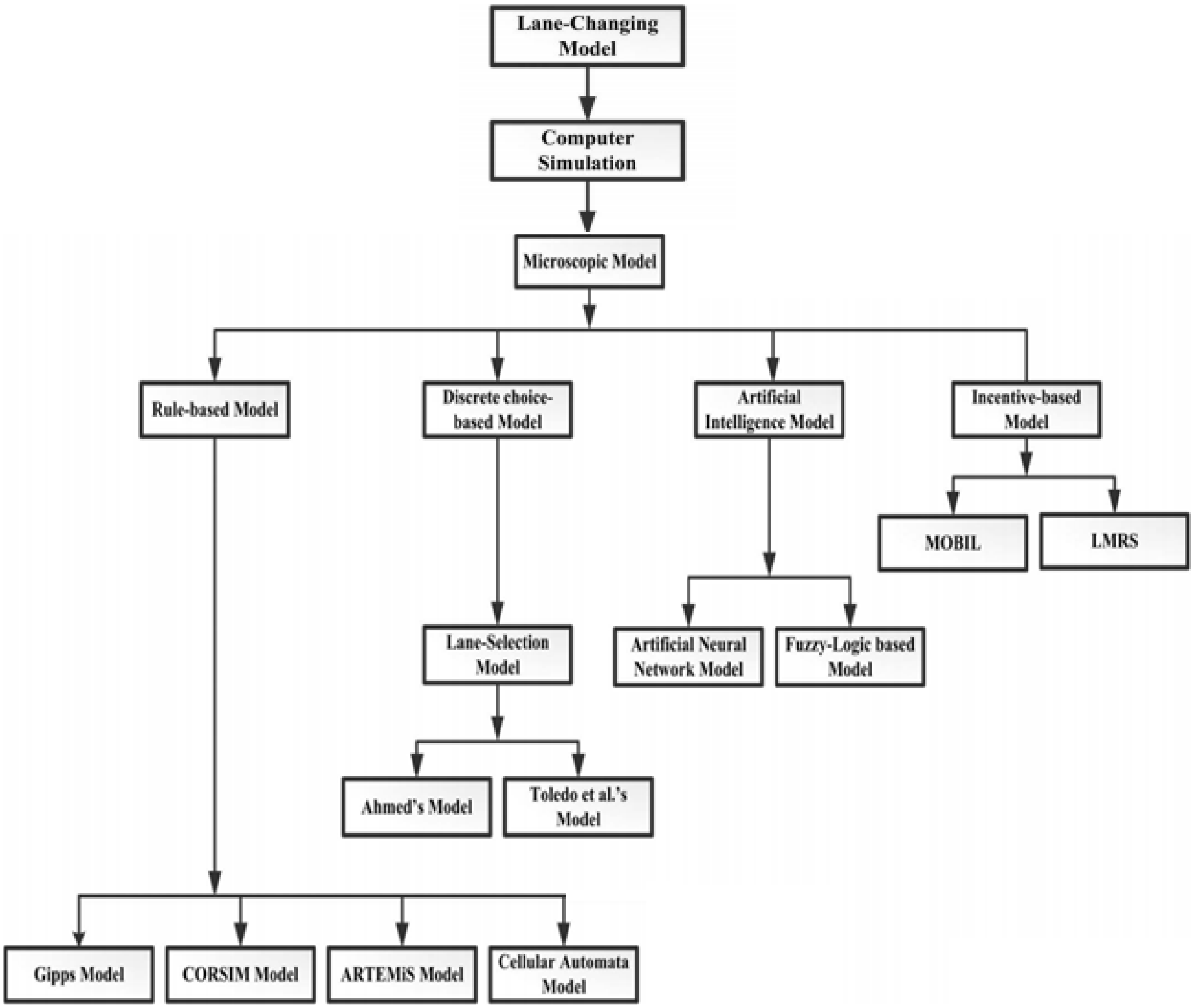


Figure 4.5: Classification of microscopic lane changing models

4.4.1.1 Rule-Based models

Gipps Model

Gipps [107] introduced the first lane changing model intended for micro-simulation tools. The model is useful in explaining lane changing decisions on various urban driving situations, in which traffic signals, transit lanes, obstructions and presence of heavy vehicles affect drivers lane selection. The model considers lane changing maneuver as the result of considering three factors: whether it is physically possible and safe to change lanes (safety), whether it is necessary to change lanes (necessity), and whether it is desirable to change lanes (desirability). Gipps model includes several factors, such as the existence of safety gap, locations of permanent obstructions, intent of turning movement,the presence of heavy vehicles, and speed advantage. Based on the judgment on these criteria, the subject drivers decide whether to move to the target lane or not. It also considers several lane changing reasons as follows [108]:

- Avoiding permanent obstructions;
- Avoiding the presence of special purpose lanes such as transit lanes;
- Turning at the downstream intersection;
- Avoiding a heavy vehicle's influence; and
- Gaining speed advantage.

In this model, he defined three zones to characterize the drivers' decisions during the lane changing process. These three zones are separated by the distance of the driver to the intended turn. When the intended turn is far away from her/his position, it has no impact on the behavior latent lane changing plan and the driver concentrates on maintaining a desired speed. When the intended turn is in a zone that is the middle of the way, lane changes will only be considered to the turning lanes or lanes that are adjacent to them. When the intended turn is close enough, the driver focuses on keeping the correct lane and ignores other considerations. These three zone areas represent a simplified tactical lane changing decision in Gipps's framework. The lane changing decision model based on his car following model [109]. His car following model was adopted to calculate the gaps between the subject vehicle and the lead vehicle(s), as well as the deceleration/acceleration required. The subject vehicle is assigned a special braking rate b_i, from which a maximum deceleration for a given lane-changing maneuver can be obtained. If the deceleration required for a lane change is not within the acceptance range, the lane change for the subject vehicle is determined as not feasible. The model equation is as follows:

$$b_i \;=\; [2 - \frac{(D_i - x_i(t))}{10v_i}]b_i^* \tag{4.35}$$

Where,

- b_i is the special braking rate that a maximum deceleration for a given lane-changing maneuver can be obtained,

- $D_i - x_i(t)$ is the distance between the intended maneuver location and the current vehicle location,
- v_i is the desired speed (free flow speed) of the driver, and
- b_i^* is the most severe braking the driver would be willing to undertake.

CORSIM Model

Halati et al. proposed a lane change model implemented in CORridor SIMulation (CORSIM). CORSIM classified lane change as mandatory (MLC), discretionary (DLC) or random (RLC) [110]. Mandatory lane change (MLC) occurs when a driver must change lane to follow a specified path or when drivers merge onto a freeway or move to the target lane to make an intended turn or avoid obstructions (e.g., lane blockage and lane drop) in a lane. Discretionary lane change (DLC) occurs when a driver changes to a lane perceived to offer better traffic conditions, such as to achieve the desired speed, avoid following trucks, avoid merging traffic, etc. DLC is applied when the speed of the leader is below a desired speed. For instance, a driver may want to pass a slow moving vehicle by changing to a neighbor lane. RLC is applied when there is no apparent reason. RLC may or may not result in an advantage for the subject vehicle over its current position. Figure 4.6 presented the lane changing model structure.

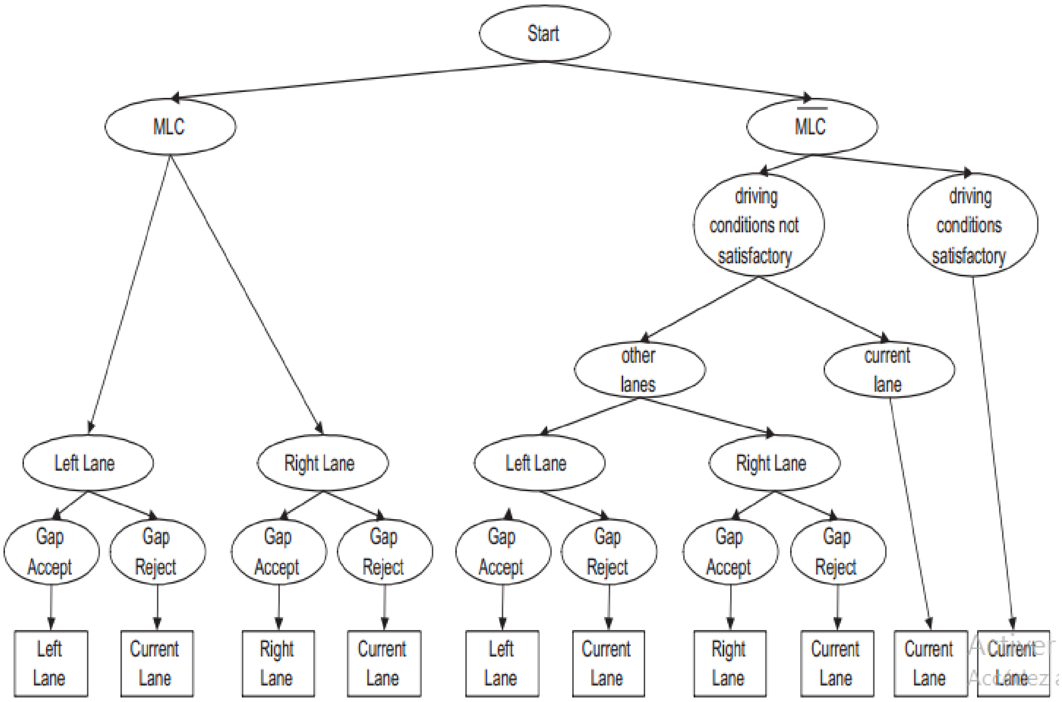


Figure 4.6: MLC and DLC lane changing model structure

CORSIM based on the gap acceptance concept in the lane change process. Gap acceptance is an important element in most lane-changing models. In order to execute a lane change, the driver assesses the positions and speeds of the lead and lag vehicles in the target lane (see Fig 4.7) and decides whether the gap between them is sufficient to execute the lane-change [111]. In CORSIM, the acceptable lead and lag gaps in lane change process (i.e., MLC, DLC, or RLC) must be available in the target lane. An acceptable lead gap is modeled utilizing the deceleration required by the subject vehicle for avoiding collision with its lead vehicle in the target lane. The target leader is assumed to decelerate with the maximum possible deceleration, and the deceleration required by the subject vehicle in order to avoid collision is computed. This computed deceleration of the subject vehicle is compared with an acceptable deceleration, which is also called the acceptable risk. If the required deceleration is less than the acceptable risk, the lead gap is accepted and the subject vehicle initiates a lane change into the target lane. This model based on three major factors for lane changing decision:

- The motivation to change lanes depends upon either the lead vehicle speed or the lead headway threshold;
- The advantage factor captures the benefits of driving in the target lane;
- The urgency of lane changing depends upon the number of lanes to change and the distance required to execute a complete lane changing maneuver.

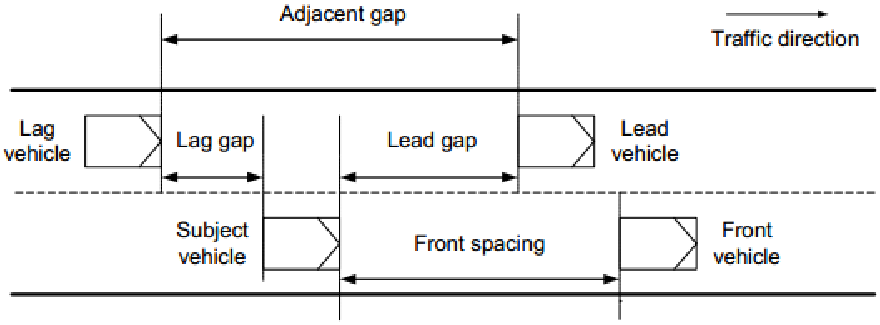


Figure 4.7: Subject vehicle and their relations with the front, lead and lag vehicles

ARTEMiS Model

ARTEMiS (Analysis of Road Traffic and Evaluation by Micro Simulation) is a microscopic traffic simulation model developed by [112], previously named Simulation of Intelligent TRAnsport Systems (SITRAS). This model describes each vehicle as a driver-vehicle object (DVO), using an autonomous agent technique to describe drivers interactions involved in a complex decision-making process. If a DVO perceives that another DVO intends to move into its lane, it may act as giving way, slowing down or not giving way, depending on road congestion conditions and individual driver characteristics [101]. This lane changing decision process was presented in Fig 4.8. Similar to other rule-based models, lane-changing reasons are evaluated, and the results were classified as "Essential", "Desirable" or "Unnecessary" based on which a target lane is chosen[94]. The following lane changing reasons was adopted by [112] (modified based on Gipps' lane-changing model) are downstream turning movements, lane drops, lane blockages, lane use restrictions, speed advantages, or queue advantages.

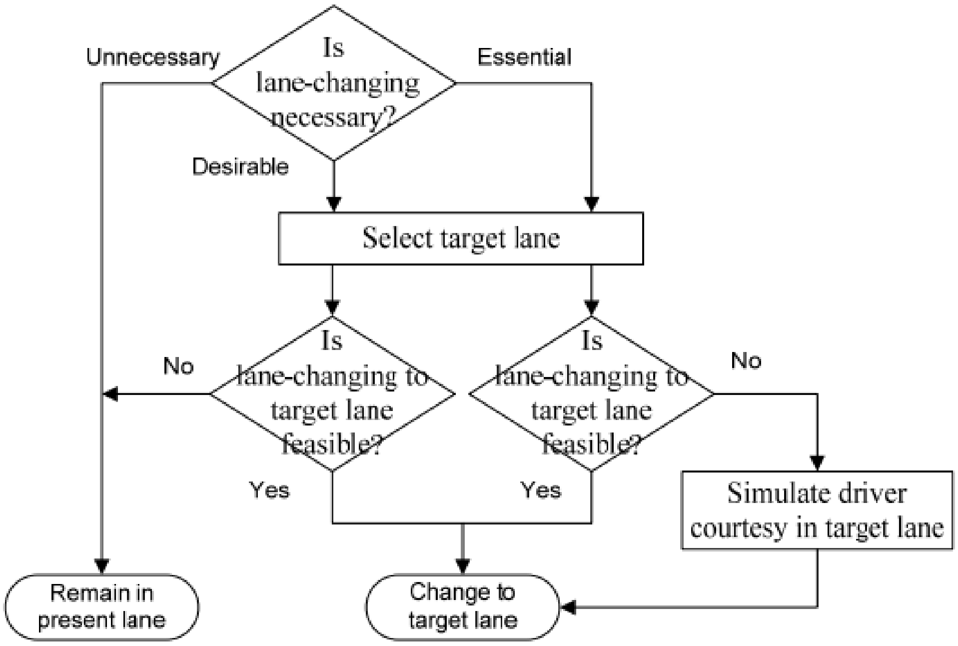


Figure 4.8: Lane changing process in ARTEMiS

Two lane-changing modes are proposed according to traffic conditions and the necessity of changing lanes: normal lane changing and courtesy/forced lane changing. A normal lane change is considered when there is a gap of sufficient size in the target lane so that the subject vehicle can move without forcing other vehicles in the target lane to slow down significantly. This lane changing mode is based on the Hidas car-following model [113], and can be expressed as:

- The acceptable deceleration (or acceleration) is required for the subject vehicle to follow the lead vehicle in the target lane,
- The acceptable deceleration is required for the lag vehicle in the target lane, so that the subject vehicle can safely serve as its lead vehicle.

The courtesy/forced lane-changing algorithm simulates the subject vehicle sending a "courtesy" signal to the subsequent vehicles in the target lane. Starting from the first lag vehicle, the required deceleration is calculated using the aforementioned Hidas car-following model to allow the subject vehicle to safely merge. Based on the calculated deceleration, a follow vehicle in the target lane can be found, and the new lead vehicle is the one right in front of the follower. A sufficient gap is created for the subject vehicle by applying the Hidas car-following algorithm for the new lead vehicle, the subject vehicle, and the new lag vehicle, so that the subject vehicle can change lane to the target lane [94].

Cellular Automata Model

Lane change cellular automata model, a vehicle changes to another lane if the following set of conditions is satisfied [114]:

- Condition 1: $gap_i(t) < \min(v_i(t) + 1, v_{max})$
- Condition 2: $gap_{i,o}(t) > \min(v_i(t) + 1, v_{max})$
- Condition 3: $gap_{i,ob}(t) > v_{max}$

with,

$gap_i(t)$ is the number of empty cells ahead in the same lane;
$gap_{i,o}(t)$ is the number of empty cells ahead in the other lane;
$gap_{i,ob}(t)$ is number of empty cells backward in the other lane;
$v_i(t)$ speed of vehicle i at time t;
v_{max} maximum speed of vehicles allowed.

The first two conditions above verify the current and target lanes for favorable speed conditions. Then, the third condition checked the availability of sufficient space to perform the lane change. In this model, lane changing conditions are classified as either symmetric or asymmetric. Based on the cellular automata model, the authors nagel et al [97] proposed various additional lane changing rules and described their characteristics in details.

4.4.1.2 Discrete-choice-based models

Ahmed's Model

Ahmed [115], [116] developed a probabilistic model to describe lane changing decisions, based on a discrete choice framework. In this model, he divided lane changing process as a sequence of four steps: 1) decision to consider a lane change, 2) choice of target lane, 3) acceptance of a gap that is sufficient to execute the lane changing, and 4) performing the lane changing maneuver. A discrete choice concept was adopted to model the impact of the surrounding traffic environment and lane configuration as well as driver characteristics. In addition, he proposed three categories of lane-changing maneuvers: MLC, DLC, and forced merging (FM). MLC situations apply when a driver is forced to change the current lane. DLC occurs when the driver is unsatisfied with the driving situation in the current lane and wishes to gain some speed advantage [117]. FM occurs when a gap is not sufficient but is created by the driver to execute a lane changing maneuver in heavy congested traffic conditions. The whole procedure is modeled as a decision tree [108], shown in Fig 4.9. Four layers, which correspond to the sequence of four steps, are included. The output from one layer is the input for the layer following. On the top level, a driver decides to respond to the MLC or DLC, and the target lane is fixed in MLC. Gaps in the target lane are checked and a lane change is invoked if the gaps are acceptable. At a DLC ($\bar{MLC}$), if a driver is not satisfied with the current lane, he/she will compare the driving conditions on the current lane with those of adjacent lanes and decide on a target lane. Similar to the MLC, the gaps in the target lane are checked and a lane change is invoked if the gaps are acceptable. Otherwise, the driver will stay in the current lane. The probability of observing a change to the left lane is given by the following equation [108].

$$\begin{aligned}
Pr_t(L|v_i) &= Pr_t(changelanes|gapacceptable, leftlanechosen, MLC, v_i) \\
&* \ Pr_t(gapacceptable|leftlanechosen, MLC, v_i) \\
&* \ Pr_t(leftlanechosen|MLC, v_i) * Pr_t(MLC|v_i) \\
&+ \ Pr_t(changelanes|gapacceptable, leftlanechosen, DLC, \bar{MLC}, v_i) \\
&* \ Pr_t(gapacceptable|leftlanechosen, DLC, \bar{MLC}, v_n) \\
&* \ Pr_t(leftlanechosen|DLC, \bar{MLC}, v_i) \\
&* \ Pr_t(DLC|\bar{MLC}, v_i) * Pr_t(\bar{MLC}|v_i)
\end{aligned} \tag{4.36}$$

where, v_i is the individual specific random term, which indicates the probability of decision to consider a lane change. Similarly, $Pr_t(J|v_n)$ for J = R or C can be formulated (R: right lane, and C: current lane).

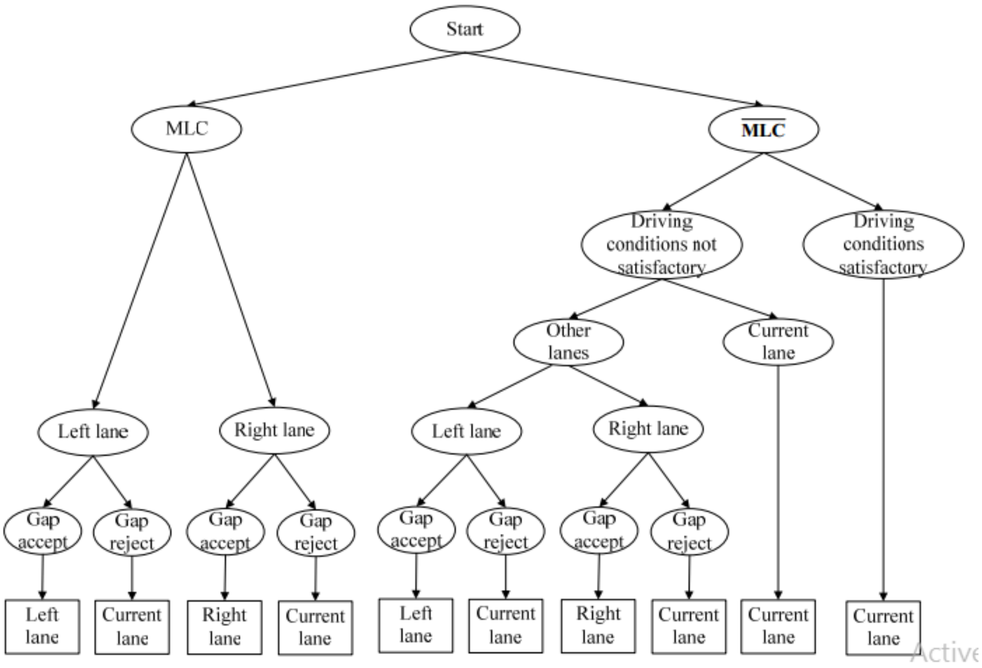


Figure 4.9: The lane changing model structure from Ahmed's dissertation [116]

The mathematical formulation of the discrete choice framework is shown in the following functions, which describe the probability that driver i performs MLC, DLC, or FM at time t as follows:

$$\begin{aligned} Pr_t(L|v_i) &= \frac{1}{1+\exp(-X_i^{LC}(t)\beta^{LC} - \alpha^{LC} v_i)} \\ LC &= MLC, DLC, FM \end{aligned} \tag{4.37}$$

where,

$Pr_t(LC|v_i)$ probability of executing MLC, DLC, or FM for driver i at time t;
$X_i^{LC}(t)$ vector of explanatory variables affecting decision to lane changes;
β^{LC} corresponding vector of parameters;
α^{LC} parameter of v_i.

In his model he defined the critical lead and lag gaps as the minimum acceptable gaps. The lane change is performed when the available lead and lag gaps in the target lane are greater than their critical gaps. The critical lead and lag gaps for lane-changing maneuvers of driver i are presented as follows:

$$\begin{aligned} G_i^{cr,gapj}(t) &= \exp(X_i^{cr,gapj}(t)\beta^{gapj} + \alpha^{gapj} v_i + \varepsilon^{gapj}(t)) \\ gapj &= lead, lag \end{aligned} \tag{4.38}$$

where,

$G_i^{cr,gapj}(t)$ critical lead and lag gaps for driver i at time t;
$X_i^{cr,gapj}(t)$ vector of explanatory variables affecting the critical gap j;
β^{gapj} corresponding vector of parameters;
α^{LC} parameter of v_i;
$\varepsilon^{gapj}(t)$ is a random term.

Toledo's Model

Toledo et al. [118], [119] developed an integrated probabilistic lane changing decision model which allows drivers to consider the trade-offs between MLC and DLC. A discrete choice framework is employed to model drivers tactical and operational lane changing decisions. The model is calibrated using the maximum likelihood estimation technique. In this model, the lane changing process consists of choice of target and gap acceptance decisions. Four groups of explanatory variables are considered in the model underlying lane-changing decisions: neighborhood variables (e.g., gaps and speeds), path plan variables (e.g., distance from the intended exit off-ramp), network knowledge and experience (e.g., avoiding the nearest lane next to the shoulder), and driving style and capabilities. In the target lane model, the set of target lane choices includes: 1) remaining in the current lane, 2) shifting to the right, and 3) shifting to the left adjacent lane. The target lane choice model, the probability of selecting a specific lane, and the critical gap model are similar to those in Ahmed's model [116]. Figure 4.10 demonstrates the structure of his proposed lane-changing model which the ovals represent latent states and rectangles represent observed outcomes.

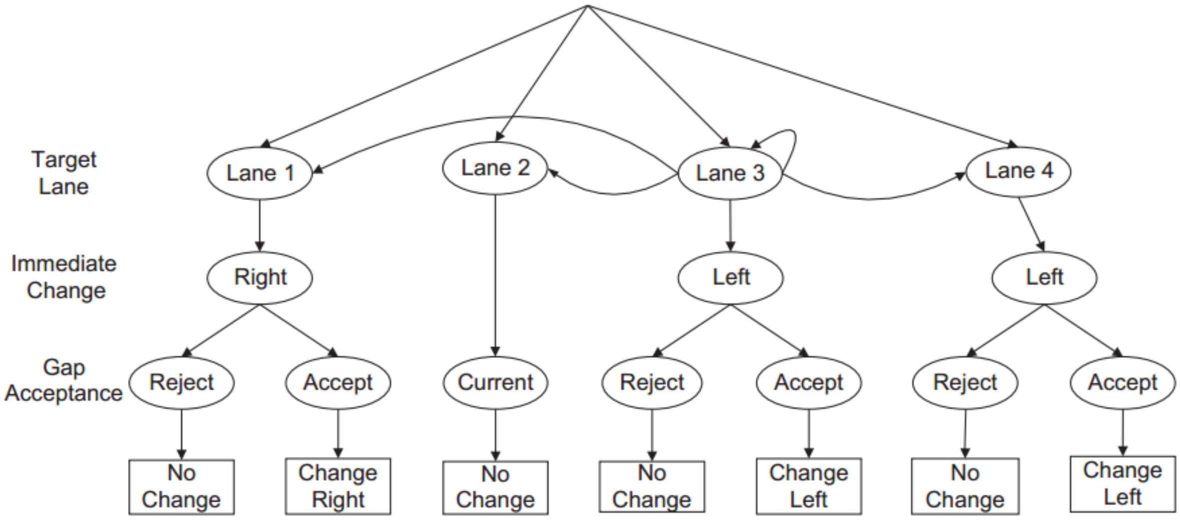


Figure 4.10: The proposed lane changing model structure from Toledo's dissertation [112]

4.4.1.3 Artificial intelligence models

Fuzzy-Logic-Based Models

Fuzzy logic based models consider the uncertainty of lane changing maneuvers and therefore, reflect the natural or subjective perception of real variables [120]. Das et al. [121] proposed a new microscopic simulation methodology based on fuzzy logic model which translate nonlinear systems into IF-THEN rules, called the software package as Autonomous Agent SIMulation Package (AASIM) [122] classified the lane changing maneuvers as MLC and DLC. In the microscopic traffic simulation package, the MLC fuzzy rules consider the distance to the approaching exit or merge point and the number of lane changes which are required. DLC is a binary decision (change lanes or not) that is based on the driver's speed satisfaction [121], but it does not consider vehicle types in lane changing decisions. In the same way, Moridpour et al. also developed a lane changing model using fuzzy logic, which is used to predict the lane changing maneuver of heavy vehicles on freeways [123]. In their model, considers three types of lane changing behavior: motivation of lane changing, selection of the target lane, and execution of the lane changing process.

ANN Model

Artificial neural network (ANN) models process information using functional architecture and mathematical models that are similar to the neuron structure of the human brain. Based on neurobiological studies and modern human brain's cognitive science, neural network models have been developed which try to simulate some functions of human brain and nerve cells. This type of model is based on self-learning ability and its structure requires the identification of the input-output (I/O) to be reproduced. Neural networks were applied broadly in the field of transport in the 1990s [124]. For instance, neural networks were used to model different driver behaviour such as prediction of drivers route choice and gap acceptance in non-signalized intersections [125][126][127][128].

Based on neural network, Hunt and Lyons [128] developed a model to predict the lane changing decisions of drivers on divided highways. They applied a preliminary approach using a predictive type of neural network with a single hidden layer and a back propagation learning algorithm to model the behaviour of an individual driver. For modeling lane changing process, Dumbuya et al. developed neural driver agents (NDAs)[129]. A multilayer NDA model was designed and implemented. A back-propagation training algorithm was used to train the NDA model, which takes inputs such as current direction of the vehicle, current speed, distance from the vehicle, preferred speed, and current lane. The output of the model includes new direction and new speed.

4.4.1.4 Incentive-Based models

MOBIL Model

Lane changing algorithm MOBIL (Minimizing Overall Braking Induced by Lane Changes) is among the most important components of a microscopic traffic simulator based on a microscopic longitudinal movement model [130]. We described the lane change process in Fig 4.11. The vehicle i refers to the lane change of the successive vehicles on the target and present lane referred by n (new one in the target lane)and o (old follower in the current lane). The three tildes $\tilde{a}_i$, $\tilde{a}_o$ and $\tilde{a}_n$ refers to parameter values after the potential lane change. The vehicles in front influence the event since the accelerations of the considered vehicle (c) are calculated according to the car following model.

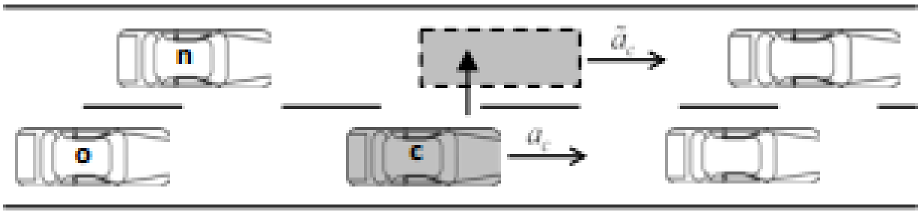


Figure 4.11: Lane changing process

A MOBIL model based on two criteria: safety and incentive criterion. The safety criterion, in terms of longitudinal accelerations, guarantees that after the lane change, the deceleration of the successor $\tilde{a}_i$ in the target lane does not exceed a given safe limit b_{safe} [130]. It should be noted that this criterion contains all the information provided by the car following model via the acceleration depending on the gap, the velocity. The safety criterion is expressed as shown below. Thus

$$\tilde{a}_i > -b_{safe} \tag{4.39}$$

The incentive criterion is based on the accelerations of the longitudinal model before and after the lane change. For symmetric overtaking rules, Kesting et al. [130] neglect differences between the lanes and propose the following incentive condition for a lane changing decision of the driver of vehicle i as follows:

$$\overbrace{\tilde{a}_i - a_i} + p(\overbrace{\tilde{a}_n - a_n} + \overbrace{\tilde{a}_o - a_o}) > \triangle a_{th} \tag{4.40}$$

The first terms in Eq (4.40) denote the possible lane change for the driver of the considered vehicle i, the politeness factor p determines to which degree these vehicles influence the lane changing decision. The factor p controls the degree of cooperation while considering a lane change. In MOBIL, $p > 1$ is for an altruistic driving behavior; $0 < p < 0.5$ is for a realistic driving behavior;$p = 0$ is for a purely selfish driving behavior; and $p < 0$ is for a malicious driving behavior. The threshold $\triangle a_{th}$ on the right-hand side of Eq (4.40) prevents lane changes if the overall advantage is only marginal as compared to keeping the current lane. In this model, two types of passing rules are considered for lane changes: symmetric and asymmetric. The symmetric passing rules are based on safety and incentive criteria. For asymmetric rule, where changing to the right lane is prohibited, unless traffic is congested or the subject vehicle is forced to change to the right lane (i.e., on-ramp, off-ramp, and lane drop), MOBIL modifies Eq (3.40) by adding a bias $\triangle a_{bias}$ to threshold $\triangle a_{th}$ when considering a lane change from right-to-left, whereas for a left-to-right decision the bias is subtracted in order to implement the keep-right directive as follows:

$$L \rightarrow R : \tilde{a}_i - a_i + p(\tilde{a}_n - a_n + \tilde{a}_o - a_o) > \triangle a_{th} + \triangle a_{bias} \tag{4.41}$$

$$R \rightarrow L : \tilde{a}_i - a_i + p(\tilde{a}_n - a_n + \tilde{a}_o - a_o) > \triangle a_{th} - \triangle a_{bias} \tag{4.42}$$

<u>LMRS Model</u>

Lane changing Model with Relaxation and Synchronization (LMRS) is a new microscopic model proposed by [131], which is structured around lane change desire. The desire is a combination of the route, speed, and keep-right incentives. The desire to change from lane i to lane j that arises from the different incentives is combined into a single desire.

$$d^{ij} = d_r^{ij} + \theta_v^{ij} * (d_s^{ij} + d_b^{ij}) \tag{4.43}$$

The equation (3.55) means that, we have a desire to follow a route d_r, to gain speed d_s and to keep right d_b, where the subscript b stands for bias to a particular side. The latter two are included with θ_v which is the level at which voluntary (discretionary) incentives are included. Desire is meaningful between -1 and 1 where negative values indicate that a lane change is not desired, and positive values mean the driver wants to change lane. based on the desire value, they distinguish lane changes as: Free Lane Changes (FLC), Synchronized Lane Changes (SLC) and Cooperative Lane Changes (CLC).

$$0 < d_{free} < d_{syn} < d_{coop} < 1 \tag{4.44}$$

Lane change desire is based on three incentives. Lane change behavior, including the accepted headway and deceleration for a lane change, varies depending on the level of lane change desire. Figure 4.12 gives an overview of the variation of lane change behaviour between processes [131]. The proposed lane changing model, which is based on the gap acceptance concept, includes seven parameters: relax headway, route desire, anticipated speed, speed desire, keep-right desire, combine desires, and gap-acceptance [132].

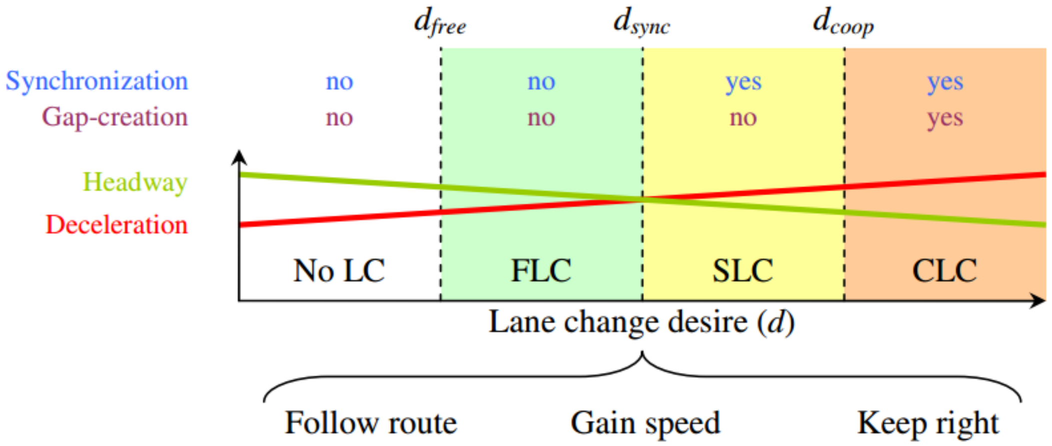


Figure 4.12: Lane change desire LMRS based on three incentives

4.4.2 Synthesis

Reviewing the existing lane changing models presented above, we provide a brief summary and systematic comparison of the four groups. For that, we based on some criterion: lane change decision, reason for lane changing, target lane selection, gap acceptance, and then, we give the strength and weakness of each group.

Rule-based lane changing models are the most popular ones in microscopic traffic simulators. For this type of models, the subject vehicle's lane changing reasons is evaluated first. If these reasons warrant a lane change, a target lane from the adjacent lane(s) is selected. The gap acceptance model used to determine whether the available gaps should be accepted.

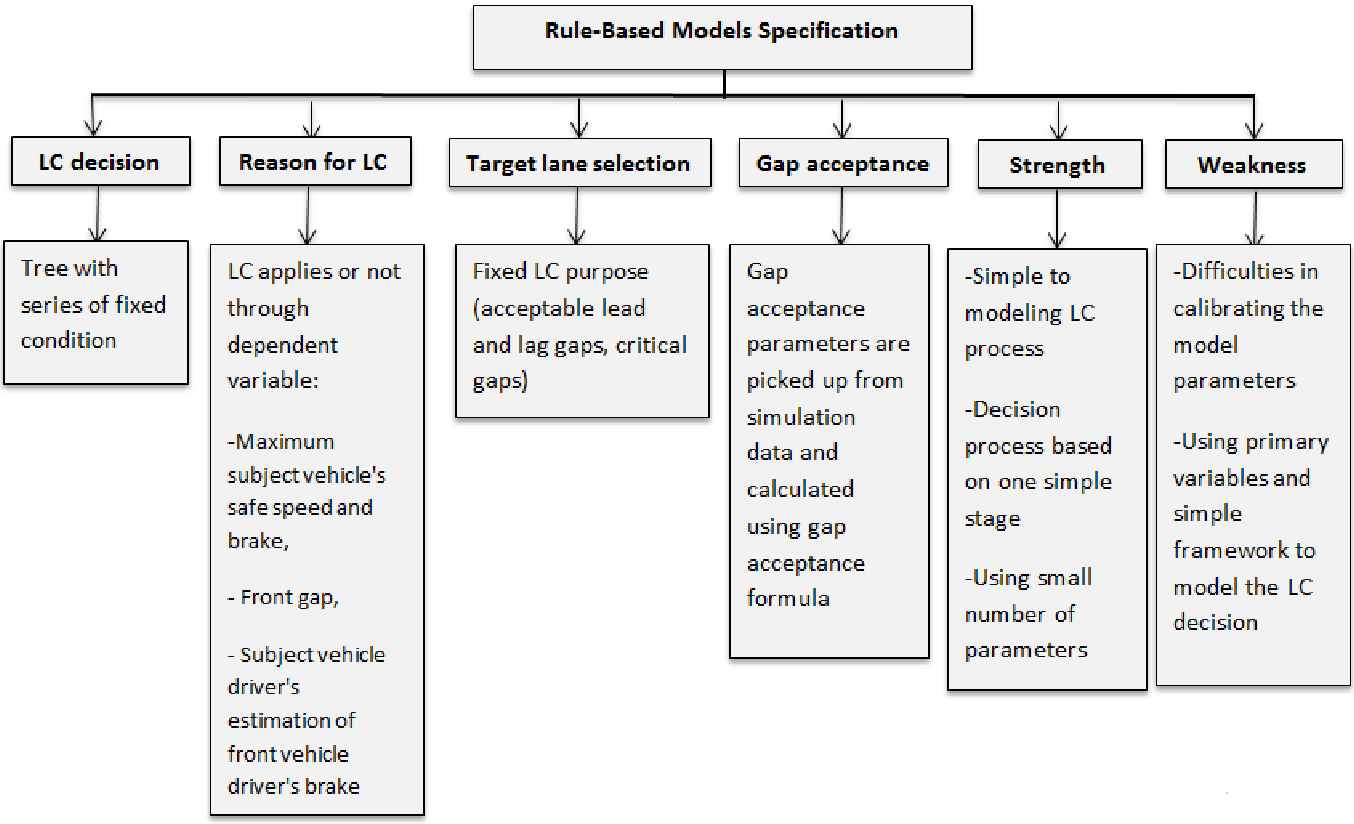


Figure 4.13: Rule-based lane changing models specification

For most discrete-choice-based lane changing models are based on logit or probit models. The lane changing process is usually modeled as either MLC or DLC. Discrete-choice-based lane changing models follow three steps: 1) checking lane change necessity, 2) choice of target lane, and 3) gap acceptance. The heterogeneity in drivers and vehicles (i.e., driver aggressiveness, driving skill level, and vehicle acceleration performance) have not been given adequate consideration because the existing traffic data and data collection technologies cannot provide information that is detailed enough for developing and testing such models.

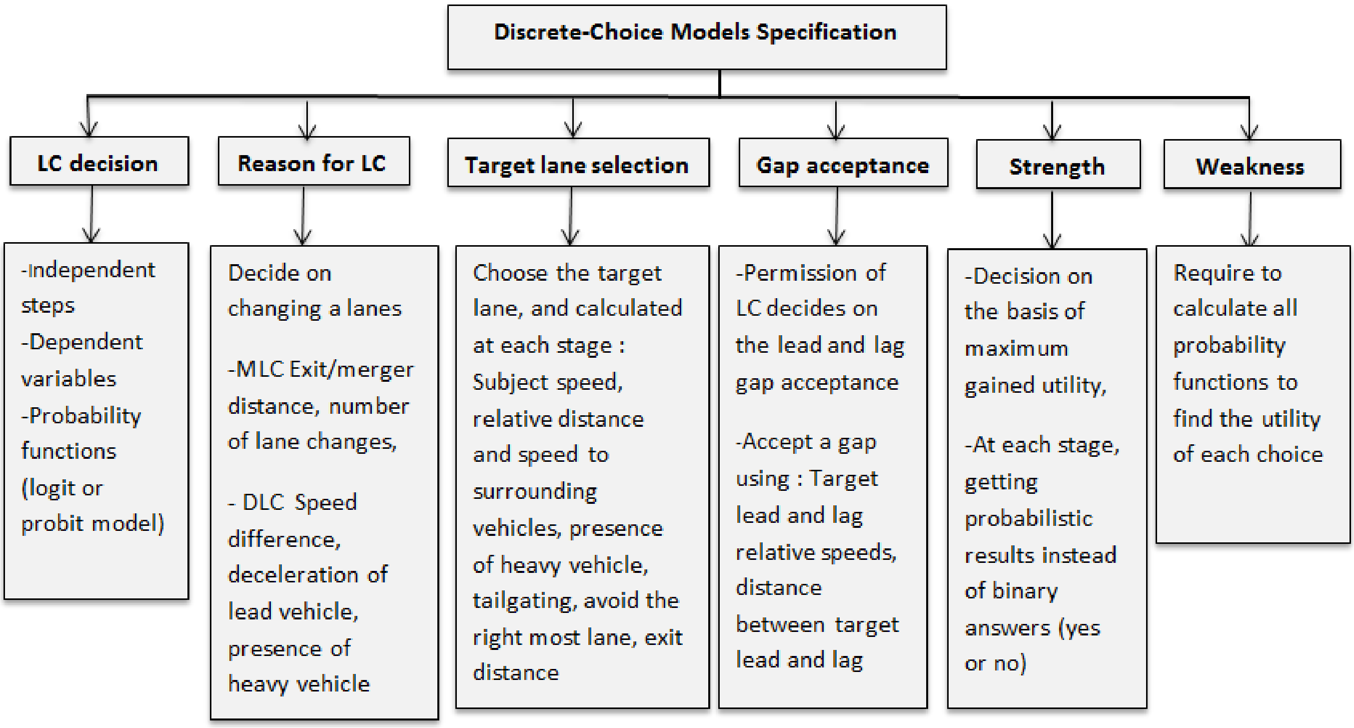


Figure 4.14: Discrete-choice-based lane changing models specification

Artificial intelligence lane changing models are fundamentally different from the rule-based and discrete choice-based models. A major advantage of them is that they can better incorporate human experience and reasoning into the development of lane changing models.

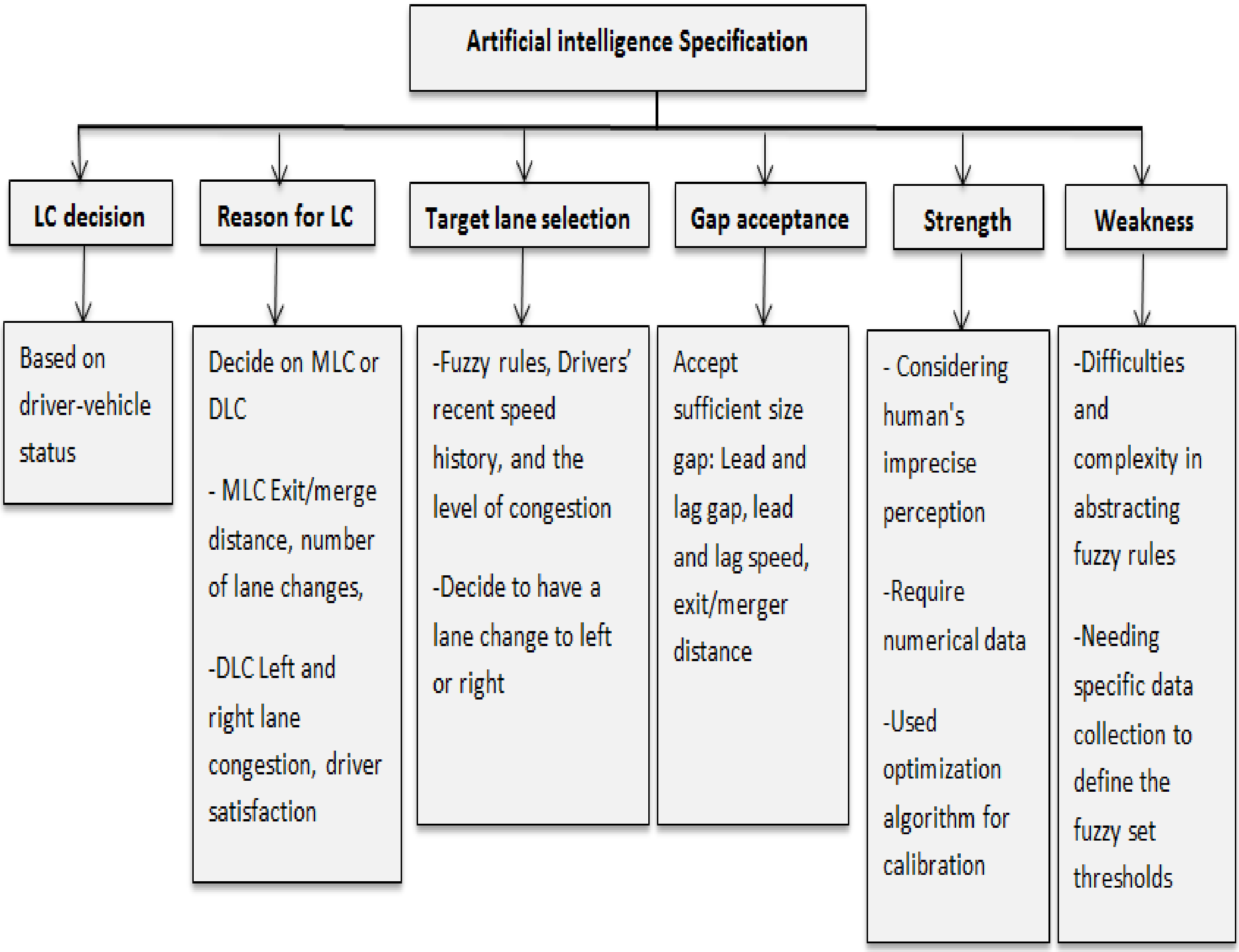


Figure 4.15: Artificial intelligence lane changing models specification

The most advantage behind incentive-based models is intuitive and straightforward (i.e drivers choose to change or not change lanes in order to maximize their benefits). The main advantage of MOBIL model is that compared against a threshold value for final decision making. For LMRS model, their advantage is to take into account the driver's desire to follow a route into consideration.

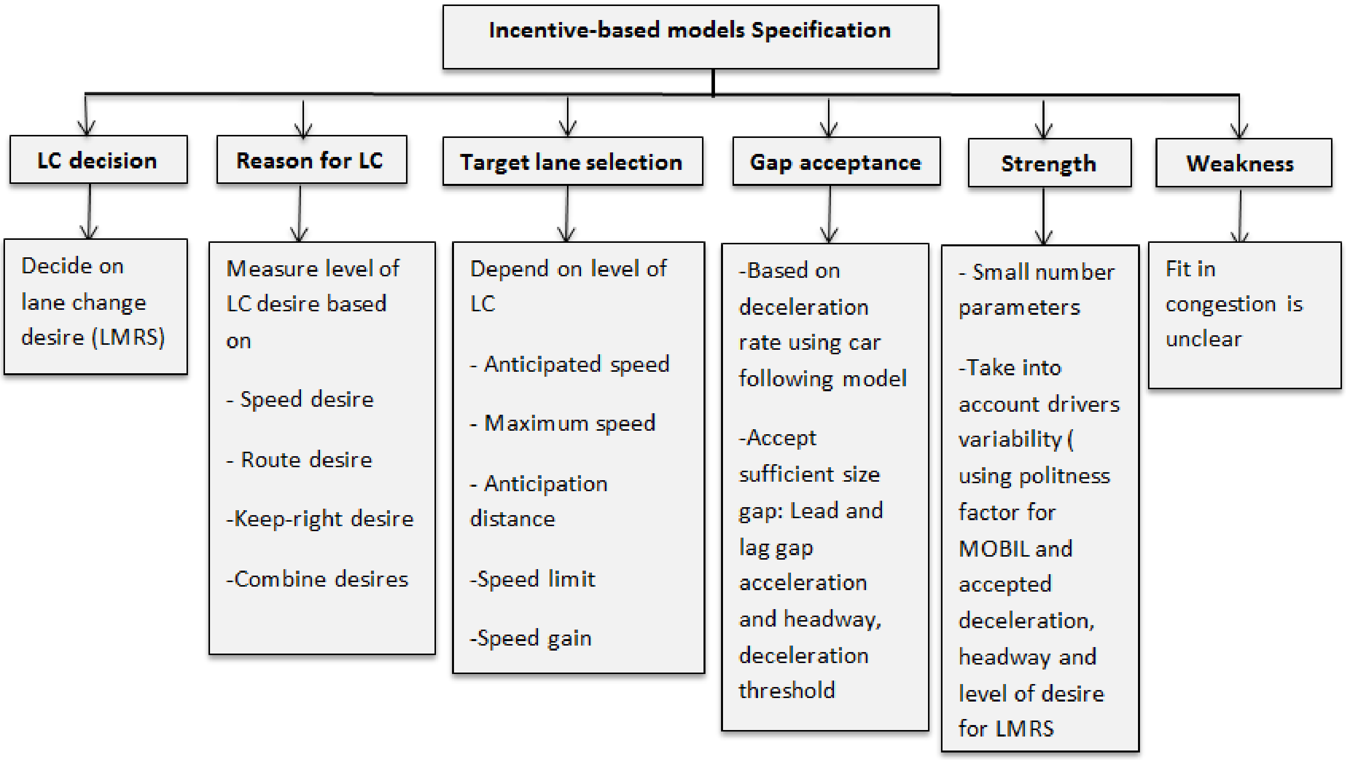


Figure 4.16: Incentive-based lane changing models specification

4.4.3 Behavior profiles

On a real traffic road network, many situations can encounter the drivers where a decision between two or more alternatives is required. This relates to many situations as lane changes or whether or not it is safe to enter the priority road at an unsignalized junction, and concern whether or not to stop at an amber-phase traffic light. All of these problems classified as discrete-choice problems that pioneering work [133] has been investigated in the context of transportation planning. However, there are fewer investigations attempting to incorporate the discrete-choice model into microscopic models of traffic flow. In fact, only very recent acceleration and discrete-choice tasks have been treated more systematically [130]. Lane change model is required to simulate multi-lane and complete the car following movement. The purpose of the thesis is to combine two fundamental motions to evaluate traffic flow in the real manner: car following rules or longitudinal model describes the concept to follow the preceding vehicle while keeping a safety distance in the same lane and lane change rule species the rational decision to change lanes. In fact, we used an adapted microscopic lane change model MOBIL to allow faster driver vehicle agents to improve their driving conditions by passing slower vehicles. The main idea of the lane change algorithm MOBIL is focused on two criteria: the safety constraint to avoid collisions by the follower in the prospective target lane $\tilde{a}_i > -b_{safe}$ and it restricts the deceleration of the lag vehicle on the target lane to values below b_{safe}. This simple condition contains the information provided by the longitudinal model via the acceleration $\tilde{a}_i$. An additional constraint called the incentive criterion $\overbrace{\tilde{a}_i - a_i} + p(\overbrace{\tilde{a}_n - a_n} + \overbrace{\tilde{a}_o - a_o}) > \triangle a_{th}$ which favors lane changes whenever the acceleration in one of the target lanes is higher. In other words, this criterion is executed if the sum of the own acceleration and those of the affected neighboring vehicle driver is higher in the prospective situation than in the current local traffic and if the first criterion is validated. Furthermore, in the MOBIL strategy, the immediately affected neighbors are considered by the politeness factor p. For $p = 0$, the incentive criterion simplifies to $\overbrace{\tilde{a}_i - a_i} > \triangle a_{th}$ which describe an egoistic driver behavior. Otherwise, For $p = 1$, lane changes are only executed if this increases the combined accelerations of the lane changing driver and all affected neighbors. For realistic lane change behavior the politeness factor in the range $0.2 < p < 0.5$. In this work, we adapted the lane change model MOBIL to proposed longitudinal models by formulating the two criteria in terms of safe braking deceleration. Moreover, the crashes due to lane changes are automatically excluded as the proposed CF itself assured collision free dynamics.

4.5 Rear-end collision risk

Rear-end collision is related to human errors in car following. The main objective of the car following is to maintain the desired speed while keeping a safe distance from the front of the vehicle. To estimate the propriety of rear-end collisions, the car following model often uses the parameter time to collision (TTC) as a surrogate measurement. The TTC is a visual information to the driver of the time to collision, its temporal derivative is used by the driver as a visual information of the risk of future rear end collision. This visual risk is given by:

$$R_{V_{opt}} = -1 + \frac{S_i(t)\ddot{S}_i(t)}{\dot{S}_i(t)^2} \tag{4.45}$$

We notice that when $R = 0$, TTC is constant. In this case, if t_c is this constant TTC value, thus the following differential equation holds: $\ddot{S}_i(t) = \frac{-1}{t_c}\dot{S}_i(t)$

On the basis of several behavior of the leading vehicle, we investigate the improvement of the risk perception introduced by the weighting factor. The risk associated with the previous car following model using optimal velocity function Eq (4.5) and the risk associated with new optimal velocity function with weighting factor is given by:

$$R_{V_{opt}} = -1 + \frac{S_i}{a_i v_i}(1 - \frac{V_{opt}(S_i)}{v_i}) \tag{4.46}$$

$$R_{V_{opt}^{new}} = -1 + \frac{S_i}{a_i v_i}(1 - \frac{V_{opt}(S_i)}{v_i} W(S_i, -v_i)) \tag{4.47}$$

v_i is the speed of the follower vehicle.

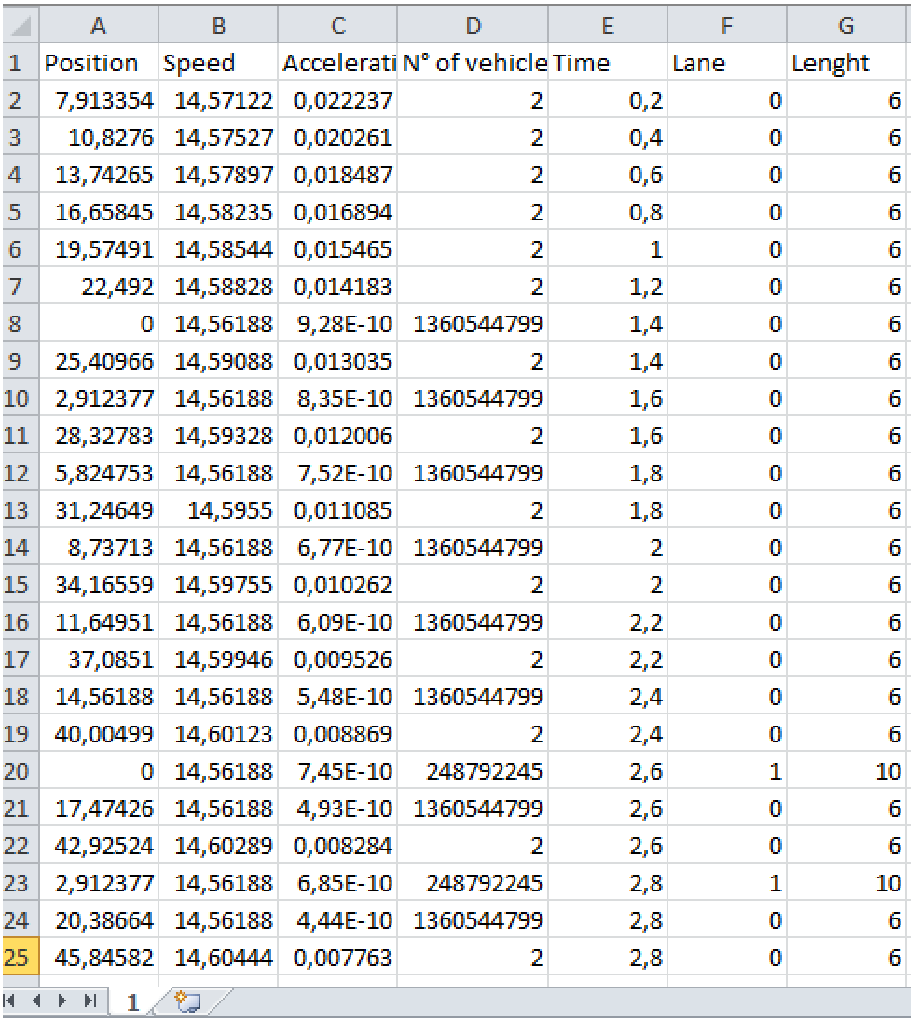
4.6 Simulation results

In order to compare the characteristics of microscopic models, for each car following model, we establish the simulation results for different scenarios. In the following, we will test the proposed approach (accelerating and braking behavior) using an open source microscopic simulator [134] to validate our approach The purpose of the simulation study is to evaluate the proposed longitudinal models (MFVD and MVSD) and demonstrate that the new optimal function introducing the weighting factor has the best effect in braking state compared as other car following models such as OV, MOV, FVD , VSD , MOV models.

In this study, we carry out the simulations to investigate whether MVSDM and MFVDM can overcome the shortcomings of previous models such as OVM, MOVM proposed by [75] , FVDM, and VSDM. We used two vehicle classes: cars and trucks. For all simulations, the parameter values used for the optimal velocity function Eq (4.5) and are adapted from [44] are $V_1 = 6.75m/s$, $V_2 = 7.91m/s$, $C_1 = 0.13m^{-1}$, and $C_2 = 1.57m^{-1}$. The parameter values calibrated for weighting factor are $A = 0.5$, $C = 0.5$, and $B = 5s$. The sensitivities parameters values are $a = 0.6m/s^2$, and $\lambda = 0.45m/s^2$. The parameters values for cars are the desired velocity $V_0 = 120km/h$, the safe time headway $T = 1.2s$, the minimum gap $S_0 = 2m$, and the vehicle length $l = 6m$. The parameters values for trucks are the desired velocity $V_0 = 80km/h$, the safe time headway $T = 1.7s$, the minimum gap $S_0 = 2m$, and the vehicle length $l = 10m$. The parameters values for lane changing are the politeness factor $p = 0$, the changing threshold $\triangle a_{th} = 0.2m/s^2$, the maximum safe deceleration

$b_{safe} = 12m/s^2$, and the bias for the slow lane $\triangle a_{bias}$.

For more information about the simulation results, we built a video to visualize clearly the validity of our proposed model MVSDM and the existing model MOVM and VSDM in the following link `https://youtu.be/adKL1O_fU8w`. When starting the simulation, we extract the necessary data in excel format in order to represent them in graph form, and this is done for each car following model and for each scenario [135]. Figure 4.17 shows the resulting data (speed, acceleration, position, type of car, length, etc.)



	A	B	C	D	E	F	G
1	Position	Speed	Accelerati	N° of vehicle	Time	Lane	Lenght
2	7,913354	14,57122	0,022237	2	0,2	0	6
3	10,8276	14,57527	0,020261	2	0,4	0	6
4	13,74265	14,57897	0,018487	2	0,6	0	6
5	16,65845	14,58235	0,016894	2	0,8	0	6
6	19,57491	14,58544	0,015465	2	1	0	6
7	22,492	14,58828	0,014183	2	1,2	0	6
8	0	14,56188	9,28E-10	1360544799	1,4	0	6
9	25,40966	14,59088	0,013035	2	1,4	0	6
10	2,912377	14,56188	8,35E-10	1360544799	1,6	0	6
11	28,32783	14,59328	0,012006	2	1,6	0	6
12	5,824753	14,56188	7,52E-10	1360544799	1,8	0	6
13	31,24649	14,5955	0,011085	2	1,8	0	6
14	8,73713	14,56188	6,77E-10	1360544799	2	0	6
15	34,16559	14,59755	0,010262	2	2	0	6
16	11,64951	14,56188	6,09E-10	1360544799	2,2	0	6
17	37,0851	14,59946	0,009526	2	2,2	0	6
18	14,56188	14,56188	5,48E-10	1360544799	2,4	0	6
19	40,00499	14,60123	0,008869	2	2,4	0	6
20	0	14,56188	7,45E-10	248792245	2,6	1	10
21	17,47426	14,56188	4,93E-10	1360544799	2,6	0	6
22	42,92524	14,60289	0,008284	2	2,6	0	6
23	2,912377	14,56188	6,85E-10	248792245	2,8	1	10
24	20,38664	14,56188	4,44E-10	1360544799	2,8	0	6
25	45,84582	14,60444	0,007763	2	2,8	0	6

Figure 4.17: Example of resulting data according to MVSDM

Figure 4.18 (a) illustrates the optimal velocity function depending only of spacing headway, however Fig 4.18 (b) weighting factor depending on spacing and relative speed, this factor increases with relative speed and approaches 1 when the spacing increases.

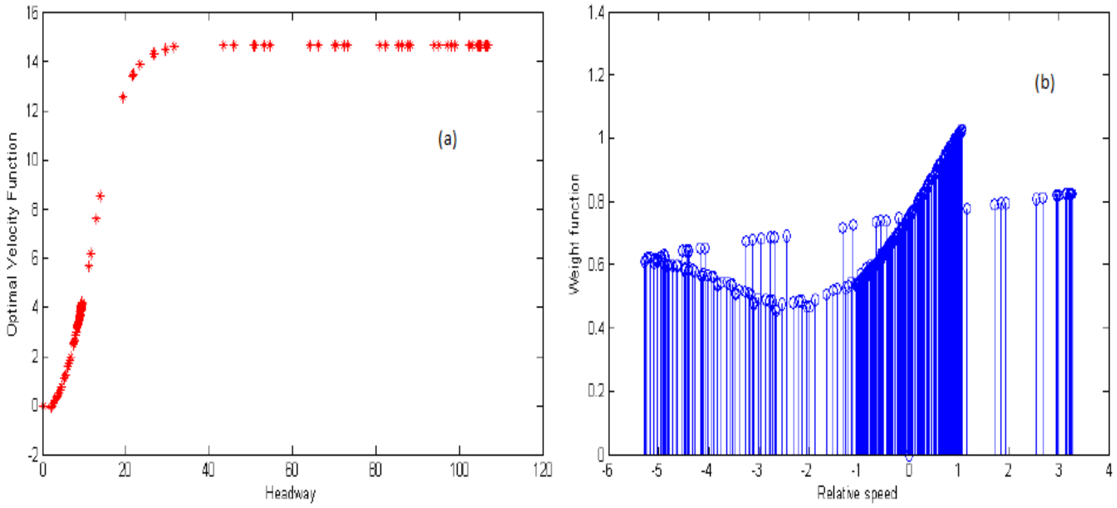


Figure 4.18: OVF: (a) Optimal velocity as function of spacing and (b) Weighting factor as function of spacing and relative speed

4.6.1 Microscopic traffic simulator

So far, the longitudinal and lane change models have been discussed which describing individual driver vehicle agents. Now we address the issue of simulation demonstrator that integrates these components into a microscopic traffic simulator. Several numbers of interactive simulators available as open source or commercial use. The commercial traffic simulation software tools like (VISSIM, AIMSUNor PARAMICS) incorporate a variety of additional modules such as emission or pedestrian models and interfaces but generally not well documented. However, there is an open source simulator for whole traffic networks, called SUMO [136] that uses the Krauss model[137]. Furthermore, another open source micro-simulation of road traffic that uses intelligent driver model [91]. We adopt the concept of an agent to implicate the complex human driving behavior and we used this latter to evaluate our contribution. This demonstrator is an educational project developed in Java source code and simulates various predefined traffic situations and different scenarios such as on-ramps, lane-closings, uphill grades and or traffic lights. Figure 4.19 shows the typical classes in a microscopic traffic simulator.

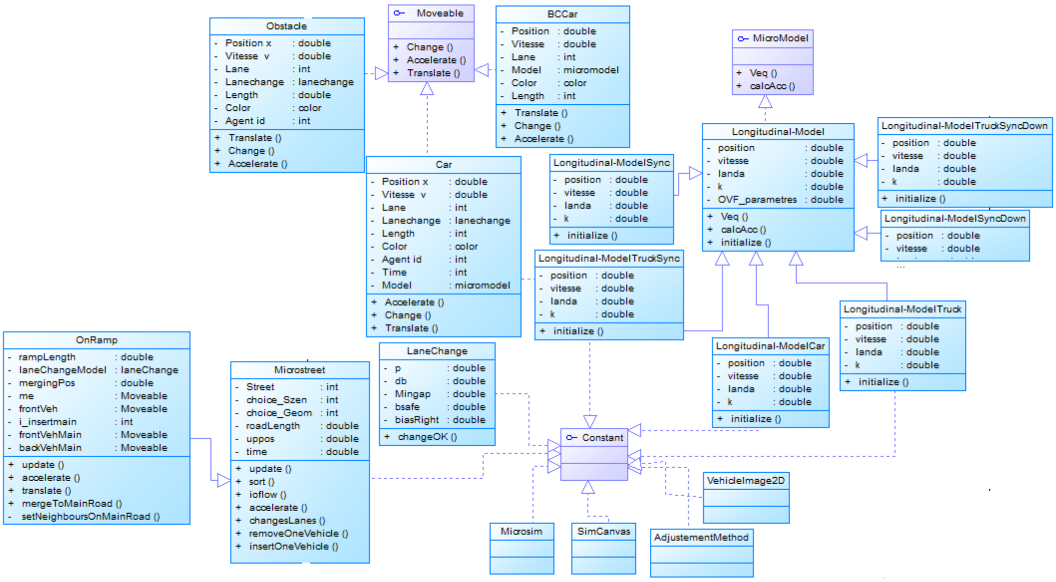


Figure 4.19: Traffic simulation class diagram

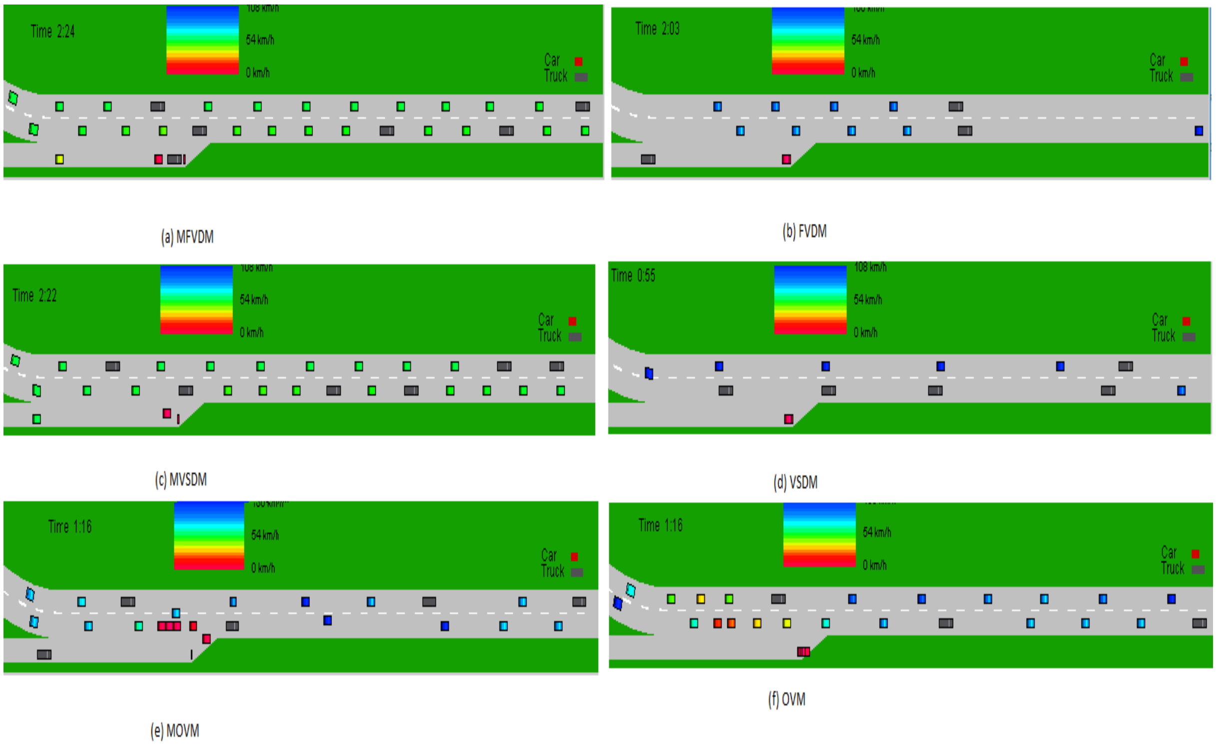
The main classes implemented here are:

- Class Car use as input the initial position of the vehicle generated x, the speed of entry of the vehicle v, the lane that the vehicle will be positioned on, the lanechange describes the nature of the lane change being performed (cars are inconsiderate and trucks are polite), the actual length of the vehicle which is depending on its type, the color of the vehicle (trucks are black and cars are red), and the number is a unique id generated for each vehicle (or agent id). The main methods are "accelerate" method for the acceleration for the agents on the freeway, " change" method is responsible for using the LaneChange class and performing necessary lane changes, and "translate" method for moving the vehicles and changing their positions dynamically.
- Class Constants contain the constants influencing the global appearance and functionality of the model. It's responsible to calibrate the model according to special needs such as different applet size, different time steps, different acceleration/deceleration, different bumper-to-bumper gap, etc ... by simply changing the numbers and recompiling the program.
- Class Longitudinal-Model is the basis class for the microscopic traffic model in which we implement the proposed car following models (MFVDM, MVSDM).
- Class Longitudinal-ModelCar and Longitudinal-ModelTruck contains all the cars and trucks parameters.
- Class LaneChange present the implementation of the lane-changing model MOBIL ("Minimizing Overall Brakings Induced by Lane-changes")

- Class MicroStreet is the core of the simulator, which implement the main functions defining the agent behavior. The main elements of this class are: "street" is a vector of Moveable's representing the agents, the update method invoked in every time step which responsible for updating the system throughout the simulation, the "sort" method for re-arranging the vehicle order in the street in the order of decreasing longitudinal positions and the "ioFlow" method in charge of the arriving agents into the system.
- Class Moveable represents a general agent object from class Car with its parameters (position, velocity,lane, etc) in each time step, the objects are updated by moving them forward (method translate), by changing the velocity (method accelerate), etc
- Class OnRamp describes the length, behavior, position, and other related fields concerning the ramp merging into the freeway.

4.6.2 Ramp Scenario: Stop and go traffic behavior

Stop and go driving has raised much attention in the literature due to its severe negative impacts like increased fuel consumption, greenhouse emissions and safety risks [138][139][140]. The ramp scenario has been recognized as one of the most effective ways for combating freeway congestion.Furthermore, the on-ramp concept poses some situations in which vehicle access an already busy road. This scenario has been added to the system to create perturbations and demonstrates the traffic breakdown provoking on the main road of the on ramp. Usually, the traffic jam occurs when the leading car decelerate for certain reasons such as lane changing maneuvers, lower speeds of leader vehicle and moving bottleneck cause stop and go traffic and amplifying delay and environment impacts. For that, it's important to study the vehicle behavior when simulating in such case. We evaluate the impacts of vehicles accessing a road in heavy traffic condition with the main flow of 2800 vehicles/h and ramp inflow of 400 vehicles/h. Figure 4.20 describes the behavior of vehicles in stop and go scenario according to MOVM, FVDM, VSDM, OVM, MFVDM and MVSDM. The vehicles wait at the ramp with a safe spacing to avoid collision and merge into the freeway. Furthermore, their entrance forced the preceding vehicle to decelerate in order to avoid crashing. Simulation results depicted in Fig 4.20 (a) and (c) show that MFVDM and MVSDM able to avoid the collision when the leading car decelerate hardly. However, simulating traffic flow according to OVM and MOVM occur crashes between different vehicles and in their entrance to freeway as we can see in Fig 4.20 (e) and (f). As we are shown in Fig 4.20 (b) and (d), when the vehicles access to freeway, the FVDM and the VSDM collide with the obstacle. It's clearly observed that the FVDM, VSDM avoid the collision sometimes, but their main drawbacks is to make more time to decelerating under emergency. The proposed approach produces more realistic results than the existing models.



(a) MFVDM (b) FVDM (c) MVSDM (d) VSDM (e) MOVM (f) OVM

Figure 4.20: Ramp simulation according to (a) MFVDM, (b) FVDM, (c) MVSDM, (d) VSDM, (e) MOVM, and (f) OVM

At $t = 0$, all cars start up according to MOVM, FVDM, VSDM, OVM, MFVDM and MVSDM, respectively. From Fig 4.21, it can be seen that the MFVDM and the MVSDM car speed maximum is under of the previous models and their velocity begins to decrease before previous models speed reaches its maximum. This is due to the introduction of the weight factor which is based on inverse TTC indicator that make MFVDM and MVSDM reacts better that other models under braking phase.

4.6.3 Traffic Lights Scenario: Behavior at stopping and approaching traffic signal

The traffic lights scenario describes the driving behavior of the vehicle when approaching a traffic signal. First a traffic signal is red and a queue of vehicles is waiting where the optimal velocity goes to 0. When the signal switch to green, at$t = 0$, vehicles start running. The virtual obstacles in each lane appeared when the light is red and removed when the light turns to green. Figure 4.22 represents the snapshot of vehicle motion and their

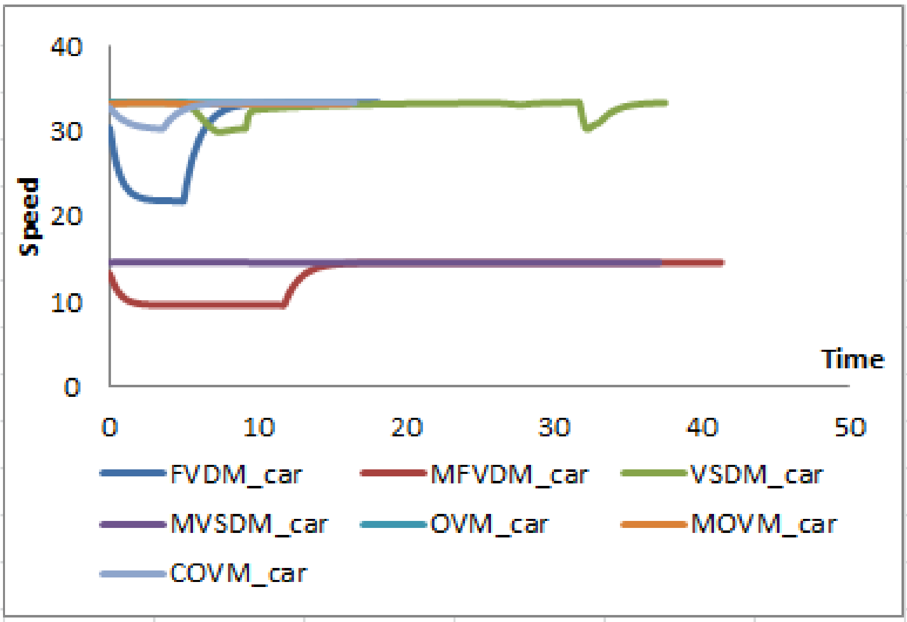
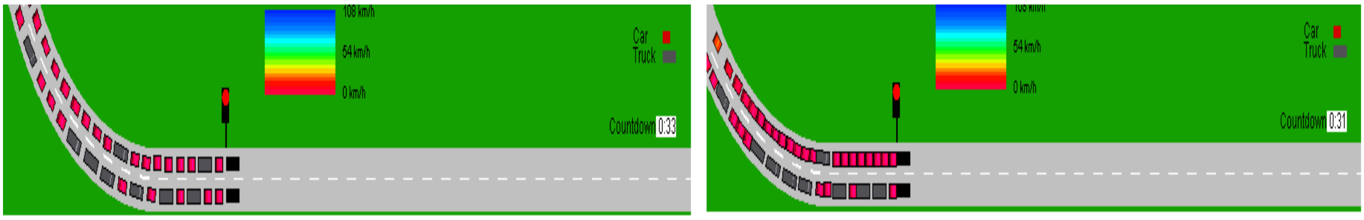


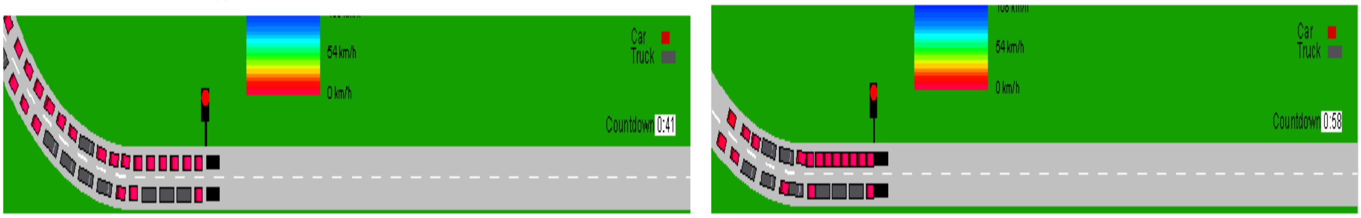
Figure 4.21: Time evolution of velocity variation according to MOVM, VSDM, OVM, FVDM, MFVDM and MVSDM

behavior according to MFVD, FVD, MVSD, VSD, OV, and MOV models. Through these results, and when approaching traffic lights, it can be observed that the vehicles collide in the previous models. However, the problems of collision in emergency case were solved. Furthermore, the simulation results show that our proposed models can exactly describe the driver's behavior when approaching traffic signal, where no crash occurs.



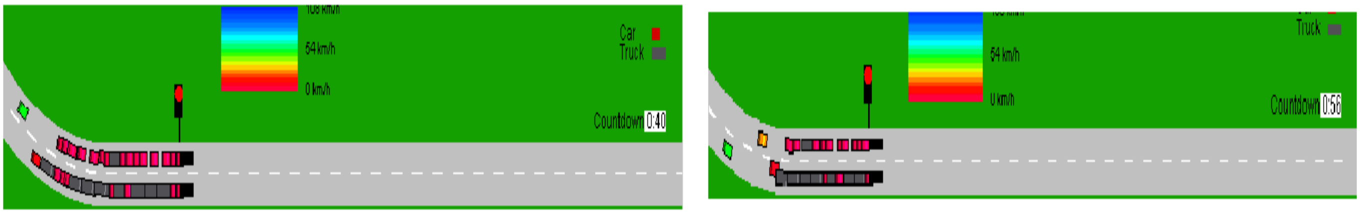
(a) MFVDM

(b) FVDM



(c) MVSDM

(d) VSDM



(e) MOVM

(f) OVM

Figure 4.22: Traffic lights simulation according to (a) MFVDM, (b) FVDM, (c) MVSDM, (d) VSDM, (e) MOVM, and (f) OVM

Figure 4.23 gives the position evolution on the road of the four simulated cars. Therefore the different positions of the cars are given by a curve in this plane. If the curves are parallel, it is because the cars don't provoke the collision. However, if two of these lines intersecting, one car has hit another.

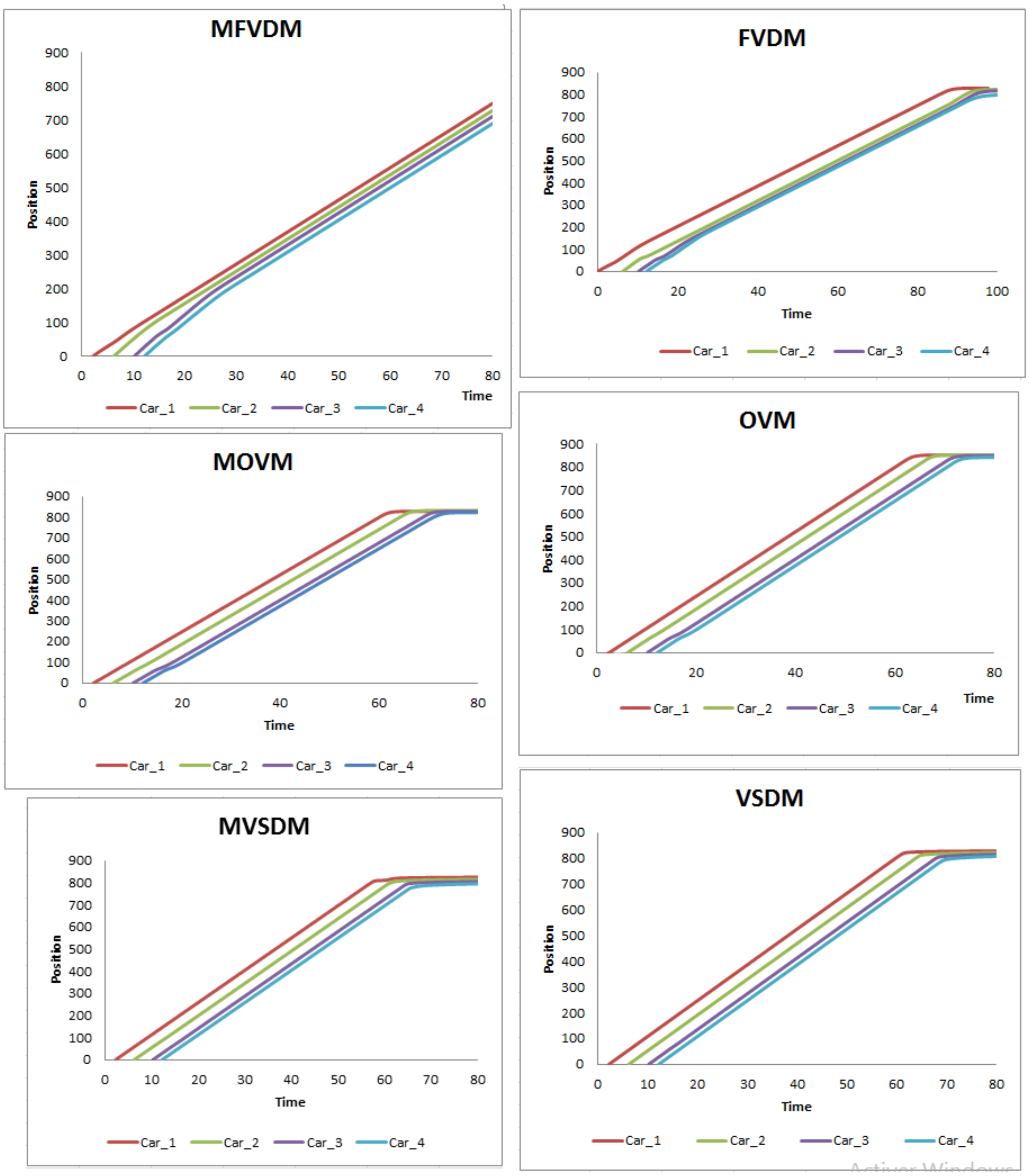


Figure 4.23: Position variation according to MFVDM, FVDM, OVM, MOVM,VSDM, and MVSDM

Figure 4.24 represents the velocity variation of two vehicles using the MVSDM in the case of several changes. At the beginning, vehicle 1 follows vehicle 2 in the same lane 0, after a few moments vehicle 1 change the lane 0 towards the lane 1 that is why two vehicles show themselves in parallel when approaching traffic lights at $t = 57$. In approaching phase, and at $t = 72$ vehicles should decelerate smoothly, which clearly shown that the vehicles stopped completely at a red light, and their velocity goes to 0. When the signal changes to green, vehicles begin to accelerate.

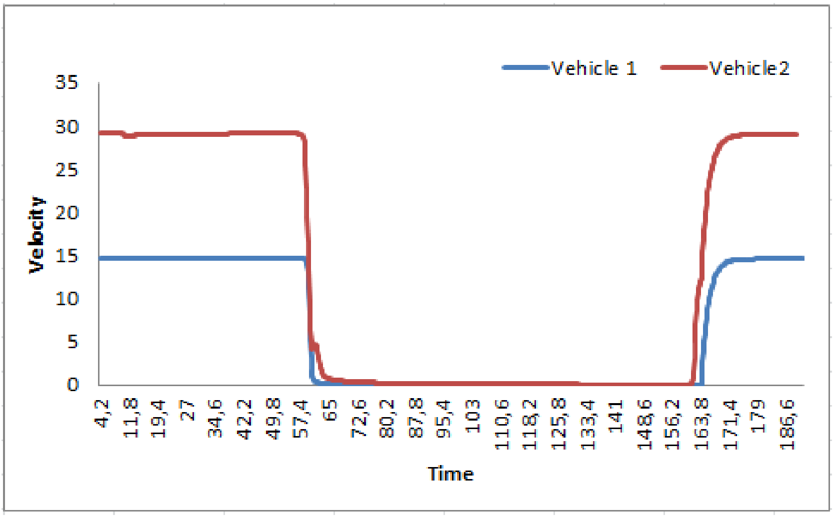
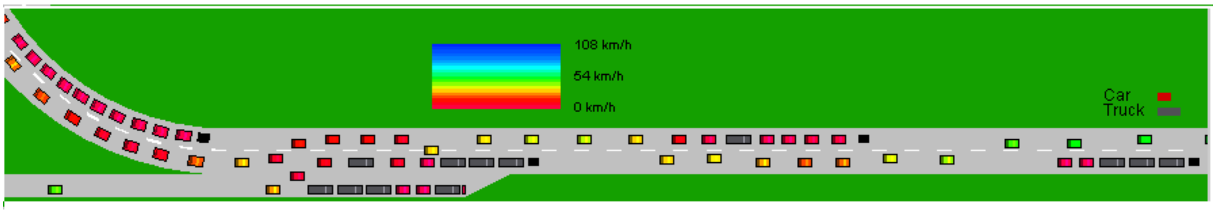


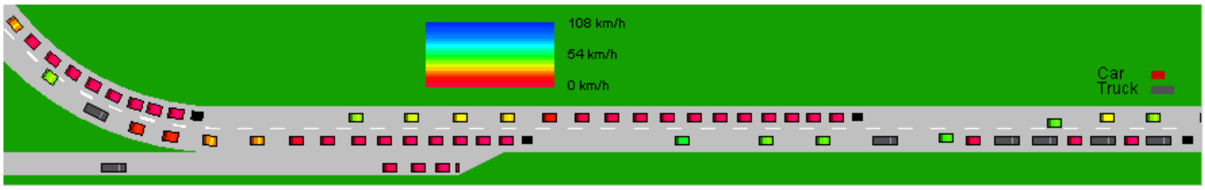
Figure 4.24: Driving behavior of two vehicles according MVSDM in each lane

4.6.4 Simulation of the close lane by standing obstacles scenario

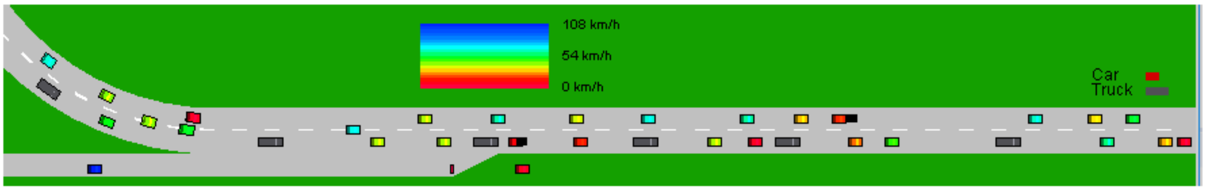
In this scenario, we applied some perturbation when the vehicles move normally. To enhance the breakdown, perturbations to the traffic flow can be added by letting one vehicle brake without reason. In fact, we forced a car to change lanes by adding standing obstacle presented in black color to close different lanes. Figure 4.25 demonstrates a driving behavior of MOVM, MFVDM, and MVSDM. It's showed clearly that the proposed models simulate realistically the traffic flow. Our models forced lane change and avoid crash when MOV model can't avoid it.



(a) MFVDM



(b) MVSDM



(c) MOVM

Figure 4.25: Ramp simulation according to (a) MFVDM, (b) FVDM, (c) MVSDM, (d) VSDM, (e) MOVM, and (f) OVM

4.6.5 Rear-end collision risk evaluation

We examine the rear-end collision risk by exceeding the speed of the optimal seed function by 10 percentage, the risk associated with optimal velocity function $R_{V_{opt}}$ and the risk associated with new optimal velocity function $R_{V_{opt}^{new}}$ described as:

$$R_{V_{opt}}(S_i, 1.1V_{opt}(S_i)) = -1 + \frac{0.1S_i}{a_i(1.1)^2V_{opt}(S_i)} \tag{4.48}$$

$$R_{V_{opt}^{new}}(S_i, 1.1V_{opt}(S_i)) = -1 + \frac{S_i}{1.1a_iV_{opt}(S_i)}(1 - \frac{1}{1.1}W(S_i, -1.1V_{opt}(S_i)) \tag{4.49}$$

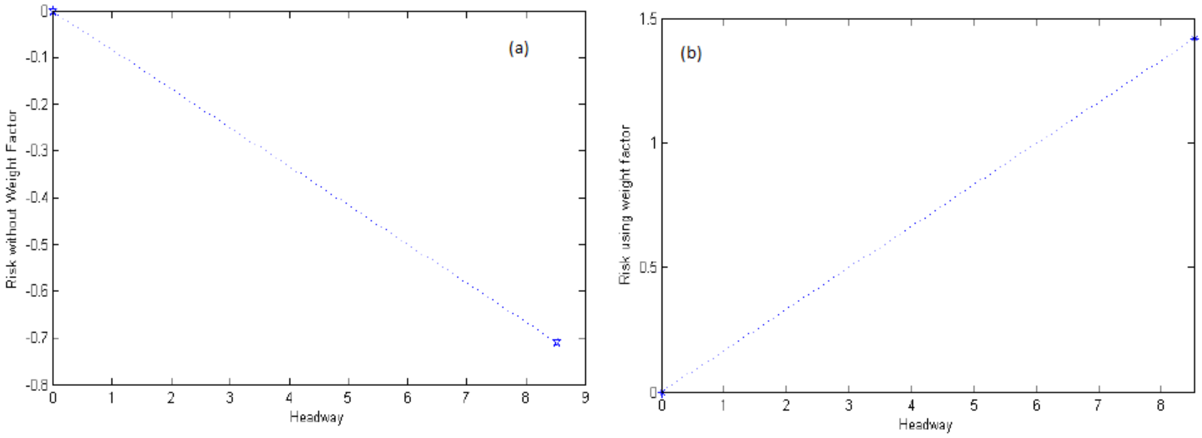


Figure 4.26: Rear-end collision risk: (a) The risk associated with optimal velocity function (b) The risk associated with weight factor

From Figure 4.26 (a), we show that the risk associated with the optimal velocity function goes under -0.7 at a spacing of 8 m. This means that the driver do not decelerate enough. Figure 4.26 (b) gives now the risk associated with the proposed optimal velocity function introducing the weight factor. The model that introducing the weight factor reacts better and remains always positive, which means that the drivers reacts well and makes the time to collision increasing.

4.7 Chapter summary

The microscopic car-following model is a favorite type of traffic flow theory to describe the individual behavior of drivers. In this chapter, we presented the most car-following model well-known the optimal velocity (OV) model and its generalizations, which has successfully revealed the dynamical evolution process of traffic congestion in a simple way. Thereafter, we have reviewed the existing car following models and the recent one and giving their drawbacks and advantages to help for developing the strong car following model which avoids the collision and interpreted the traffic flow in a real manner. Consequently, we suggested an extended car following models basis on acceleration which is a continuous function incorporating different driving modes for all velocities in freeway traffic as well as city traffic. The introduction of a new optimal velocity function on MFVDM and MVSDM depends on weighting factor which incorporate time to collision indicator besides the headway and the actual speed. The weighting factor plays an essential stabilizing role in real traffic, especially when approaching traffic jams and avoiding rear-end collisions. To simulate the car motion and to describe traffic flow, we examine certain properties of traffic microscopically in such situations: stop and go traffic, close lane by standing obstacles, approaching and stopping at traffic lights, evaluation of rear-end collision risk.

The choice of MOBIL lane changing model is not arbitrary. Most of the published lane-changing models follow a rule-based approach with different gap-acceptance conditions. This approach often tends to lead to complex models with many parameters. However, the lane changes model MOBIL based on the acceleration-based decisions. This means, both the incentive criterion and safety constraints can be expressed in terms of the acceleration function of the underlying car following model. The model is able to describe lane changes as well as symmetric and asymmetric lane changes in a consistent way. To interpret traffic road, effectively, we proposed to implement the extended car following models MFVDM and MVSDM using lane changing model MOBIL. Through the experiment results, the proposed approach demonstrate that can overcome the shortcomings of previous models and explain the good performance of the underlying car-following models.

CHAPTER 5

Conclusion and future work

5.1 Conclusion and main findings

The aim of this final chapter is to summarize the main achievements of this dissertation thesis. In section 5.1.1 a summary is given of the main research aims and the approach used to achieve these aims. Major contributions of this thesis are discussed in section 5.1.2. Finally, suggestions for future research are presented.

5.1.1 The Acceleration Model and Lane changing Model

The driving task is an interesting task that consists of all tasks a driver must execute to reach the destination safely, comfortably, and timely. Traffic flows modeling is a huge research topic in which several car following models have been proposed to govern the longitudinal movement of vehicles in a traffic stream. Generally, car following or acceleration models can be classified into: sensitivity-stimulus, and safety or non-collision models. We interested, particularly, in safety or non-collision models which assume that a driver maintains a safe distance to prevent a collision at any time of movement. Existing general purpose microscopic models do not offer a suitable result for safety study purposes. The motivation for analyzing this particular behavior that the longitudinal driving behavior of individual drivers determines a large extent the characteristics of traffic flow as a whole. To complete a driving task, the lane change model required. For a driver considering a lane change, a change increases with the gap to the new leader in the target lane. However, if the speed of this leader is lower, it may be favorable to stay in the present lane despite the smaller gap. In this dissertation, we focused on the longitudinal component of the maneuvering and control behavior of a driver. We analyzed how vehicles interact with other combinations driving on multi-lane roads using lane changing MOBIL including both situations is the difference between the accelerations after and before the lane change. The proposed approach was tested using a microscopic traffic simulator and under different scenarios.

5.1.2 Contributions

The aim of this study was to look at existing microscopic simulation models from a safety point of view. The final purpose of this research was to put forward a novel and enhanced CF model. In the meantime, the proposed CF model was required to be more robust than the present CF models in replication of the safety metrics. The model should provide the traffic analyzer assurance of being capable of relying on the microscopic simulation models for safety evaluation. In this research, we examined current microscopic simulation models including the factors and regulations that administrate the microscopic sub-models, mainly , the CF and LC models. Therefore the following contributions are presented:

- We contributes to the state of the art in modeling drivers' acceleration and lane changing behavior in two major areas: enhancing existing models and proposing new models.
- The car following model is extended by assuming that the new OV function including TTC as safety factor for traffic flow theory.
- The combination of proposed CF models with lane change models treated in this study.
- Validation of theoretical approach by micro-simulator under different variety of scenarios.

5.2 Recommendation for future research

This dissertation focused on the car following models' accuracy for safety evaluation. there are unlimited fields of research and application of the traffic road that makes the study as only a partial contribution and that several perspectives are open for the continuation of this work. The most significant areas for further research are as below:

- An equivalent macroscopic model for the car following model can add to the strengths of the model and highlight the model's different perspectives.
- Proposing and focusing on the other behavioral models such as lane changing would be valuable.
- Testing the proposed approach using lane change behavioral in bidirectional roads.
- Using real microscopic traffic data to estimate both the acceleration and lane changing models.

- Fuel consumption and emission production must be examined.
- Another challenging issue for the next generation of Intelligent Transportation Systems is the transmission of information within the transportation network using wireless communication technologies.

Bibliography

[1] Marilleau, N., Lang, C., Chatonnay, P., and Philippe, L. Un méta-modèle à base d'agents pour modéliser la mobilité urbaine, Computer science laboratory of the University of Franche-Comté, 3nd conferences of electronic sciences, 2005.

[2] Pariota, L. Driving behaviour for ADAS: theoretical and experimental analyses, Doctoral Thesis, pp.1-132, 2013. DOI:10.6092/UNINA/FEDOA/9074.

[3] Tarko, A., Davis, G., Saunier, N., Sayed, T., and Washington, S. Surrogate measures of safety. White paper, ANB20(3) Subcommittee on Surrogate Measures of Safety, 2009.

[4] Andreas, P., Princess, N., and Oliver, S. Intelligent transportation system for traffic and road infrastructure-related data. International Journal of Advanced Logistics, 5(1), pp.19-29, 2016. DOI:10.1080/2287108X.2016.1144372.

[5] Kaveh, B. The development of a naturalistic car following model for assessing managed motorway systems' safety effects. Doctoral Thesis, pp.201, 2013. https://eprints.qut.edu.au/61499/

[6] Hidas, P. A car following model for urban traffic simulation. Traffic Engineering + Control, 39(5), pp. 300-305, 1998.

[7] Sven, M., Bart, D. M., Transportation Planning and Traffic Flow Models. ArXiv preprint physics/0507127. pp. 1-51, 2005. DOI:https://arxiv.org/abs/physics/0507127.

[8] Kazi, A. Modeling Drivers' Acceleration and Lane Changing Behavior. Doctoral Thesis, pp.1-189, 1999.

[9] Sarbaz, O. Safety Evaluation of Road Characteristics. Doctoral Thesis, pp.1-130, 2011.

[10] Fink, K. L., Krammes, R. A. Tangent Length and Sight Distance Effects on Accident Rates at Horizontal Curves on Rural Two-Lane Highways. Journal of Transportation Research Record, (1500), 162-168, 1995.

[11] Fullar, R., Santos, J. Human Factors for Highway Engineering. Emerald Group Publishing. Oxford, U.K, 2002.

[12] Stigson, H. A Safer Road Transport System – Factors Influencing Injury Outcome for Car Occupants. Ph.D Thesis. Karolinska Institute, 2009.

[13] Urry, J. Sociology Beyond Societies: Mobilities for the Twenty-First Century, London, Routledge, 2000.

[14] Orfeuil, J. P. L'évolution de la mobilité quotidienne : comprendre les dynamiques, éclairer les controverses, Synthèse INRETS, 37, pp.146, 2000. DOI : 10.1016/S0761-8980(01)90137-2

[15] Newman P., Kenworthy J., , Cities and Automobile Dependence: An International Sourcebook, Gower, Aldershot, 1989.

[16] Anand, P., Naveen, C., Alfred, D., and Seungmin, R. Chapter 2 - Intelligent transportation systems, In Intelligent Vehicular Networks and Communications, Elsevier, pp. 21-41, 2017. DOI: https://doi.org/10.1016/B978-0-12-809266-8.00002-8

[17] Lucia, J., Silvia, Č. Improving Safety of Transportation by Using Intelligent Transport Systems, In Procedia Engineering, 134, pp. 14-22, 2016. DOI:https://doi.org/10.1016/j.proeng.2016.01.031.

[18] Ling, S., Yameng, L., and Jian, G. Architecture and Application Research of Cooperative Intelligent Transport Systems, In Procedia Engineering, 137, pp.747-753, 2016. DOI:https://doi.org/10.1016/j.proeng.2016.01.312.

[19] Jean-Paul, R. The geography of transport systems. Fourth edition, New York: Routledge, pp.440, 2017. ISBN 978-1138669574. https://people.hofstra.edu/geotrans/eng/ch6en/conc6en/ch6c4en.html

[20] Muhammad Junaid, F. Modeling and Analysis of Inter-vehicle Communication: A Stochastic Geometry Approach. Ph.D Thesis, pp.100, 2015.

[21] Davies, V. Evaluating Mobility Models within an Ad Hoc Network , MS thesis, Colorado School of Mines, 2000.

[22] Mohammad Mostafa, S., Ibrahim M.I, R., and Abobakr Mohamed, I. Development of traffic stream characteristics models for intercity roads in Egypt. In Alexandria Engineering Journal, 55(3), pp.2765-2770, 2016, ISSN 1110-0168. DOI: https://doi.org/10.1016/j.aej.2016.04.031.

[23] Jerome, H., Fethi, F., and Christian, B. Mobility Models for Vehicular Ad Hoc Networks: A Survey and Taxonomy. Research Report RR-06-168, 2007.

[24] Legendre F., Borrel V., de Amorim M.D., Fdida S. Modeling Mobility with Behavioral Rules: The Case of Incident and Emergency Situations. In: Cho K., Jacquet P. (eds) Technologies for Advanced Heterogeneous Networks II. AINTEC 2006. Lecture Notes in Computer Science, 4311. Springer, Berlin, Heidelberg, 2006. DOI:$https://doi.org/$10.1007/11930181$_1$4

[25] Champion, A. Mécanisme de coordination multi-agent fondé sur des jeux: application à la simulation comportementale de trafic routier en situation de carrefour, PhD thesis, pp.181, 2003.

[26] Lighthill, M. J., Whitham, G. B. On kinematic waves. II. A theory of traffic flow on long crowded roads. Proc. R. Soc. Lond, 1955.

[27] Mallikarjuna, Ch., Ramachandra Rao, K. Heterogeneous traffic flow modelling: a complete methodology. Transportmetrica, 7(5), pp.321-345, 2011. DOI: http://dx.doi.org/10.1080/18128601003706078

[28] Puspita, D. Heterogeneous Motorised Traffic Flow Modelling using Cellular Automata. Ph.D Thesis, pp.139, 2007.

[29] Treiber, M., Kesting, A. General Aspects- Traffic Flow Dynamics: Data, Models and Simulation. Springer Berlin Heidelberg journal. Book. 2013. DOI:10.1007@978-3-642-32460-46

[30] Costeseque, G. Modélisation et simulation dans le contexte du trafic routier, In F. Varenne et M. Silberstein Eds, Modéliser and simuler. Epistémologies et pratiques de la modélisation et de la simulation, Editions Matériologiques, 2013.

[31] Darbha, S., Rajagopal, K., Tyagi, V. A review of mathematical models for the flow of traffic and some recent results. Nonlinear Analysis: Theory, Methods and Applications. 69(3), pp. 950-970, 2008. DOI: 10.1016/j.na.2008.02.123

[32] Aghabayk, K., Sarvi, M., Young, W. A State-of the-Art Review of Car-Following Models with Particular Considerations of Heavy Vehicles. Transport Reviews. 35(1), pp. 82-105, 2015. DOI: 10.1080/01441647.2014.997323

[33] Pipes, L. A. An Operational Analysis of Traffic Dynamics. Journal of Applied Physics. 24(3), pp. 274-281, 1953. DOI: 10.1063/1.1721265

[34] Kometani, E., Sasaki, T. A Safety Index for Traffic with Linear Spacing. Operations Research. 7(6), pp. 704-720, 1959. DOI: 10.1287/opre.7.6.704

[35] Gipps, P. A behavioral car-following model for computer simulation. Transportation Research Part B: Methodological. 15(2), pp. 105-111, 1981. DOI: 10.1016/0191-2615(81)90037-0

[36] Brackstone, M., McDonald, M. Car-following: a historical review. Transportation Research Part F: Traffic Psychology and Behaviour. 2(4), pp. 181-196, 1999. DOI: 10.1016/s1369-8478(00)00005-x

[37] Jabeena, M. Comparative Study of Traffic Flow Models And Data Retrieval Methods From Video Graphs. International Journal of Engineering Research and Applications. 3(6), pp. pp. 1087-1093, 2013.

[38] Chandler, R., Herman, R., Montroll, E. Traffic Dynamics: Studies in Car Following. Operations Research. 6(2), pp. 165-184, 1958. DOI: 10.1287/opre.6.2.165

[39] Helly, W. Simulation of Bottlenecks in Single-lane Traffic Flow. In: Proceedings of the Symposium on Theory of Traffic Flow, Elsevier, pp. 207-238, 1961.

[40] Gazis, D., Herman, R., Rothery, R. Nonlinear Follow-the-Leader Models of Traffic Flow. Operations Research. 9(4), pp. 545-567, 1961. DOI: 10.1287/opre.9.4.545

[41] May, A. D., Keller, H. E. M. Non integer car following models. Highway Research Record. 199, pp. 19-32, 1967.

[42] Heyes, M., Ashworth, R. Further research on car-following models. Transportation Research. 6(3), pp. 287-291, 1972. DOI: 10.1016/0041-1647(72)90036-6

[43] Ceder, A., May, A. D. Further evaluation of single and two regime traffic flow models. Transportation Research Record. 567, pp. 1-30, 1976.

[44] Zeng, Y., Zhang, N. Review and New Insights of the Car-Following Model for Road Vehicle Traffic Flow. E. Qi (ed.), Proceedings of the 6th International Asia Conference on Industrial Engineering and Management Innovation, pp. 87-96, 2016. DOI:$10.2991/978-94-6239-148-2_9$

[45] Kesting, A., Treiber, M., Helbing, D. Agents for Traffic Simulation. In: Multi-Agent Systems: Simulation and Applications. (Uhrmacher, A., Weyns, D. (ed.)), Chapter 11, pp. 325-356. CRC Press, Boca Raton, Florida, USA. 2009. DOI: 10.1201/9781420070248.

[46] Lighthill, M. J., Whitham, G. B. On kinematic waves. II. A theory of traffic flow on long crowded roads. Proc. R. Soc. Lond. 1955.

[47] Richards, P.I. Shock waves on the highways, Operation Research, 4,pp.42-51, 1956.

[48] Daganzo, C.F. Requiem for second-order fluid approximation of traffic flow. Transportation Research, 29 B, pp.277-286, 1995.

[49] Papageorgiou, M. Some remarks on macroscopic traffic flow modeling, Copyright © 1998 Elsevier Science Ltd, S0965-8564(97)00048-7, Transpn Res.-A, 32(5), pp. 323-329, 1998.

[50] Payne, H.J. Models of freeway traffic and control, In: Bekey, G.A. (Ed.), Mathematical model of public systems, Simulation Council Proceeding, 1, pp. 51-61, 1971.

[51] Greenshields, B. D. A Study of Traffic Capacity. Highway Research Board Proceedings 14, pp. 448-477, 1935.

[52] Greenberg, H. An analysis, of traffic flow, Operations Research, 7(1), pp. 79-85, 1959.

[53] Cassidy, M.J. Bivariate relations in nearly stationary highway traffic flow, Transportation research, 32B (1), pp.49-59, 1998.

[54] Drake A. Statistical Analysis of Speed Density Hypotheses. Highway Research Record, 154, pp. 53-87, 1967.

[55] Daganzo, C., Laval, J., Munoz, J.C. The strategies for freeway congestion mitigation with advanced technologies, California PATH research report UCB-ITS-PRR-2002-3, 2003.

[56] Underwood, R. T. Speed, Volume, and Density relationships. In: Quality and Density of Traffic Flow, Yale Bureau of Traffic, pp. 66-76, 1961.

[57] Jabeena, M. Comparative Study of Traffic Flow Models And Data Retrieval Methods From Video Graphs. International Journal of Engineering Research and Applications. 3(6), pp. 1087-1093, 2013.

[58] Gerlough, D.L., Huber, M.J. Monograph on traffic flow theory. Transportation Research Board, Special report 165, 1975.

[59] Zhang, H.M. A theory of non-equilibrium traffic flow. Trans. res.-B, 32(7), pp. 485-498, 1998. PII:S0191-2615/98/00014-9

[60] Leclercq, L. Modélisation dynamique du trafic et application à l'estimation du bruit routier, Thèse de doctorat INSA de Lyon, ENTPE/INRETS, 2002.

[61] Aw, A., Rascle, M., Resurrection of "Second Order" Models of traffic flow. Siam, J. Appl. Math. 60, pp. 916-938, 2000.

[62] Zhang, H.M. A non-equilibrium traffic model devoid of gas like behavior. Transportation Research Part B, 36(3), pp. 275–290, 2002.

[63] Olstam, J. J., Tapani, A. Comparison of Car-following models.VTI meddelande 960A, 2004.

[64] Hayward, J.C. Near miss determination through use of a scale of danger (traffic records 384). Highway Research Board, Washington,DC, 1972.

[65] Behbahani, H., Nadimi, N., Alenoori, H.,Sayadi, M. Developing a New Surrogate Safety Indicator Based on Motion Equations. PROMET - Traffic and Transportation, 26(5), 2014. DOI:10.7307/ptt.v26i5.1388.

[66] Minderhoud, M., Bovy, P. Extended time-to-collision measures for road traffic safety assessment. Accident Analysis and Prevention, 33(1), pp.89-97, 2001.DOI:10.1016/s0001-4575(00)00019-1.

[67] Vogel, K. A comparison of headway and time to collision as safety indicators. Accident Analysis and Prevention, 35(3), pp.427-433, 2003.DOI:10.1016/s0001-4575(02)00022-2.

[68] Chin, H., Quek, S. Measurement of traffic conflicts. Safety Science, 26(3), pp.169-185, 1997. https://doi.org/10.1016/S0925-7535(97)00041-6

[69] Van Der Horst, A.R. A time-based analysis of road user behavior in normal and critical encounters, Dissertation Delft University of Technology. 1990.

[70] Minderhoud, M. M., Bovy, P. H.L. Extended time-to-collision measures for road traffic safety assessment. Accident Analysis and Prevention 33(1), pp.89-97, 2001. https://doi.org/10.1016/S0001-4575(00)00019-1

[71] Cooper, P.J. Experience with Traffic Conflicts in Canada with Emphasis on Post Encroachment Time Techniques. In International Calibration Study of Traffic Conflicts, NATA ASI Series, Vol. F5, Springer-Verlag, Heidelberg, pp.75-96, 1983.

[72] Archer, J. Indicators for traffic safety assessment and prediction and their application in micro-simulation modelling: A study of urban and suburban intersections. Doctoral Thesis, 2005.

[73] Lazar, H., Rhoulami, K., Rahmani, M. D. A Review Analysis of Optimal Velocity Models. Periodica Polytechnica Transportation Engineering, 44(2), pp.123-131, 2016. DOI : 10.3311/pptr.8753.

[74] Newell, G. F. Nonlinear effects in the dynamics of car-following. Operations Research. 9(2), pp. 209-229, 1961. DOI: 10.1287/opre.9.2.209

[75] Bando, M., Hasebe, K., Nakanishi, K., Nakayama, A. Analysis of optimal velocity model with explicit delay. Physical Review E. 58(5), pp. 5429-5435, 1998. DOI: 10.1103/physreve.58.5429

[76] Helbing, D., Tilch, B. Generalized force model of traffic dynamics. Physical Review E. 58, pp. 133-138, 1998. DOI: 10.1103/physreve.58.133

[77] Lenza, H., Wagner, C.K., and Sollacher, R. Multi-anticipative car-following model. Eur. Phys. J. B 7, pp.331-335, 1999.

[78] Jiang, R., Wu, Q., Zhu, Z. Full velocity difference model for a car following theory. Physical Review E. 64(1), 2001. DOI: 10.1103/physreve.64.017101

[79] Mammar, S., Mammar, S., Haj Salem, H. A Modified Optimal Velocity Model for Vehicle Following. IFAC proceeding, (2005). https://doi.org/10.3182/20050703-6-CZ-1902.02043

[80] Zhao, X., Gao, Z. A new car-following model: full velocity and acceleration difference model. The European Physical Journal B. 47(1), pp. 145-150, 2005. DOI: 10.1140/epjb/e2005-00304-3

[81] Zhi-Peng, L., Yun-Cai, L. A velocity-difference-separation model for car-following theory. Chinese Physics. 15(7), pp. 1570-1576, 2006. DOI: 10.1088/1009-1963/15/7/032

[82] Lijuan, L., Ning, Z. A New Car Following Model Considering the Acceleration of Leading Car. In: E-Product E-Service and E-Entertainment (ICEEE), 2010 International Conference on 7-9 November 2010, Henan, pp. 1-4, 2010. DOI: 10.1109/iceee.2010.5661080

[83] Li, Y., Sun, D., Liu, W., Zhang, M., Zhao, M., Liao, X., Tang, L. Modeling and simulation for microscopic traffic flow based on multiple headway, velocity and acceleration difference. Nonlinear Dynamics. 66(1-2), pp. 15-28, 2011. DOI: 10.1007/s11071-010-9907-z

[84] Jing, P., Juan, Z., Gao, L. Improvement of the Full Velocity Difference Car-following Model. Journal of Computational Information Systems. pp. 3651-3659, 2011.

[85] Tian, J., Jia, B., Li, X. A New Car Following Model: Comprehensive Optimal Velocity Model. Communications in Theoretical Physics. 55(6), pp. 1119-1126, 2011. DOI: 10.1088/0253-6102/55/6/29

[86] Liu, Y., Zhang, H., He, L. Cooperative Car-Following Model of Traffic Flow and Numerical Simulation. Chinese Physics Letters. 29(10), p. 104-502, 2012. DOI: 10.1088/0256-307x/29/10/104502

[87] Xu, H., Liu, H., Gong, H. Modeling the asymmetry in traffic flow (a): Microscopic approach. Applied Mathematical Modelling. 37(22), pp.9431-9440, 2013. DOI: 10.1016/j.apm.2013.04.037

[88] Xu, X., Pang, J., Monterola, C. Asymmetric optimal-velocity car-following model. Physica A: Statistical Mechanics and its Applications. 436, pp. 565-571, 2015. DOI: 10.1016/j.physa.2015.04.023

[89] Yi-Rong, K., Di-Hua, S., Shu-Hong, Y. A new car-following model considering driver's individual anticipation behavior. Nonlinear Dynamics. 82(3), pp. 1293-1302, 2015. DOI: 10.1007/s11071-015-2236-5

[90] Milan, B., Elen, T. Optimal velocity functions for car-following models. Journal of Zhejiang University-Science A (Applied Physics and Engineering), Faculty of Maritime Studies and Transport, University of Ljubljana, Slovenia, 2012.

[91] Lazar, H., Rhoulami, K., Rahmani, D. A Modified Full Velocity Difference Model Based on Time To Collision as a Safely Indicator for Braking State. In: 2nd IEEE World Symposium on Web Applications and Networking (WSWAN). Sousse, 21-23 March 2015. DOI: 10.1109/wswan.2015.7210342

[92] Lazar H., Rhoulami K., Rahmani M.D., A Novel Velocity-Separation Difference Model for Traffic Flow Theory. In: El Oualkadi A., Choubani F., El Moussati A. (eds) Proceedings of the Mediterranean Conference on Information and Communication Technologies 2015. Lecture Notes in Electrical Engineering, 381. Springer, Cham, 2016. DOI: 10:1007/978-3-319-30298-01.

[93] Moridpour, S., Sarvi, M., Rose, G. Lane Changing Models: A Critical Review. Transportation Letters The International Journal of Transportation Research. 2(3), pp.1-28, 2010. DOI: 10.3328/TL.2010.02.03.157-173

[94] Rahman, M., Chowdhury, M., Xie,Y., He, Y. Review of Microscopic Lane-Changing Models and Future Research Opportunities. IEEE Transactions on Intelligent Transportation Systems, 14(4), pp.1942-1956, 2013. DOI: 10.1109/TITS.2013.2272074

[95] Toledo, T. Driving behavior: Models and challenges. Transport Reviews, 27(1), pp. 65–84, 2007.

[96] Lygeros, J., Godbole, D. N., Sastry, S. Verified hybrid controllers for automated vehicles. IEEE Trans. Autom. Control, 43(4), pp. 522–539, 1998.

[97] Nagel, K., Wolf, D. E.,Wagner, P. , Simon, P. Two-lane traffic rules for cellular automata: A systematic approach. Phys. Rev. E, 58, pp. 1425–1437, 1998.

[98] Maerivoet, S., de Moor, B. Cellular automata models of road traffic. Phys. Rep., 419(1), pp. 1–64, 2005.

[99] Eidehall, A., Pohl, J.,Gustafsson, F., Ekmark, J. Toward autonomous collision avoidance by steering. IEEE Trans. Intell. Transp. Syst., vol. 8(1), pp. 84–94, 2007.

[100] Salvucci, D. D., Mandalia, H. M. Lane-change detection using a computational driver model, Human Factors Ergonom. Soc., 49(3), pp. 532–42, 2007.

[101] Doshi, A., Trivedi, M. A comparative exploration of eye gaze and head motion cues for lane change intent prediction. In Proc. IEEE Intell. Veh. Symp., pp. 49–54, 2008.

[102] Kiefer, R. J., Hankey, J. M. Lane change behavior with a side blind zone alert system. Accid. Anal. Prev., vol. 40(2), pp. 683–690, 2008.

[103] Li-Sheng, J,Wen-Ping, F., Ying-Nan, Z., Shuang-Bin, Y., Hai-Jing, H. Research on safety lane change model of driver assistant system on highway. In Proc. IEEE Intell. Veh. Symp., pp. 1051–1056, 2009.

[104] Sukthankar, R., Baluja, S. Hancock, J. Evolving an Intelligent Vehicle for Tactical Reasoning in Traffic. Proceedings of the International Conference on Robotics and Automation, pp.519 – 524, 1997.

[105] Alexiadis, V., Gettman and Hranac, R. Next Generation Simulation (NGSIM): identification and prioritization of core algorithm categories. Department of Transportation Federal HighWay Administration (FHWA), 2004.

[106] Treiber, M., Kesting, A. Chapter 14: Lane-Changing and Other Discrete-Choice Situations- Traffic Flow Dynamics: Data, Models and Simulation. Springer Berlin Heidelberg journal. Book. 2013. DOI:10.1007@978-3-642-32460-414

[107] Gipps, P. G. A model for the structure of lane-changing decisions. Transp. Res. Part B, Methodol., 20(5), pp. 403–414, 1986.

[108] Sun, D.J. A lane-changing model for urban arterial streets. Ph.D. dissertation, 2009.

[109] Gipps, P. G. A behavioral car-following model for computer simulation, Transp. Res. Part B, Methodol., 15(2), pp. 105–111, 1981.

[110] Halati, A., Lieu, H.,Walker, S. CORSIM—Corridor traffic simulation model. In Proc. Traffic Congest. Traffic Safety 21st Century Conf., pp. 570–576, 1997.

[111] Toledo, T. Integrated driving behavior models. Ph.D. dissertation, Dept. Civil Environ. Eng., Massachusetts Inst. Technol., Cambridge, USA, 2002.

[112] Hidas, P. Modelling vehicle interactions in microscopic simulation of merging and weaving. Transp. Res. Part C, 13(1), pp. 37–62, 2005.

[113] Hidas, P., Behbahanizadeh, K. SITRAS: A simulation model for ITS applications. In Proc. 5th World Congr. Intell. Transp. Syst., Seoul, Korea, 1998.

[114] Rickert, M., Nagel, K., Schreckenberg, M., Latour, A. Two lane traffic simulations using cellular automata. Phys. A, 231(4), pp. 534–550, 1996.

[115] Ahmed, K. I., Ben-Akiva, M. E., Koutsopoulos, H. N., Mishalani, R. G. Models of freeway lane changing and gap acceptance behavior. In Proc. 13th Int. Symp. Theory Traffic Flow Transp., pp. 501–515, 1996.

[116] Ahmed, K. I. Modeling drivers' acceleration and lane-changing behavior. M.S. thesis, Dept. Civil Environ. Eng., Massachusetts Inst. Technol.,1999.

[117] Yang, Q., Koutsopoulos, H. N. A microscopic traffic simulator for evaluation of dynamic traffic management systems. Transp. Res. Part C, 4(3), pp. 113–129, 1996.

[118] Toledo, T., Koutsopoulos, H. N., Ben-Akiva, M. E. Modeling integrated lane-changing behavior.Transp. Res. Rec., 1857, pp. 30–38, 2003.

[119] Toledo, T., Koutsopoulos, H. N. and Ben-Akiva, M. Estimation of an integrated driving behavior model. Transportation Research C, 17(4), pp. 365-380, 2009.

[120] Ma, X. Toward an integrated car-following and lane-changing model based on neural-fuzzy approach. In Proc. Helsinki Summer Workshop, 2004.

[121] Das, S., Bowles, B. A., Houghland, C. R., Hunn, S. J., Zhang, Y. A fuzzy logic model of freeway driver behavior. In Proc. Int. ICSC Congr. Comput. Intell. Methods Appl., New York, NY, USA, pp. 5, 1999.

[122] Das, S., Bowles, B. A. Simulations of highway chaos using fuzzy logic. In Proc., 18th Int. Conf. North Amer. Fuzzy Inf. Process. Soc., pp. 130–133, 1999.

[123] Moridpour, S., Sarvi, M., Rose, G., Mazlami, E. Lane-changing decision models for heavy vehicles drivers. J. Intell. Transp. Syst., Technol., Plan., Oper., 16(1), pp. 24–35, 2012.

[124] Aghabayk, K., Moridpour, S., Wang, Y., Sarvi, M.,Young,W. Understanding the lane changing behavior of large vehicles on arterial roads. 24th ARRB Conference – Building on 50 years of road and transport research, pp.1–15, 2010.

[125] Yang, H., Akiyama T., Sasaki T. A neural network approach to the identification of real time origin destination flows from traffic counts. Proceeding of International Conference on Artificial intelligence Applications in Transportation Engineering, San Buenaventura, CA, 1992.

[126] Lyons, G. Calibration and validation of a neural network driver decision model. Traffic Engineering Control, 36, pp.10-15, 1994.

[127] Pant, P. D., Balakrishman, P. Neural network for gap acceptance at stop-controlled intersections. Journal of Transportation Engineering, 120(3), pp.432-446, 1994.

[128] Hunt, J.G., Lyons, G.D. Modelling dual carriageway lane changing using neural networks. Transportation Research, 2C(4), pp.231-245, 1994.

[129] Dumbuya, A., Booth, A., Reed, N., Kirkham, A., Philpott, T., Zhao, J., Wood, R. Complexity of traffic interactions: Improving behavioural intelligence in driving simulation scenarios. In Complex Systems and Selforganization Modelling. New York, NY, USA: Springer-Verlag, pp. 201–209, 2009.

[130] Kesting, A., Treiber, M., Helbing, D. General Lane Changing Model MOBIL for Car-Following Models. Transportation Research Record: Journal of the Transportation Research Board, pp.86-94, 2007.DOI:http://dx.doi.org/10.3141/1999-10.

[131] Schakel, W. J., Knoop, V. L., van Arem, B. Integrated lane change model with relaxation and synchronization. Transp. Res. Rec., J. Transp. Res. Board, 2316, pp. 47–57, 2012.

[132] Balal, A., Cheu, R.L., Gyan-Sarkodie, T., Miramontes, J. Analysis of Discretionary Lane Changing Parameters on Freeways. International Journal of Transportation Science and Technology. 3(3), pp. 277-296, 2014.

[133] Hausman, J., McFadden., D. Specification Tests for theMultinomial Logit Model. Econometrica, 52(5), pp.1219–1240, 1984.

[134] Treiber, M. and Kesting, A. An Open-Source Microscopic Traffic Simulator. IEEE Intelligent Transportation Systems Magazine, 2(3), pp.6-320, 2010. DOI:10.1109/mits.2010.939208.

[135] Lazar, H., Rhoulami, K., Rahmani, D. Microscopic Evaluation of Extended Car-following Model in Multi-lane Roads.Informatica journal. Accepted paper.

[136] SUMO (Simulation of Urban MObility). Open source traffic simulator, http://sumo.sourceforge.net.

[137] Krauss, S.,Wagner, P., Gawron, C. Metastable states in a microscopic model of traffic flow. Physical Review E, 55(5), pp.5597–5602, 1997.

[138] Bilbao-Ubillos, J. The costs of urban congestion: estimation of welfare losses arising from congestion on cross-town link roads. Transportation Research Part A, 42 (8), pp.1098–11082, 2008.

[139] Zheng, Z., Ahn, S., Chen, D., Laval, J. Applications of wavelet transform for analysis of freeway traffic: bottlenecks, transient traffic, and traffic oscillations. Transportation Research Part B, 45 (2), pp. 372–384, 2011a.

[140] Zheng, Z., Ahn, S., Chen, D., Laval, J.A. Freeway traffic oscillations: microscopic analysis of formations and propagations using wavelet transform. The 19th International Symposium on Transportation and Traffic flow Theory, pp. 717–731, 2011b.

ROYAUME DU MAROC
Université Mohammed V جامعة محمد الخامس
- RABAT - – الرباط –
Faculté des sciences
كلية العلوم

CENTRE D'ETUDES DOCTORALES - SCIENCES ET TECHNOLOGIES

Prénom NOM : Hajar LAZAR
Structure de Recherche : Laboratoire de Recherche en Informatique et Télécommunications
Discipline : Sciences de l'ingénieur
Spécialité : Informatique et Télécommunications

Résumé

Cette thèse porte sur l'analyse et la compréhension des comportements des conducteurs en traitant les comportements de poursuite et de changement de voie. En outre, nous contribuons au développement de modèles microscopiques du trafic en haute performance qui incluent les modèles d'accélération et de changement de voie. Nous avons revu les modèles microscopiques existants pour les améliorer et en développer de nouveaux. Une autre contribution majeure dans cette thèse est de tenir compte de la sécurité du trafic, les modèles existants sont actuellement inadéquats pour évaluer la sécurité et éviter les collisions. Ceci nécessite d'un examen critique des modèles microscopiques actuels pour déterminer quels composants et paramètres ont un effet en termes de sécurité. Notre objectif final dans cette étude est d'établir de nouveaux modèles de poursuite pour évaluer l'impact de différents scénarios de trafic. D'autre part, nous avons combiné les modèles d'écoulement proposés avec le modèle de changement de voie. Les modèles sont validés à l'aide d'un simulateur microscopique de flux de trafic avec différents scénarios: avancer et s'arrêter, s'approcher et s'arrêter au feu de circulation, et perturber la voie en posant des obstacles.

Abstract

This thesis deals with the analysis and understanding of drivers' behaviors during car-following and lane changing. Furthermore, we contribute to the development of microscopic traffic performance models which include the acceleration and lane changing models. We reviewed the existing microscopic models to improve the existing models and develop new ones. Another major contribution of this thesis is to consider the traffic safety; the existing models are currently inadequate to assess safety and to avoid collisions. Our final aim of this study is to establish a new CF model to appraise the impact of different traffic scenarios. On the other hand, we combined the proposed car following models with lane change model. The models are validated using a microscopic traffic simulator with different scenarios: go and stop, approaching and stop at traffic light, and close lane by standing obstacles.

🖂 Faculté des Sciences, avenue Ibn Battouta, BP. 1014 RP, Rabat –Maroc
☎ 00212(0) 37 77 18 76 🖷 00212(0) 37 77 42 61 ; http://www.fsr.ac.ma