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Cellular Automata modeling and simulation of pedestrians and vehicular traffic at the intersections

JURY

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Dedication

I Dedicate this thesis to my parents, my wife and the whole family who have always encouraged and supported me, and who have taught me the value of work and knowledge, which I warmly acknowledge.

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Abstract

Traffic networks are complex systems, and predicting traffic behavior is crucial for planning and operation purposes. Computer simulations have become important tools for evaluating control and management strategies in traffic systems, and among the various simulation models, Cellular Automata (CA) models have gained significant popularity due to their efficient performance in computer simulations. This thesis emphasizes the importance of CA models in describing and predicting traffic flow situations in intersections. The traffic flow situation was studied in three types of intersections: roundabout, traffic circle, and un-signalized intersection. The energy dissipation rate was studied in a roundabout system, and the study showed that the free flow phase is just a quasi-free flow where vehicles decelerate at each entry point of the rotary. Additionally, it was found that traffic circles have a better traffic flow in low densities, and the presence of large-sized and splitters islands enhances the fluidity and performance of the rotary. In the investigation of hybrid traffic flow at un-signalized intersections, a new model was proposed that takes into account the interactions between pedestrians and vehicles. The study found that the gridlock phase is reached when pedestrians have the right of way over vehicles, and their injection rate is larger than a critical value. The study also emphasized the importance of crosswalk location and vehicles changing direction in enhancing traffic flow conditions. Overall, the thesis highlights the importance of CA models in predicting and improving traffic flow situations in complex intersections.

Keywords: Traffic flow, Cellular automata, Intersections, Pedestrians, Energy dissipation.

Résume

La thèse examine l'utilisation des modèles d'automates cellulaires pour prédire et améliorer la circulation routière, en se concentrant sur trois types d'intersections : le carrefour giratoire, le rond-point et l'intersection non signalée. Les modèles de CA sont efficaces pour les simulations informatiques en raison de leur précision relativement faible à l'échelle microscopique. Le taux de dissipation d'énergie a été étudié dans un système de carrefour giratoire et l'étude a montré que la phase d'écoulement libre est juste un écoulement quasi-libre où les véhicules décélèrent à chaque point d'entrée du giratoire. De plus, il a été constaté que les giratoires ont un meilleur écoulement du trafic dans les faibles densités, et que la présence d'îlots de grande taille et de séparateurs améliore la fluidité et la performance du rond-point. Dans l'étude du trafic hybride aux intersections non signalées, un nouveau modèle a été proposé prenant en compte les interactions entre les piétons et les véhicules. L'étude a montré que la phase de blocage est atteinte lorsque les piétons ont la priorité sur les véhicules et que leur taux d'injection est supérieur à une valeur critique. L'étude a également souligné l'importance de l'emplacement des passages piétons et des changements de direction des véhicules dans l'amélioration des conditions de circulation. En conclusion, cette thèse met en évidence l'importance des modèles de CA dans la prédiction et l'amélioration des situations de circulation dans des intersections complexes.

Mots-clés : Trafic routier, Automates cellulaires, Intersection, Piétons, Dissipation énergie

Contents

Introduction

Over the past decade, traffic congestion has become a serious problem day after day in cities. It is said that the major cause of traffic jam is the increase in the number of vehicles due to the increase in the population and the development of economy. In addition, the irrational distribution and the lack of conscience make the traffic worse and worse. The head offices, the universities or hospitals are often located in downtown attracting a heavy flow of people in rush hour. Besides, the highway and road network are incapable of meeting the requirement of the increasing number of vehicles. Facing these challenges, public transportation such as bus, subway or train could relieve road congestion. However, the process of decentralization of cities has been facilitated by car and has resulted in dispersed travel patterns, reducing the possibility of promoting public transport [78]. Hence, the construction of new road is not affordable and publicly acceptable due to the expensive costs and scarce of land, especially in urban areas.

To overcome the problems of traffic congestion, many solutions and strategies were proposed in order to use the available infrastructures more efficiently. However, before giving solutions one should know the causes of traffic congestion genesis in order to reproduce their appearance and to perform reliable predictions. In this context, since the beginning of the twentieth century, scientists from different field have paid more attention to traffic problems researches, especially physicists whose have brought a great contribution of knowledge. Indeed, by using simulation models (i.e. simulation models analyze and forecast very large traffic problems which are way too expensive or very dangerous), many models reproducing the traffic flow dynamics have been proposed. In the literature three models are presented, microscopic, mesoscopic and macroscopic models. The macroscopic models describe collective properties without distinguishing individual vehicles, whereas the microscopic models describe the spatiotemporal behavior of each vehicle and their interactions, it is more detailed models, in the case of the mesoscopic models' vehicles are described as individual entities while the traffic properties are considered as collective.

Indeed, our interest will be focuses on the microscopic models, which can reproduce a large variety of phenomena observed in traffic that cannot be captured by most macroscopic models. The microscopic models are based on three laws: car following (i.e. only the longitudinal spacing between vehicles defined the rules of movement),lane changing (i.e. the transfer of a vehicle from one lane to next adjacent lane)and the gap acceptance (i.e. the minimum size of gap (time or space) in traffic flow that vehicles are willing to accept when entering or crossing a traffic stream, or while changing lanes). Among the microscopic models, Cellular Automata (CA) has been increasingly used in simulations of traffic flow on account of their simplicity and flexibility to computing simulation.

In CA models, time and spatial state variables are discrete, and accordingly, speed, acceleration, and deceleration have also discrete values. This discreteness is also taken into account in the definition of the model and its dynamics. These characteristics make them ideally adapted for high-speed computer simulations, allowing to precisely obtaining the willing behavior in a much simpler way. The cellular automata models (CA) have been used successfully in modeling the real behavior of traffic flow and have become a popular tool for management of traffic. In 1992, Nagel and Schreckenberg [7] proposed the well-known NaSch model. Although the model is fairly simple, however it is able to represent the effect of stop-and-go traffic on vehicle starts, acceleration, and deceleration activities by location on a second-by-second basis and it can reproduce some complex phenomena appearing in real traffic, such as the occurrence of phantom traffic jams.

In this thesis our contribution to the traffic flow research's field is reflected by studying the characteristics of traffic at the urbane intersections (i.e. intersection, roundabout, traffic circle.etc) based on the slot acceptance law and the CA model (NaSch). For the reason that the intersections are critical elements of road networks and their control type and geometric configuration can affect significantly vehicular traffic.

Intersections are locations where two or more roads meet, cross or converge and traffic moving in different directions all comes together. They come in many different designs, configurations, and sizes. Intersections have been described as one of the most complex traffic situations that motorists, pedestrians, cyclists and other road users encounter daily. The crossing and turning maneuvers that occur at intersections create opportunities for vehicle-vehicle, vehicle-pedestrian conflicts, which may result in traffic crashes and blocking roads. Therefore, managing intersections and taking precautions behind the wheel are important and useful steps to avoid all congestion or accidents in an intersection.

As we know, solving congestion in intersection has taken much more intentions. Using traffic signal or road sign is one of the classical methods to solve traffic congestion; however, those methods help us improving the situation of the roads, indeed, to improve the traffic fluidity and the security level, it is necessary to apply some methods to control the traffic. In this perspective, our aimed subject is to propose recommendations to understand all the features of the traffic at intersections. This thesis will be presented in four chapters.

In the first chapter, before exposing our contribution to the traffic flow theory, we will expose the main achievements in understanding the traffic flow. For that purpose, we will proceed by giving a short bibliographical overview of the different components, variables and the most used measuring instruments, as well as traffic flow models and the associated modeling approaches. In addition, we will expose the different empirical findings.

In the second chapter, we will take into account other important parameters that reproduce additional empirical features of traffic flow, namely, the energy dissipation.

Clearly, in the simulation framework, studying the energy dissipation in the roundabout system will enable us to deeply understand the structure of the phases, and it would be a help to traffic engineers in optimizing and predicting the traffic flow and the dissipating energy.

In the third chapter, we will investigate with sufficient traffic flow dynamics at acicular traffic, that is, by using the cellular automata model. It is worth to mention that the studying system is the same as the roundabout system with a different priority rule.

In the fourth chapter, we will consider an important component in the transportation and mobility, namely, the presence of the pedestrians and the crosswalks at an un-signalized intersection. In this context, we will use an open boundary condition to investigate the features of the hybrid traffic (i.e. vehicles-pedestrians), which can affect the road fluidity or the safety.

Finally, we achieve our manuscript with a conclusion and the presentation of same perspectives.

Chapter 1

Traffic modeling: bibliographical investigation.

1.1. Introduction

Nowadays, modeling and simulation of road traffic became a very effective way to predict and solve traffic problems. Modeling and simulation techniques could be used to evaluate and to predict the optimal control of the flow in cities. Hence, this chapter is devoted to presents a bibliographical investigation of some traffic models and simulation techniques. In addition, the traffic components and traffic measuring techniques will be described. Traffic phases and some interesting empirical results will be discussed.

1.2. Components of road traffic

In general, road traffic consists of two major components: the mobile and the infrastructure.

1. The mobile components are defined as road users who drive their vehicles within the infrastructure. Vehicles can be trucks, buses, cars, etc. Although, the pedestrians are an important factor in the urban dynamic, however, there are not considered as a component of road traffic.
2. Infrastructure is defined as road facilities and equipment, including the network, parking spaces, stopping places, draining system, bridges and footpaths.

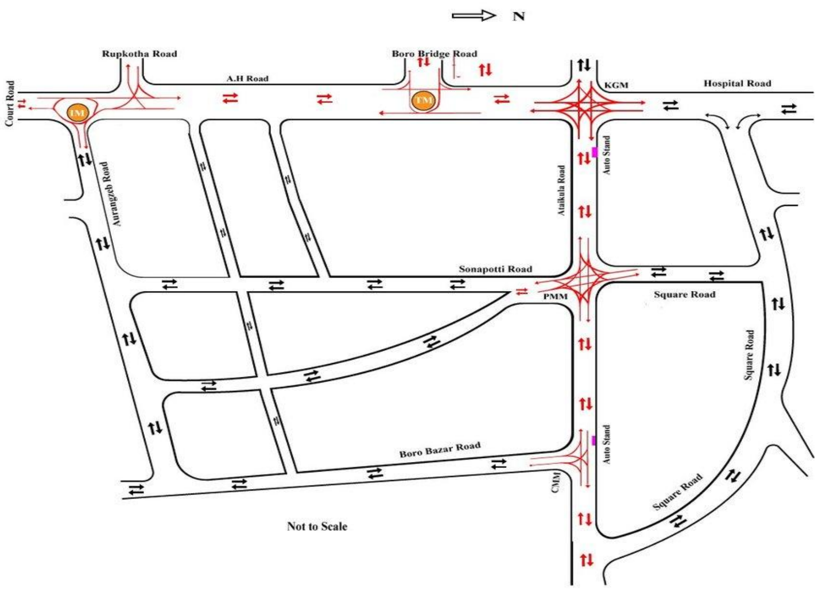


Figure 1.1: road network representation

1.3. Road network

The road network consists of a system of interconnected paved carriageways which are designed to carry all type of vehicles see Figure 1.1. The road network generally provides links with all other areas, both within and beyond the boundaries of the urban area. It is considered as the most basic level of transport infrastructure within urban areas. Road network can be divided into parts such as intersections, urban road and interurban roads, however, the intersections present the most important part, they are the link and the transition between the different roads. At the following, we will give an overview of the roads classification and intersections types that we will discuss in the next chapters.

1.4. Classification of Roads

The roads are named according to the type of constructions, jurisdiction and important function, etc. Names like earth, metalled roads, asphalt roads, and concrete roads indicate the type of constructions. Names like local roads, district roads, state highways, national highways indicate their jurisdiction. Names like rectangular roads, ring roads, and diagonal roads, radial, and circular roads indicate their geometric shape. Names like Avenue, Promenade (a pleasure drive, with the waterfront at least on the side), Boulevards and Parkways indicate their dominant function.

The urban roads are classified as per their importance such as:

- Limited-Access Facility
- Arterial roads
- Secondary or sub-arterial roads
- Local roads
- Other roads

1.4.1. Limited-Access Facility

- **Express-ways**

The express-way is meant to function as road for the movement of fast moving traffic in the big metropolitan cities. Two to three such express-ways are necessarily to be provided around big cities of modern days to face the tremendous growth of the traffic. They however should not form a part of the regular road system, although they should be suitably joined and linked with them. Express-ways are designed with easy gradients and smooth curves so as to carry the traffic speedily and safely. These are originated from the German Autobahnen and Italian Autostrade. These are comparable next to railways in cost and carrying capacity of traffic.

- **Free-ways**

These are the special routes meant to carry fast moving traffic and therefore designed with high standard of alignment, clear visibility, wide carriage way, easy gradient and smooth curves etc. There is no access from adjacent properties as a result full width of free-way is made available for the fast-moving vehicles without any obstruction. The free-ways function as roads passing around the city with controlled access. They also act as main entrances and exits as such they form a part of major road system.

1.4.2. Arterial roads

Those roads connect the cities to the limited access facility. They pass through the city limits and carry a large amount of traffic and therefore should be planned as straight as possible, avoiding sharp curves. Change in direction should be an accompanied by smooth curves. These should not enter into the heart of the city at any cost, should have very few road junctions, which should be controlled by roundabouts or flyovers. They should have no obstructions such as frontage of buildings, loading or unloading areas, parking places, and pedestrians on the carriage way. Further these roads may be made more pleasing creating squares, erecting public and semi- public buildings at the focal points to invite through traffic and encourage speedy transportation by removing all types of traffic barriers. The width of these roads should not be less than 25 m to 30 m.

1.4.3. Secondary or Sub-Arterial Roads

Also known as major roads they run within the limits of the town connecting its important centers. They are designed for slow moving traffic and cover a short distance. The sub-arterial roads act as a link between the arterial roads and local roads. The sub-arterial roads should be improved and provided with safety measures at intersections.

1.4.4. Local Roads

These roads, also known as minor roads, are meant to provide approach to the buildings, officers, shops, schools, colleges etc. There should be no through traffic here and so the local roads are not linked with the arterial roads. These roads need not be straight but can follow the contours of the land.

These roads are used for residential units, shopping and business centers. They therefore form the pocket or precinct roads mainly to serve the non-vehicular traffic. The width of the seroads should not be less than 7m to 10 m.

1.4.5. Other type of Roads:

- **By-pass Roads**

When the main or through roads pass through the congested areas of the towns, there will be considerable reduction in the speed of the vehicles and the smooth flow of the traffic is largely affected resulting loss of time and fuel. In order to maintain the smooth and speedy flow of traffic, bypass roads are constructed. These are also called as loop-roads (Figure 1.2) through which the main traffic can pass from one side and again join on the main road on the other side thus avoiding the congested area or ribbon develop

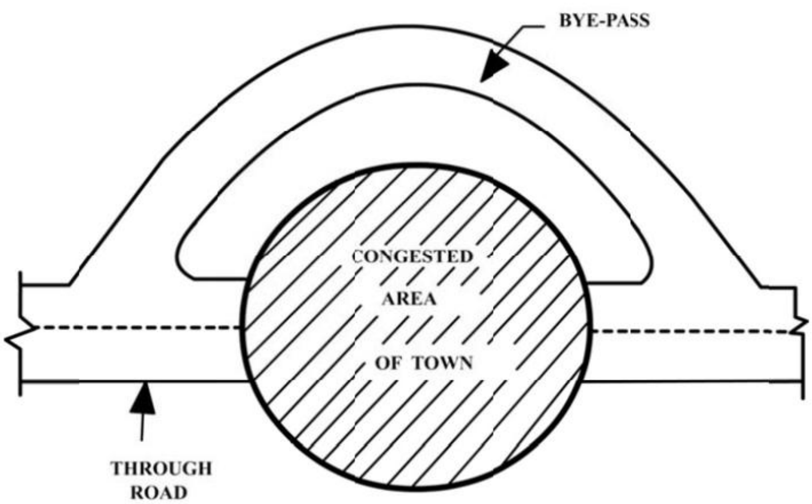


Figure 1.2: Bye-pass lane sketch

- **Outer and innerRing Roads**

These roads are in the form of circles or rings and hence the name, See Figure 1.3. The outer ring road is meant to divert the through traffic approaching the town. The inner ring road is meant to divert the local from through traffic. These ring roads help to reduce the traffic congestion of the large towns.

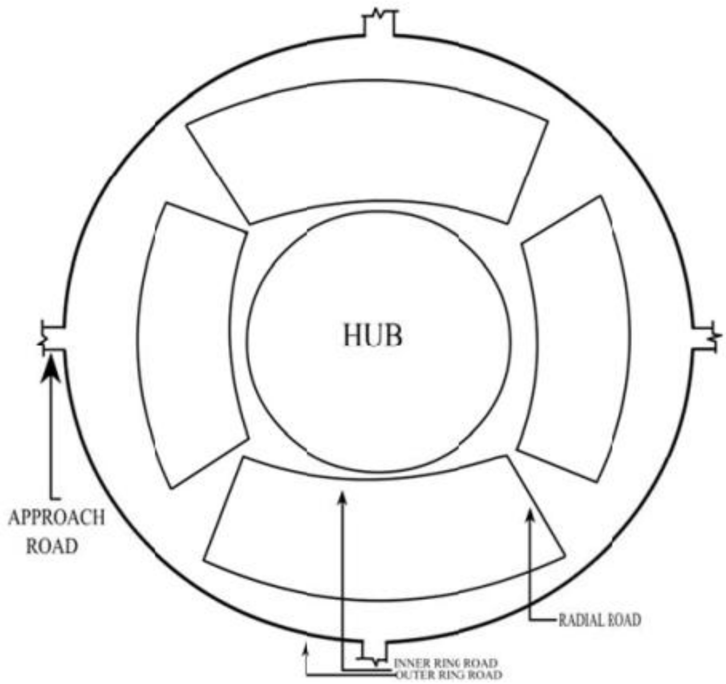


Figure 1.3: Outer and innerRing Roads sketch

1.5. Road intersections

An intersection is where two (or more) roads cross each other. Intersections maybe classified by number of road segments, traffic controls, and/or lane design (see Figure 1.4).

- **Uncontrolled intersections**, without signs or signals (or sometimes with a warning sign).Priority (right-of-way) rules may vary by country: on a 4-way intersection traffic from the right often has priority; on a 3-way intersection either traffic from the right has priority again, or traffic on the continuing road. For traffic coming from the same or opposite direction, that which goes straight has priority over that which turns off.

- **Signal-controlled intersections** depend on traffic signals, usually electric, which indicate which traffic is allowed to proceed at any particular time
- **Circular intersections** are a type of intersections at which traffic streams are directed around a circle. Types of traffic circles include roundabouts, 'mini-roundabouts', 'rotaries', "STOP"-controlled circles, and signal-controlled circles. Some people consider roundabouts to be a distinct type of intersection from traffic circles (with the distinction based on certain differences in size, priority rule and engineering).

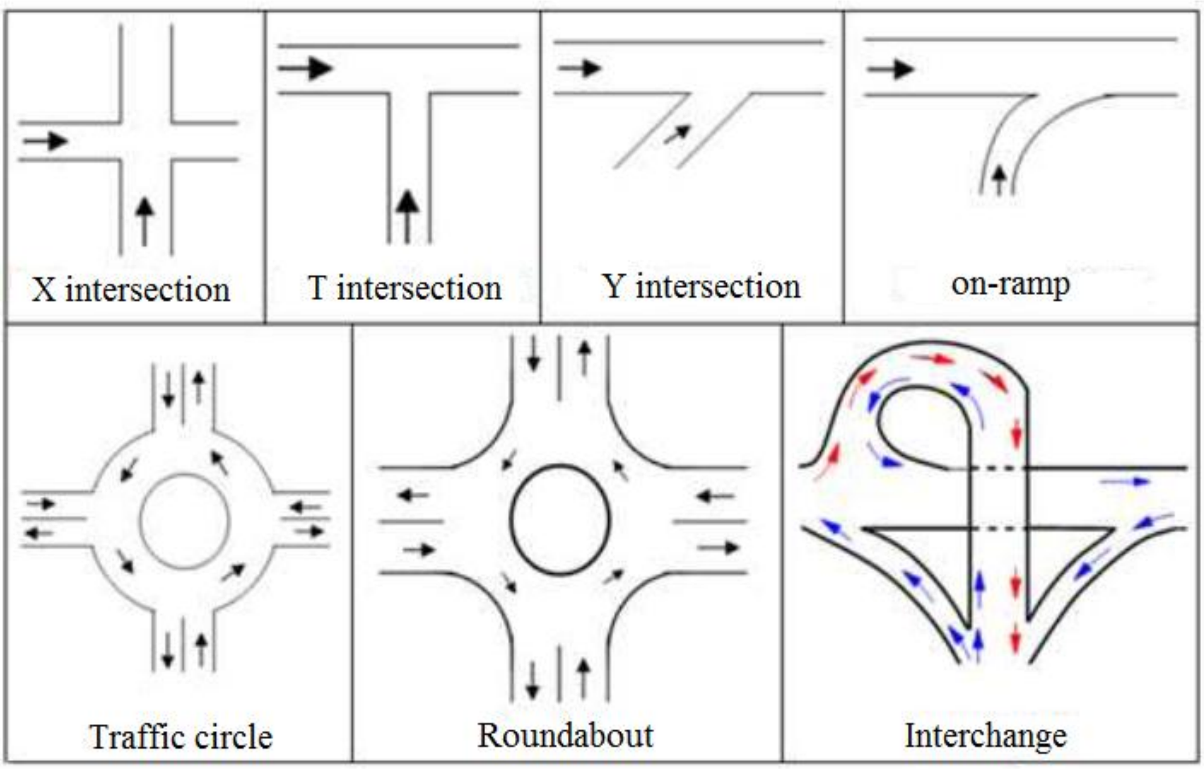


Figure 1.4: intersections type

The use of these different infrastructures requires an appropriate control, which consist of actions that reduce the effects of congestions, to achieve this objective it is necessary to collect information's about traffic flow quality, in other words to measure the traffic variables.

1.6. Traffic measuring detectors

The detection of vehicular presence and road occupancies has historically been performed primarily on or near the surface of the road. The exploitation of new electromagnetic spectra and wireless communication media in recent year, has allowed traffic detection to occur in a non-intrusive fashion, at locations above or to the side of the roadway. The most commonly used detector types are:

1.6.1. Video Camera

Figure 1.5: video camera detector

Video image processing system use machine vision technology to detect vehicles and capture details about individual vehicles when it is necessary Figure 1.5. A video processing system usually monitors multiple lanes simultaneously, and therefore it requires high level of computing power. Typically, the operator can interactively set the desired traffic detection points anywhere within the systems view area. Algorithms are used to extract data required for the detection of the raw data feeds. Due to the complexity of the images, it is not recommended that they should be processed outdoors as this can give poor results. The system is useful for traffic counting and give a +/- 3% tolerance and is not appropriate for vehicular speed and their classification.

1.6.2. Micro-millimeter wave Radar detectors.

Radar detectors actively emits radioactive signals at frequencies ranging from the ultra-high frequencies (UHF) of 100 MHz, to 100 GHz, and can register vehicular presence and speed depending upon signals returned upon reflection from the vehicle.

They are also used to determine vehicular volumes and classifications in both traffic directions. Radar detectors are very little susceptible to adverse weather conditions, and can operate day and night. However, they require comparatively high levels of computing power to analyze the quality of signals

1.6.3. Pneumatic tubes

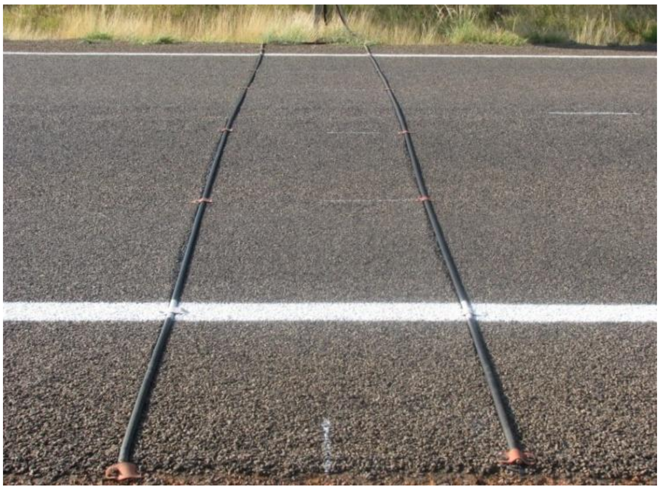
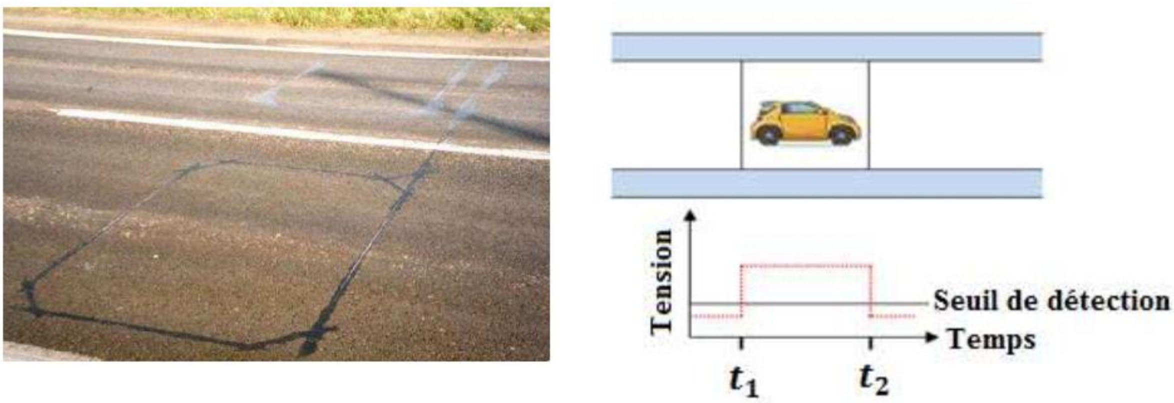


Figure 1.6: pneumatic tube detector

These are tubes placed on the top of road surfaces at locations where traffic counting is required. As vehicles pass over the tube Figure 1.6, the resulting compression sends a burst of air to an air switch, which can be installed in any type of traffic counting devices. Air switches can provide accurate axle counts even when compressions occur more than 30 m from the traffic counter. Although the life of the pneumatic tubes is traffic dependent as they directly drive over it, it is used worldwide for speed measurement and vehicle classification for any level of traffic. Care should be exercised in placing and operating the system, to ensure its efficient operation and minimize any potential error in the data.

1.6.4. Inductive loops

Inductive loop detector consists of embedded turned wire from which it gets its name Figure 1.7 (a). It includes an oscillator, and a cable, which allows signals to pass from the loop to the traffic counting device. The counting device is activated by the change in the magnetic field when a vehicle passes over the loop see Figure 1.7 (b). Inductive loops are cheap, almost maintenance-free and are currently the most widely used equipment for vehicle counting and detection. Single loops are incapable of measuring vehicular speed and the length of a vehicle. This requires the use of a pair of loops to estimate speed by analyzing the time it takes a vehicle to pass through the loops installed in series. An inductive loop can also, to a certain degree, be used to detect the chassis heights and estimate the number of axles.



(a) (b)

Figure 1.7: (a) inductive loops, (b) detection Principe

By using the inductive loops, the length of the vehicle is therefore derived from the time taken by the vehicle to drive from the first to the second loop (driving time) and the time during which the vehicle was over the first and the second loop (cover time). The resulting length is called the electrical length and is in general less than the actual length of the passing vehicle. This is caused by the built-in detector threshold, the road surface material, the feeder length, the distance between the bottom of the vehicle and the loop, but also, to a large extent, the synthetic materials used in modern cars. The system could be used for any level of traffic.

1.6.5. Other types of detectors

- Aerial photography
- Weigh-in-Motion detectors
- acoustic detectors
- floating vehicle technique
- ultrasonic detectors
- Piezo-ceramic detectors

1.7. The main Aggregated Data of traffic flow

Most detectors aggregate the microscopic single-vehicle data by averaging over fixed time intervals Δt and transmit only the macroscopic data to the traffic control center. In this section we present the main observables of traffic flow.

1.7.1. The flow

The traffic flow or the flux is defined as the number of vehicles N that have passed through a detector at a given position during a time interval t.

$$J(x,t) = \frac{N}{\Delta t} \tag{1}$$

The unit is usually given by (veh/h) or (veh/s).

The flux can also be expressed as the inverse of the mean time headways Δt.

$$J(x,t) = \frac{1}{\Delta t} \tag{2}$$

Where

$$\Delta t = \frac{1}{N-1}\sum_{n=1}^{N-1}(t_{n+1} - t_n) \tag{3}$$

1.7.2. Time-Headways:

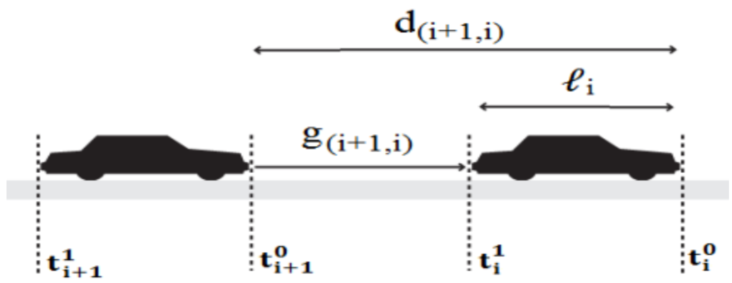


Figure 1.8: different parameter to calculate time headway

The time resolution of the single-vehicle data allows the calculation of the time-headway t_h and the distance-headway d of the n-th vehicle through (see Figure 1.8)

$$t_h(i+1,i) = t^0_{i+1} - t^0_i \tag{4}$$

Its unit is usually given by (s/veh)

1.7.3. The mean velocity

To measure the mean velocity of a given traffic situation, two kinds of mean velocity may be adopted. The difference in the value of the two mean velocities might be significant if a given threshold is reached. This fact will be explained in the following.

1.7.4. The time mean velocity

The time mean velocity is the average velocity of vehicles passing across a detector at a given position during a given time interval.

$$V(x,t) = < v_i > = \frac{1}{N}\sum_{i=1}^{N} v_i \tag{5}$$

Where v_i is the instantaneous speed of a vehicle which passes through a detector and it's giving by:

$$v_i = \frac{\Delta d}{t_{d2} - t_{d1}} \tag{6}$$

Here Δd is the distance between the detectors, and $t_{d2} - t_{d1}$ denotes the time elapsing between the passing of the vehicle between the two detectors (i.e. two successive induction loops)

1.7.5. The space mean velocity

The space mean velocity is called usually the harmonic mean velocity. Basically, it is an average performed over the number of vehicles on a road of length L at a given time t. The formula is given by the following:

$$V_H(x,t) = \frac{1}{< \frac{1}{v_i} >} = \frac{N}{\sum_{i=1}^{N} \frac{1}{v_i}} \tag{7}$$

1.7.6. Occupancy

The occupancy measures the aggregation time interval during which a given detector is occupied by a vehicle.

$$O(x,t) = \frac{1}{\Delta t}\sum_{i=1}^{N}(t_i^1 - t_i^0) \tag{8}$$

$t_i^1 - t_i^0$ denotes the time elapsed on a detector at a given position.

1.7.7. The traffic density

The traffic density is given by the number of vehicles or particles occupying a given portion of the road with a length L, namely:

$$\rho = \frac{N}{L} \tag{9}$$

In this context, the density satisfies the hydrodynamic relation:

$$J(x,t) = \rho V \tag{10}$$

The density can be also expressed as the inverse of the mean distance headway $< d >$. Namely:

$$\rho = \frac{1}{< d >} \tag{11}$$

1.7.8. The correlation function

The correlation function quantifies the interdependence or the coupling between two observables [11]. Those variables are characterized by a mean and a variance.

Thus, the correlation function is given by:

$$CC = \frac{< XY > - < X >< Y >}{\sqrt{< X^2 > - < X >^2}\sqrt{< Y^2 > - < Y >^2}} \tag{12}$$

This correlation tells us how strongly the value of the observable Y depends on the value of the observable X (i.e. when the observables X and Y are weakly correlated, $cc \approx 0$. In contrast, the variables X and Y are strongly correlated mean that $cc \approx 1$).

1.8. Characteristics and history of traffic

In the beginning of the twentieth century, researchers began to elaborate the first traffic flow models by introducing the concept of the fundamental diagram [1]. This concept was based on the assumption that the vehicles average velocity is a function of the average headway. This relation was first studied by Greenshields in 1934 who is considered as the founder of traffic flow theory [1].

The introduction of the fundamental diagram concept triggered the emergence of the macroscopic, the mesoscopic and the microscopic models. The Figure1.9 depicts the genealogy of those models' appearance and their history [1]. The beginning of the second half of the twentieth century has been characterized by the emergence of the first macroscopic model, i.e. LWR model [4] which deals with the observed analogy between the traffic flow and the fluid dynamics. Meanwhile, the first microscopic car following model has been proposed by Pipes [5; 1] based on the stimulus-response principle. Later Cremer et al [6] proposed the first cellular automata model applied to the traffic flow context. This model was prototyped by Nagel and Schreckenberg with minimal and simple rules [7]. The most recent model is the intelligent driver model which was proposed by Treiber et al [8].The aforementioned traffic flow models belong to the fundamental diagram approach in which the flow is always assumed to be a function of the density. However, there is also other type of models based on the three-phase theory which was firstly proposed by Kerner [9].

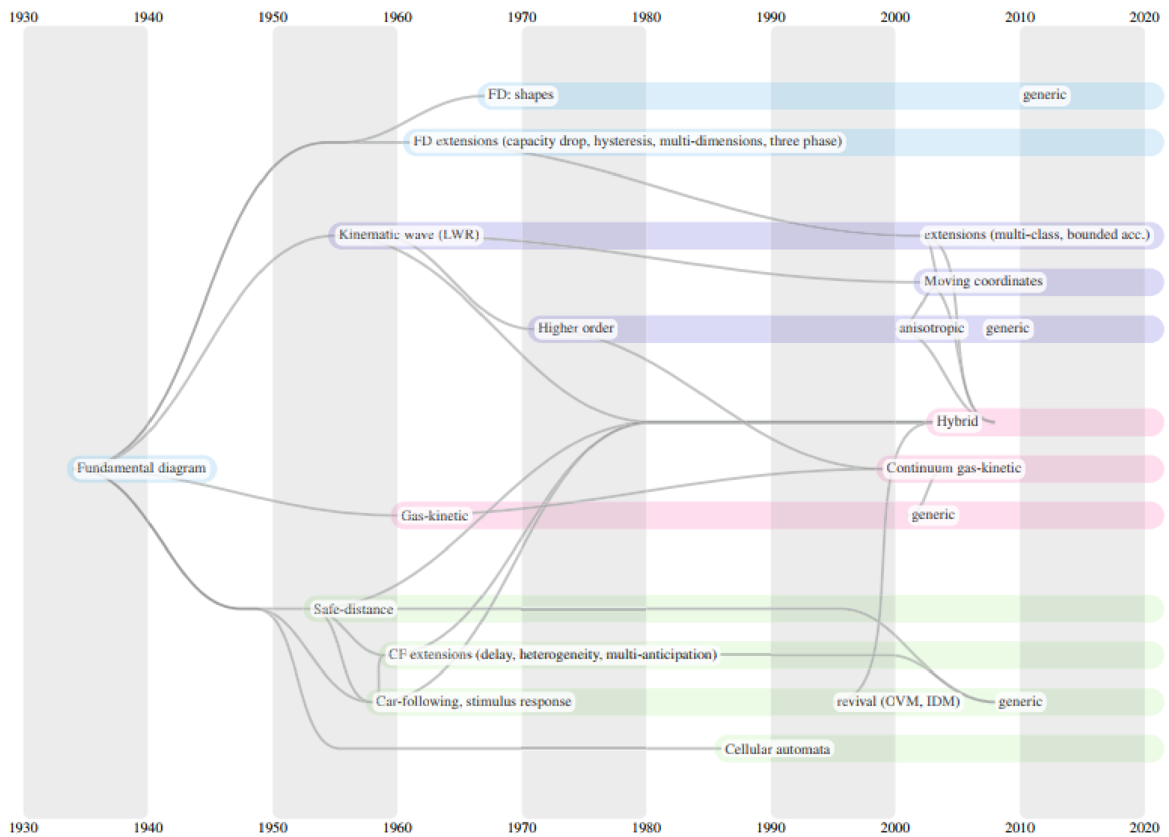


Figure 1.9: Genealogical tree of traffic flow models

1.8.1. The fundamental diagram

The fundamental diagram is the most important tool used by researchers and traffic engineers to describe the traffic flow. Accordingly, the flux J is a function of the density ρ, e.g. $J = \rho v$. In this context, there are three different equivalent forms of the fundamental diagram, namely J(ρ) or v(ρ) or v(J). The generic shape of the fundamental diagram is shown in Figure 1.10. We can see through those various shapes the different traffic regimes. The first branch in which the flux J increases with increasing the density ρ corresponds to the free flow regime. After attaining the maximum point which is traffic capacity, we should deal with the second branch in which J decreases with increasing ρ. The second branch corresponds to the congested regimes.

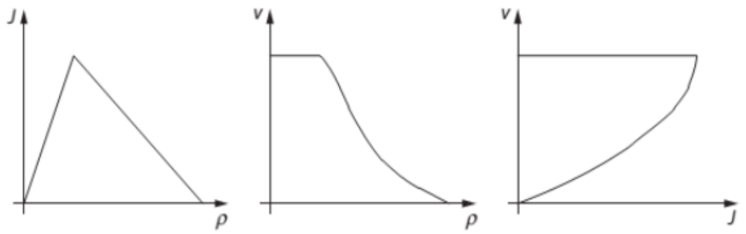


Figure 1.10: Schematic forms of the fundamental diagram in different representations related through the hydrodynamic relation $J = \rho v$.

The aforementioned fundamental diagrams aim to reproduce the empirical fundamental diagram (i.e. the data have been collected by counting loops on a Canadian highway) in Fig. 1.11 that is, by considering the scattered points as statistical fluctuations. Thus, performing the fitting with an appropriate function, many forms have been proposed [10]. Figure 1.12 shows that the diagram fundamental present the inverse λ form with the presence of a discontinuity in some forms of the diagram fundamental figure A and B. This structure explains the existence of the metastable states and hysteresis effects.

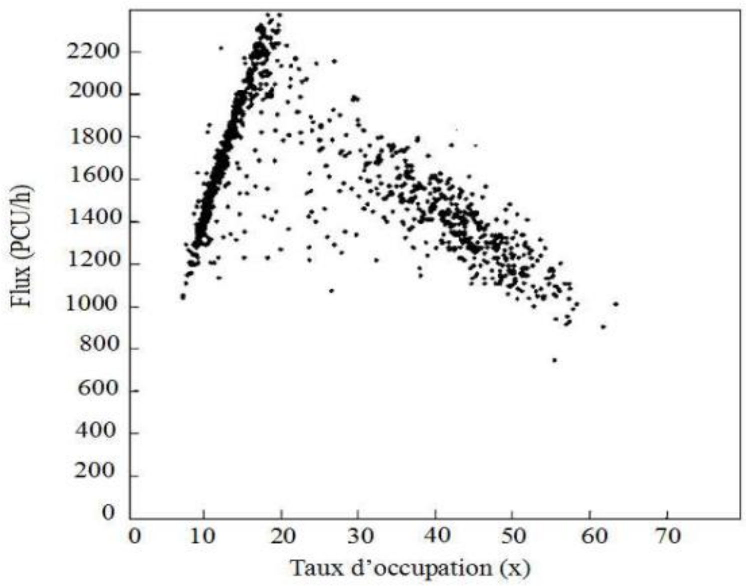


Figure 1.11: The empirical fundamental diagram from a Canadian freeway, the data are averaged over 5 min [11]

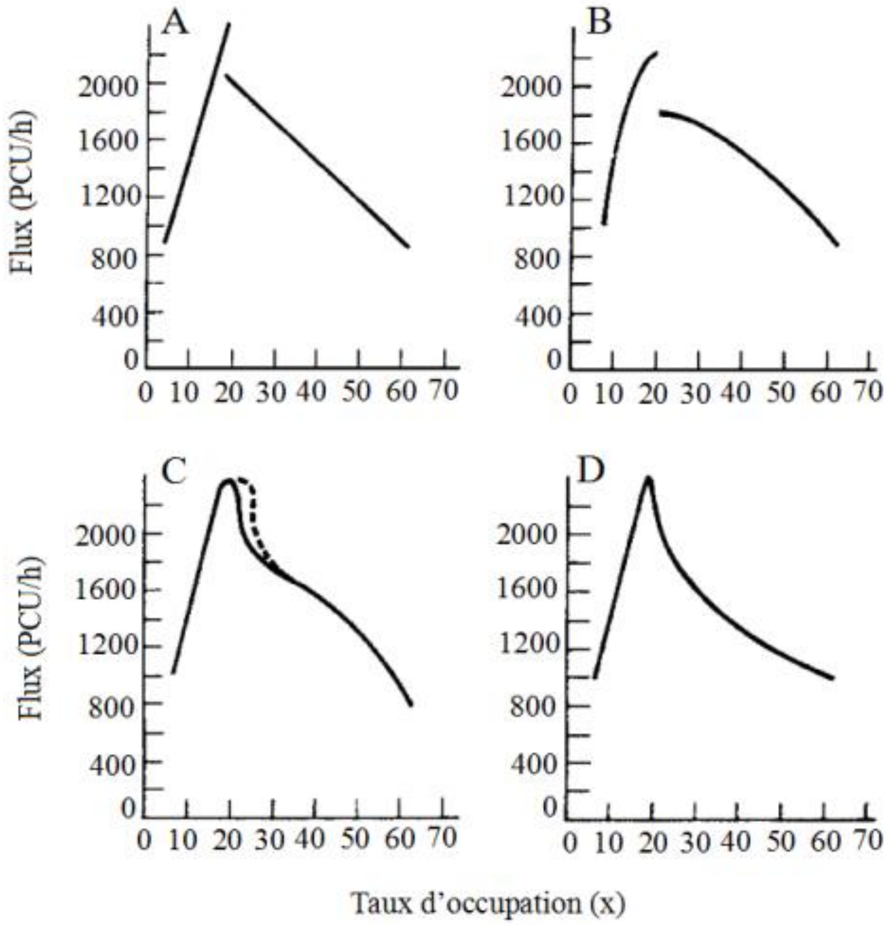


Figure 1.12: the four fundamental diagram shapes

1.8.2. Metastability and Hysteresis

In the real traffic, the flow does not depend solely on the density in the intermediate values of the fundamental diagram in Figure1.13. In this respect, the observed flux depends on the adopted initial configuration.

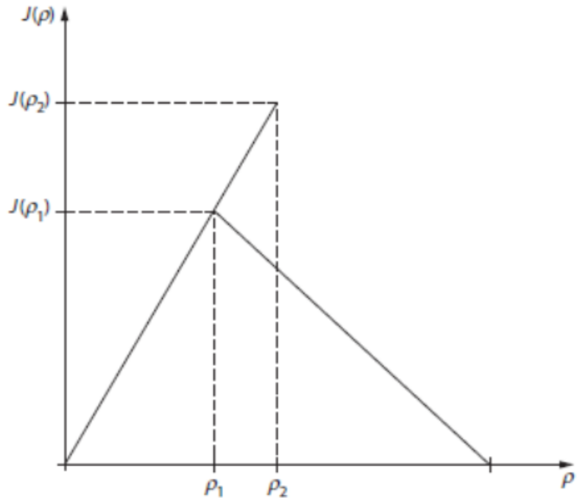


Figure 1.13: An 'inverse V shape' fundamental diagram where the metastability of density is exhibited in the interval [ρ1, ρ2].

For a given value of the density belonging to the interval [ρ_1, ρ_2] (See Fig. 1.13), if at t=0, the vehicles on the road were distributed homogeneously with the same inter-vehicular headway, the corresponding flux would be high. In contrast, if the vehicles were distributed compactly on the road, the corresponding flux would be low. This fact is due to the hysteresis effect or the metastability. For the intermediate values of the density, the traffic state is highly sensitive to the initial configuration. The metastability is thus associated with the observed capacity drop, see Fig. 1.13.

The metastability phenomenon was demonstrated empirically at the transition free flow-congested state, see the hysteresis loop in Fig. 1.14.

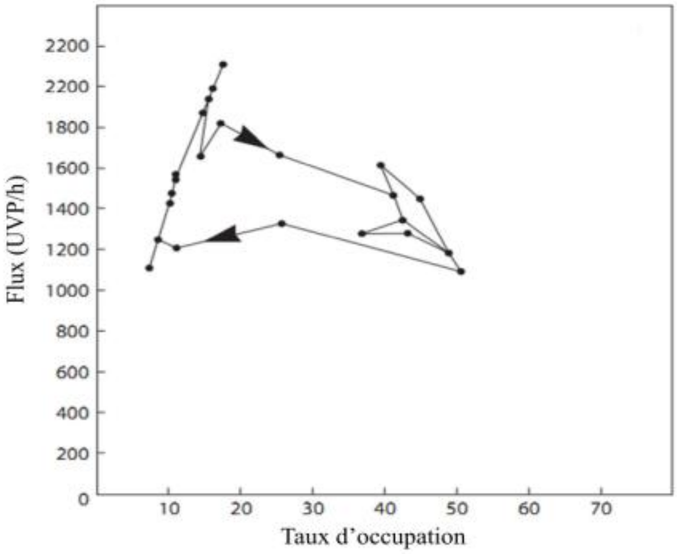


Figure 1.14: An empirical hysteresis loop, the flow, and the density are averaged over 5 min [11].

1.8.3. The three-phase theory

As we have seen before the adjustment of the fundamental diagram does not reveal all the phenomena of the traffic especially when the traffic is congested, for that kerner [9] proposed a theory which uses the spatiotemporal configurations (average velocity (flux or density), position and time) see Figure 1.15, we call this theory "three phase theory".

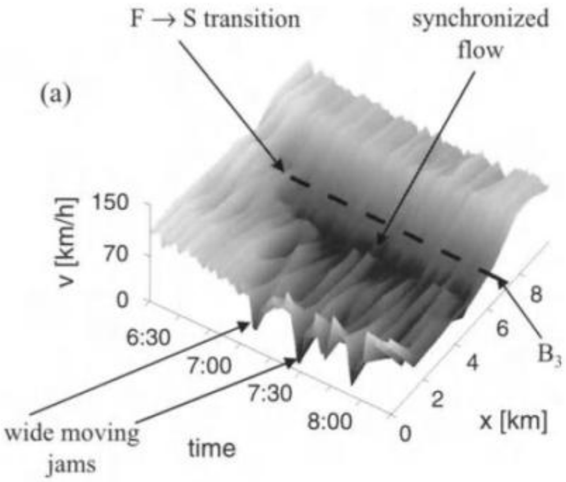


Figure 1.15: The spatiotemporal evolution of the mean velocity on a given freeway, the three-phase appearance (F, S and J) could be distinguished

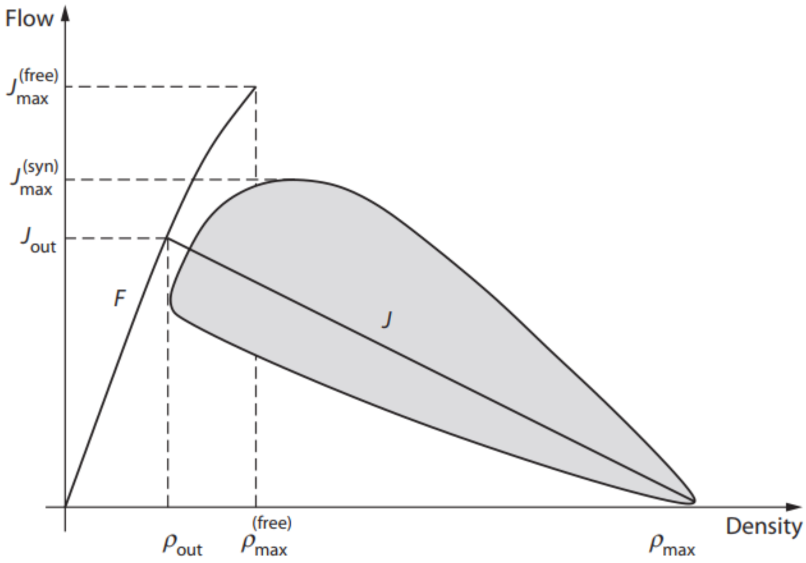


Figure 1.16: Schema form of the flow-density relation in three-phase traffic theory. *F* denotes the free flow branch and the line *J* is determined by the properties of wide moving jams.

In this theory, one can distinguish three different traffic phases (see figure 1.16)

- **Free flow**

In this phase, interactions between vehicles are rare. Every car moves with its desired velocity. Therefore, the flow increases linearly with the density of cars. The part of the branch with flow larger than J_{out} is called metastable branch. It corresponds to a region where the flow is not uniquely determined by the density.All states not of free flow type are called congested states. They are characterized by an average velocity that is smaller than the "desired" velocity of the drivers. Two congested phases can be distinguished.

- **Wide moving jams**

Wide moving jams are regions of very high density and negligible average velocity and flow. Their width is much larger than the fronts at both ends where the speed of vehicles changes sharply. The jam front moves upstream (i.e., opposite to the driving direction) at a typical velocity $V_{jam} \approx 15\ km/h$ [28]. Figure 1.16 presents this phenomenon where two dark waves have an identical propagation speed which remains constant.

- **Synchronized flow**

In synchronized flow the average velocity is significantly lower than in free flow, but the flow can be much larger than in wide moving jams. The main characteristic is the apparent absence of a functional flow-density form, i.e., the corresponding data points are spread irregularly over a large two-dimensional area (Fig. 1.17). In time-series of flow-density measurements, the flow can increase or decrease with increasing density, in sharp contrast to the free-flow (jammed) phase where the flow always increases (decreases). Here flow and density are independent of each other. Furthermore, on a multilane highway, the time-series of measurements on different lanes are highly correlated, i.e., synchronized. This was the motivation for denoting this traffic state as synchronized traffic.

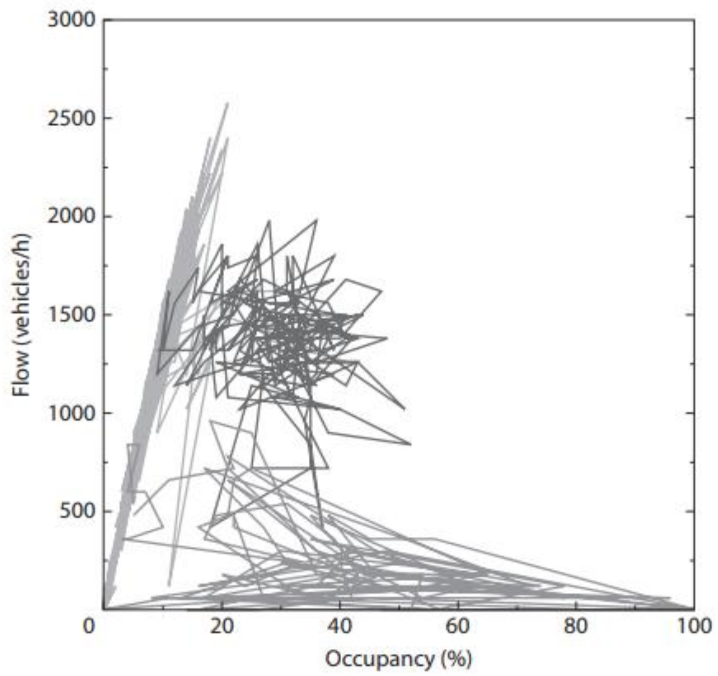


Figure 1.17: Empirical flow–density relation.

1.9. Modeling road Traffic

The traffic models aim to explain and predict the vehicles interactions and the traffic flow of the roads in order to better reproduce the reality and to allow a better optimization of the infrastructures. Schematically, modeling can have three objectives: (i) describe (summarize) the data (ii) predict (simulate) (iii) explain (understand) the empirical results.

Generally, road traffic models can be classified according to different criteria: type of variables (continuous/discrete), level of detail, representation of the process (deterministic/stochastic). Throughout this thesis, road traffic models will be classified according to the level of detail adopted: macroscopic, microscopic and mesoscopic.

In this section, we begin with a quick description of the existing flow models. Subsequently, we are mainly interested in models of cellular automata, in particular the Nagel and Schreckenberg model [7].

1.9.1. The different modeling approaches

Nowadays, a huge number of models have been developed to explain the traffic flow dynamics. Those models are encompassed mainly within two different approaches of modeling, namely, the fundamental diagram approach and the three-phase theory.

1.9.1.1. The fundamental diagram approach

In the framework of the fundamental diagram approach, the traffic state variation is considered as a function of the concentration (the density). This assumption has been developed by the pioneers of traffic modeling. In this context, Lithham wrote: The fundamental hypothesis of the theory is that at any point of the road, there is a functional relationship between the flow and the concentration. Accordingly, the achievements of the fundamental diagram approach are given as follow:

- The phantom traffic jams.
- The Moving jam emergence.
- The metastability of traffic flow.

1.9.1.2. The three-phase theory approach

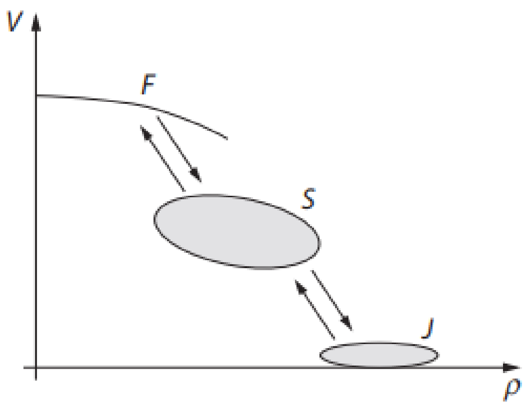


Figure 1.18: Transitions between the phases of the three-phase traffic theory in the velocity–density plane.

In the framework of the three-phase theory, three traffic states could be distinguished:

- The free flow phase (F).
- The synchronized congested pattern (S).
- The wide moving jam congested pattern (J).

From the three-phase theory perspective, the transition F→J which characterizes the fundamental diagram approach is inexistent and inconsistent with the real traffic flow. Instead, the traffic state should undergo the transition F→S see figure 1.18 before getting to the jamming phase (J). Those transitions are known to be as first order transition [28-31]. The main achievements of the three-phase approach are given as follow:

- ***The synchronized congested pattern**:* The synchronized congestion pattern owes his name to the synchronization of the density and the flux between the lanes with a relatively high flow. Generally, the property that distinguishes synchronized traffic from wide moving jams is the behavior at bottlenecks. Wide moving jams propagate through bottlenecks maintaining the mean velocity of the downstream front. This is not the case for synchronized flow, which typically has a downstream front that is fixed at the bottleneck.
- ***The capacity concept**:* from the point of view of the fundamental diagram approach, there is a maximum value above which the traffic breakdown should occur. In the literature, this is called the traffic capacity. This concept is widely used in the

engineering applications. In the three-phase theory, this definition of the capacity is inconsistent with the real traffic data [31]. Indeed, the empirical studies have shown that the capacity is not a single value, instead, the capacity is stochastic and belongs to an interval [J_{min}, J_{max}] [31, 9, 36]. Each value within the interval is associated with a certain probability P see the Fig. 1.19.

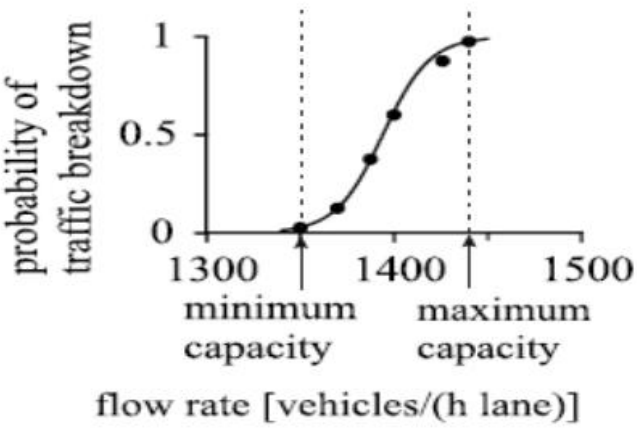


Figure 1.19: The probability of traffic breakdown for different values of the flow within the interval [$qmin$, $qmax$].

1.9.2. Model Characteristics

There are several characteristics that can be used to classify the modeling approaches:

- **Microscopic/Macroscopic:** In microscopic models, each vehicle is represented separately. Such an approach allows introducing different types of vehicles with individual properties. In contrast, in macroscopic models' different individuals cannot be distinguished. Instead, the state of the system is described by densities.
- **Discrete/Continuous:** Each of the three basic variables for a description of a system of particles, namely space, time, and state variable (e.g., velocities), can be either discrete (i.e., an integer number) or continuous (i.e., a real number).
- **Deterministic/Stochastic:** The dynamics of the particles can be either deterministic or stochastic. In the first case, the behavior at a certain time is completely determined by the present state. In stochastic models, the behavior is controlled by certain probabilities such that the particles can react differently in the same situation.

1.9.3. Traffic models

Generally, each traffic model is characterized by specific parameters and variables that describe its level of detail according to the three criteria of classification we can differentiate three models: Macroscopic, Mesoscopic and Microscopic.

1.9.3.1. Macroscopic model

In the macroscopic models, the whole traffic is considered as a compressible fluid [12]. The first and the basic model was proposed by Lighthill-Whitham [4]. Macroscopic traffic models formulate the relationships between traffic flow characteristics such as density ($\rho(x,t)$), flow ($J(x,t)$) and mean velocity ($V(x,t)$) of a traffic stream. All macroscopic traffic models share two fundamental relations. The first one is the vehicle conservation law (see Eq. 13, where x denotes distance and t denotes time) and the second one is the flow-density-speed relation (see Eq. 14):

$$\frac{\partial \rho(x,t)}{\partial t} + \frac{\partial J(x,t)}{\partial x} = 0 \quad (13)$$

$$J(x,t) = \rho(x,t)V(x,t) \quad (14)$$

There are two main types of macroscopic traffic models: first-order and higher-order models. ***First-order models*** [4] assume that the flow-density-speed relation observed in stationary traffic conditions applies also to dynamic traffic conditions. This type of models can be solved in discrete time and space using the Cell Transmission Model [2]. Recently, it has been shown that this type of models can be solved in three different two-dimensional coordinate systems arising in the space of vehicle number, time and distance [75]

Higher-order models assume that the flow-density-speed relation observed in stationary traffic conditions does not hold in dynamic traffic conditions. As a result, they can reproduce phenomena that can generally not be reproduced by first-order models, such as smooth shocks, the capacity drop and stop-and-go waves. An example of this type of models is the Payne model [76]. For more details on macroscopic models' readers can refer to [27].

1.9.3.2. Mesoscopic model

Mesoscopic traffic flow models were developed to fill the gap between the family of microscopic models that describe the behavior of individual vehicles and the family of macroscopic models that describe traffic as a continuum flow [14-19]. Traditional mesoscopic models describe vehicle flow in aggregate terms such as in probability distributions. However, behavioral rules are defined for individual vehicles. The family includes headway distribution models [16-17], cluster models Mahnke and Kühne (2007), gas-kinetic models [18] and macroscopic models derived from them [19].

Macroscopic and mesoscopic models are applied to large-scale networks (highways, expressways, etc.) and over long periods. But they do not lend themselves easily to traffic situations where there is a large variation in driver's behavior or in the case where certain local phenomena become dominant. For more details on mesoscopic models' readers can refer to [13].

1.9.3.3. Microscopic model

The microscopic models track the individual particles with a high level of aggregation, namely, each vehicle or particle is described apart. Hence, the whole system evolves according to the interactions between the particles.

The first proposed microscopic model is the Car following models [20-22] describes one-dimensional (i.e. longitudinal) movement of individual vehicle behavior by considering interaction among vehicles. In typical car-following models, a vehicle speed is determined by considering distance to the leading vehicle and speed of it.

Lane-changing models describe lane-changing (i.e., lateral) movement of individual vehicle behavior by considering interaction among vehicles. In typical lane changing models, a vehicle determines its lane by considering its desired speed, safety and destination, Bando et al [23] propose the optimal velocity model (OVM) where the driver regulates his speed not based on that of the vehicle he follows but also on a speed guaranteeing him in case of sudden braking to avoid any risk of collision with the vehicle in front. However, some proposed models are based on particle models [7] and [24-27]. Subsequently, we are mainly interested in particle models (cellular automata).

These models are mainly utilized for investigating traffic safety, capacity drop, and effects of introducing new types of vehicles, in other words, where heterogeneity among drivers significantly affects the results and is the main interest. Their reproductivity in the macroscopic scale is not always required, mainly due to their too many parameters, difficulty to be calibrated and mathematical intractability.

1.9.4. The cellular automata model

The cellular automata models will be used throughout this work. Hence, it is of utmost importance to recall their origins and the corresponding properties.

1.9.4.1. Definition and Generalities

The cellular automata concept was introduced in the 50’s by Von Neuman [30, 41]. However, the corresponding applications in studying dynamical systems were mainly performed by Wolfram [42]. The cellular automata explain the evolution of non-equilibrium systems with the simplest time evolving rules. Those rules mimic the interactions between the components of a given non-equilibrium system (a dynamical system) and its interaction with the environment.

By using the cellular automata approach, the self-organizing property of the non-equilibrium systems has been reproduced [42]. The self-organization property denotes the evolvement of the non-equilibrium systems from the disordered state to more ordered state [42]. This property exhibits often a complicated structure: the self-similar pattern called fractals, for example, the outlines of the snowflakes (See Fig. 1.20), the flow pattern in turbulent fluid, etc. Thus, cellular automata provide simple models to describe a wide variety of physical, chemical and biological models.

The main properties of cellular automata model are as follows:

- Space is discrete and subdivided with identical cells.
- Each cell could have a finite and discrete ensemble of states.
- The time is discrete as well and evolves with a given step Δt.
- The state of a cell i at time t+1 depends on both its state and the state of its neighbors at time t.

Those proprieties make the cellular automata model an efficient tool to model various complex physical systems. In addition, they are suitable for computer simulations.

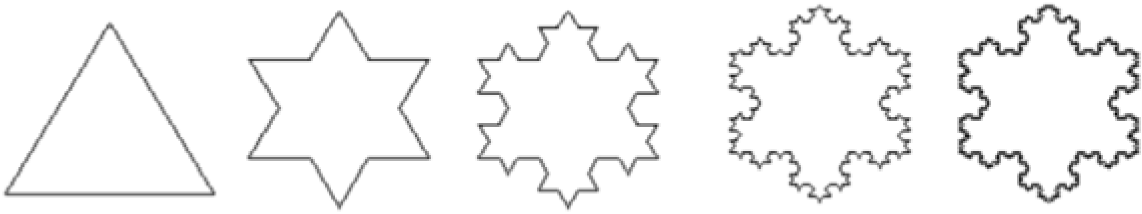


Figure 1.20: The self-similar shape pattern of a snowflake based on a cellular automata mode

1.9.4.2. TASEP model (Totally Asymmetric Simple Exclusion Process)

TASEP [48] is the simplest model of interaction systems and is considered the archetype of non-equilibrium transport models. It is based on the discretization of time and space. This model describes traffic on a single-lane road of length L (L represents the number of sites) with cyclic (closed loop) or open (see Fig.1.21) boundary conditions. The exclusion rule prohibits two particles at the same time on the same site. The vehicles move from the left to the right if it is empty with a probability P. On the other hand, if the site in front is occupied the vehicle does not move during this time step. Thus, the dynamics can be sequential and random or parallel.

1.9.4.3. The boundary conditions

In order to study the traffic flow with any one of the aforementioned models, with numerical simulation or analytic methods, researchers use different boundary conditions. In this context, two major boundary conditions are adopted for modeling the traffic flow: the periodic boundary conditions and the open boundary conditions.

To describe clearly the two different boundary conditions, let us consider a one-dimensional road or lattice where vehicles move according to the rules of the cellular automaton model (TASEP, NaSch, etc.).

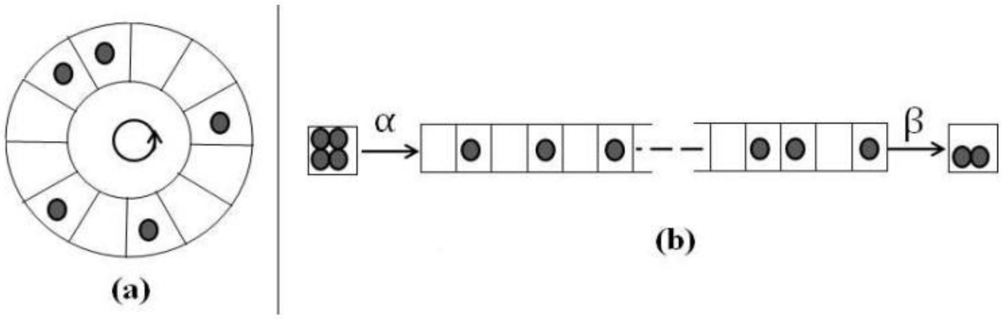


Figure 1.21: (a) periodic boundary conditions (b) open boundary conditions

1.9.4.3.1. The periodic boundary conditions

In the periodic boundary conditions, the road is considered as a loop where vehicles are present with a certain density and moving according to the rules described above. Clearly, this kind of boundary conditions is an idealization of the reality since it represents an approximation of extended and lengthy facilities [30]. However, those boundary conditions should be considered for theoretical investigation before taking into account the open boundary conditions which are more realistic. Indeed, it enables us to control the density of the road before performing any study.

1.9.4.3.2. The open boundary conditions

The open boundary conditions are more realistic and reproduce an important observed traffic phenomenon namely, the phase transitions which are induced by the boundaries [49]. In open boundary conditions, vehicles are injected into the lattice (the left boundary) with an injection rate α and extracted (the right boundary) with an extraction rate β. The injection of vehicles could model the vehicles injected from a traffic light, an intersection, on-ramp, etc. The extraction rate constraint could model the existence of a defect or another form of obstruction.

1.9.4.3.3. Boundary-Induced Phase Transitions

One of the most important differences between systems with open boundary and periodic boundary conditions is the particle density in the road. In the periodic systems for a given density, the number of particles in the road is preserved. However, in the open systems, the situation is totally different because we have to handle two different parameters: the injection rate α and the extraction rate β, here the density will be a parameter. The influence of α and β on the density implies that the parameters such as the global density, flux, and the density profiles show a different behavior than the periodic systems. This behavior is called "the phase transition induced by the boundary conditions" [50, 52]. The simplest example of the latter is presented by the TASEP model [47]

i. Periodic boundary condition

With the periodic boundary condition, we obtain the fundamental diagram shown in the figure 1.22, here we distinguish two states the free flow state and the congested flow state

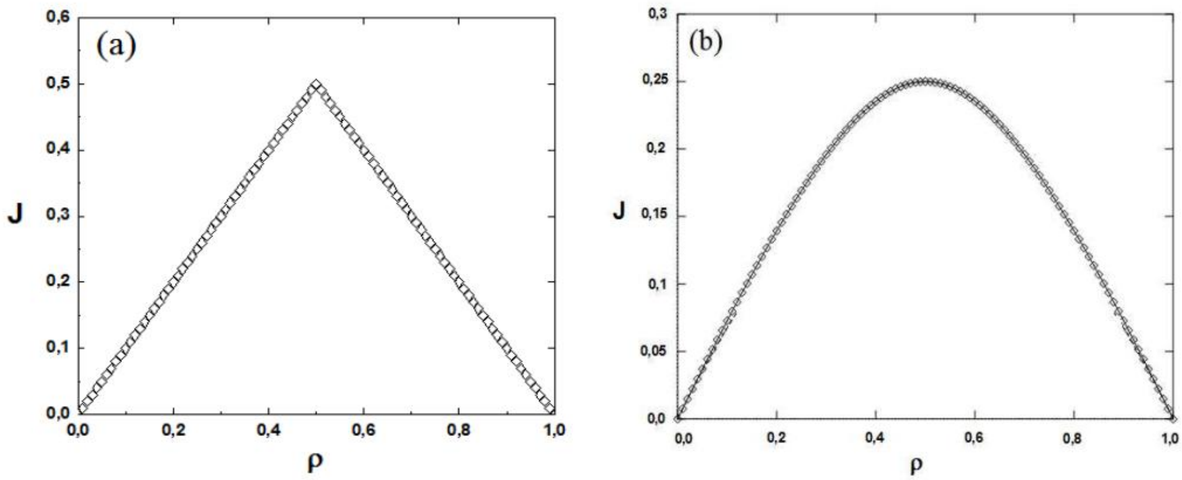


Figure 1.22: Fundamental diagram of the TASEP in parallel dynamic (a) P=1 and (b) P=0.75

ii. Open boundary conditions

With open boundary conditions the system is controlled by different conditions from two parameters α and β. so the phase diagram will be more illustrative than the fundamental diagram to reproduce the different states of the system. When crossing the transition lines on the phase diagram a phase change occurs from an ordered state (high density) to a disordered state (low density) or vice versa.

In the TASEP model three states can be observed, hence, each state is characterized by a density profile, see Figure 1-23

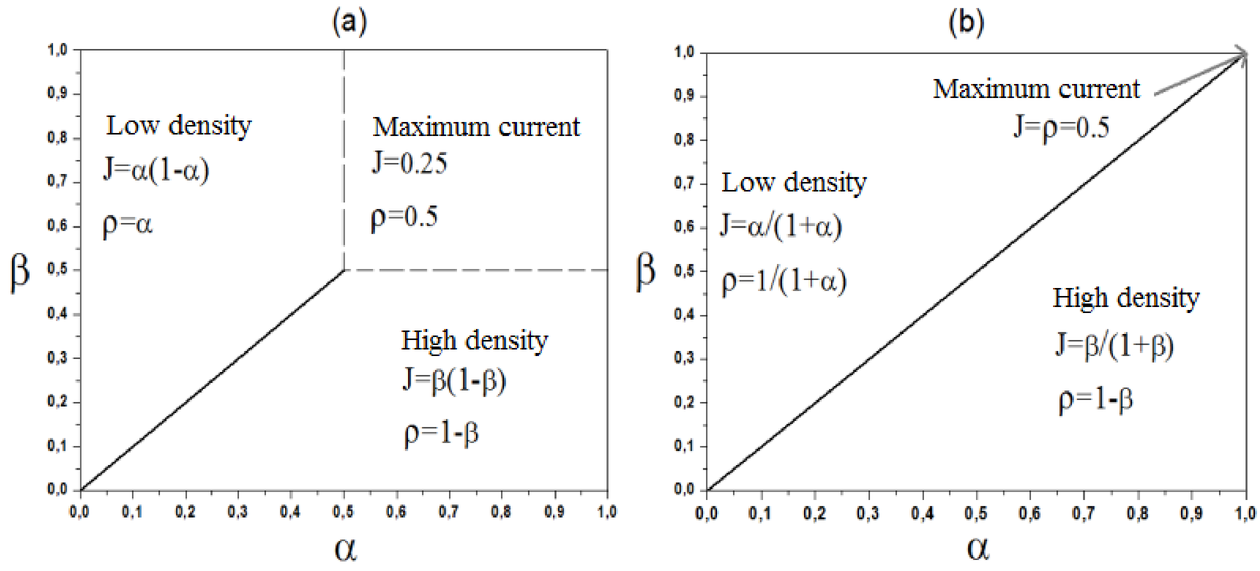


Figure 1.23: the phase diagram of the TASEP with P=0.5 (a) sequential dynamics (b) parallel dynamics

1. Low density: for a low rate of injection and a high rate of extraction, here the value of the flux and density is imposed by α, the density profile shows that the density is independent of β except for the low β where there are small traffic jams near the exit see figure 1-24 (a)
2. High density: the system is in the congested stat, if we inject a lot of particles by having a low extraction rate, here the value of the flow and the density is imposed by the extraction rate β. The density profile is presented in Figure 1-24 (b),with a higher value of the injection rate α, traffic jam spreads all of the road while the density decreases from the starting point to the low value of α
3. Maximum current: in contrast to the two previous phases, the factor is no longer α or β but the road itself. The flow reaches its maximum value. However, the density profile shows that the density decreases from the starting point see figure 1-24 (c), this phase can be reached when the probability $P_b \neq 0$ in several models like the NaSch model and their extension.

The difference between TASEP phase diagrams with parallel dynamics and sequential dynamics is obvious. With the sequential dynamics the phase of the maximum current is specified by $0{,}5 \leq \alpha \leq 1$ et $0{,}5 \leq \beta \leq 1$. In contrast, it is reduced to the point $\alpha = \beta = 1$ in the parallel dynamics. The difference indicates that the updating rules the system can lead to different phase structures even in the simplest case.

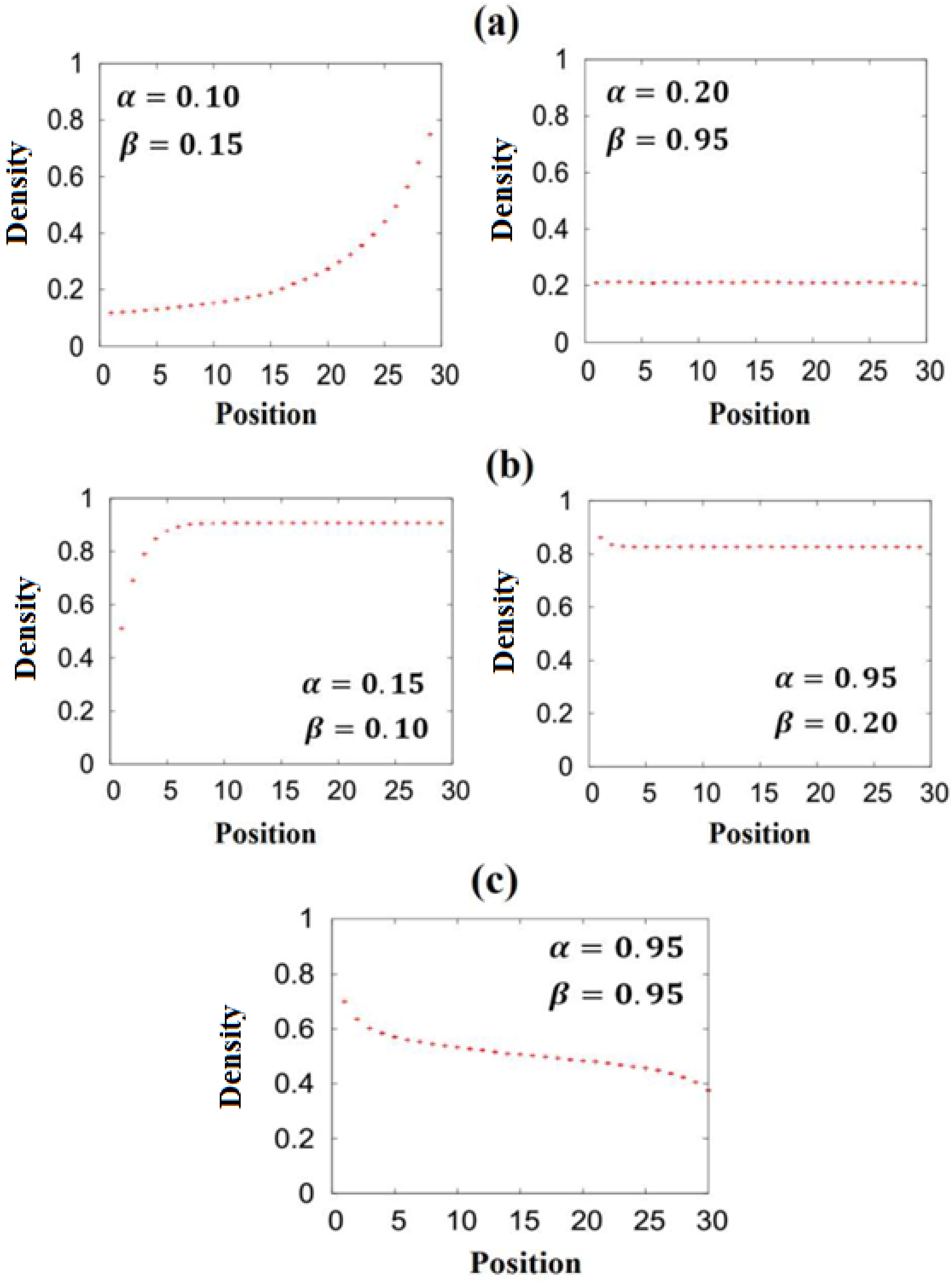


Figure 1.24: profile density in the different phases of the phase diagram of the TASEP with the sequential dynamics

1.9.4.4. The NaSch Cellular automata model

The cellular automata model is an efficient tool to model the traffic flow. The first proposed models were introduced by Cremer et al [6] then prototyped by Nagel and Schreckenberg [7].

The last model is known as the NaSch model. This model mimics the basic motions of a one-dimensional traffic flow which are the following:

- The conductor's propensity to accelerate and attaining the desired velocity.
- The conductor's tendency to decelerate to avoid collisions with the other vehicles.

In the NaSch cellular automaton model, space, the time and the velocity are discretized variables. The road is a one dimensional chain represented by cells. Each cell can be either empty or occupied by one vehicle. Thus, the one cell length is given by the inverse of the blockage density which is approximately 7.5 m [30].

Subsequently, each vehicle hopes to attain its maximal velocity under two constraints:

- The gap between two successive vehicles,
- And the driver nature which is quantified by a probability of spontaneous deceleration.

In traffic flow, the dynamics discussed above are parallel, namely, the velocities corresponding to each vehicle are updated simultaneously at a time t. Hence, the vehicular motion according to the NaSch model is given by the following at a given time t:

- **Acceleration:** $V_n \rightarrow min(V_{max}, V_n + 1)$, V_{max} is the vehicles maximum velocity which takes discrete values.
- **Deceleration:** $V_n \rightarrow min(V_n, d_n)$, where $d_n = x_{n+1} - x_n - 1$is the gap between the leadingand the preceding vehicle.
- **Randomization:** If $V_n > 0$, $V_n \rightarrow max(V_n - 1, 0)$, with probability P.This rule quantifies the spontaneous deceleration of a given driver, *P*=0 corresponds to aggressive or commuter drivers.
- **Vehicle motion:** $X_n \rightarrow X_n + V_n$

x_n and $V_n$will denote respectively, position and velocity of the vehicle *n*. After the vehicular motion, the time is increased by 1 step. We recall that 1-time step is 1 second in real time. (see Fig. 1.25)

It is worth mentioning that V_{max} which is the maximal velocity value is discrete. In order to express it with the usual unit (*Km/h*), we should perform the following operation: $V\left(\frac{Km}{h}\right) = V_{max} \times 7.5 \times 3.6$. The second term in the operation n is the vehicle's length and the third term is atime convert.

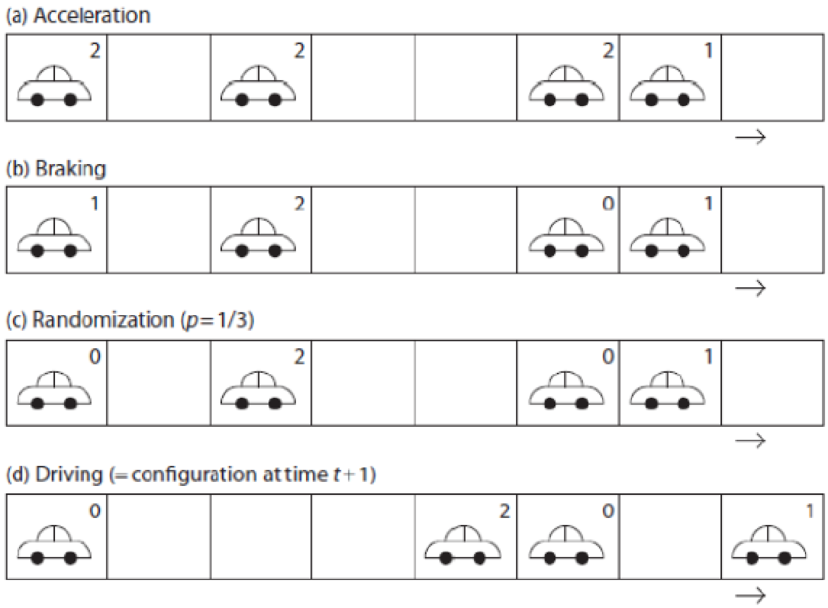


Figure 1.25: A typical configuration in the NaSch model. The number in the upper corresponds to the velocity of each vehicle.

It worth mentioning that all we mentioned early about the boundary conditions (see TASEP model section) remains valid for all others CA models. Regarding the open boundary condition, vehicles at the right boundary are controlled by a rate β, where if a vehicle reaches the end of the lattice it could leave the system with the rate β or it will stay at the system with (1-β), the inclusion of exit rate can be related to the traffic status in the exit direction.

However, at the left boundary, vehicles are injected (from an infinite particle reservoir) with a rate α. In this context two major strategies of injection were proposed, namely:

- The standard injection strategy [77], the road is modeled as a one-dimensional lattice with L sites that are labeled in sequence by $1 \ldots L$ from the left. The stochastic left boundary is implemented by an additional site 0 on the left of site 1; with probability α, a vehicle with velocity $V = V_{max}$ is created at site 0. If site 1 is occupied by another vehicle, the injected vehicle is deleted.

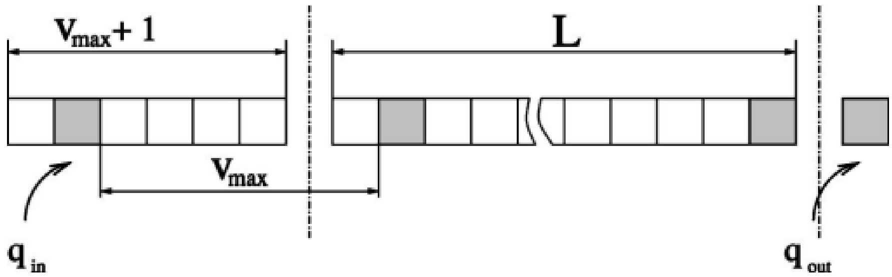


Figure 1.26: the injection rule with $V_{max} = 5$

- The expanded injection strategy, proposed by Barlovic et al. [33] because it supplies a proper insertion strategy that permit us to study the whole spectrum of possible system states, in which the maximum entering flux into the system must identify to the maximum possible flux Figure 1.26. At each time-step, the mini-system and the single cell are cleared (i.e. both are updated as the principal road because if the vehicle created at step time *t* still exist in the mini-system at step time that means that this vehicle cannot enter the principal road with its maximum velocity and as motioned previously, to achieve the high inflow vehicle should enter the road with maximum speed. Thus, the mini-system is cleared. Furthermore, the single cell is emptied because the vehicle at this cell is already out from the principal road and has no effect on outflow). Indeed, at the entrance, a new vehicle with its maximum speed enters the mini-system with rate α and takes sites as headway to the last vehicle in the road.

1.9.4.5. Other CA Models

As a matter of fact, NaSch model can be extended in many ways, some models modify the randomization rules (e.g. Velocity-Dependent-Randomization model), others models provide some additional rule to mimic the anticipation of vehicles, while other model modify the acceleration rule (e.g. Fukui–Ishibashi model**)**. etc. (see. Fig 1.27)

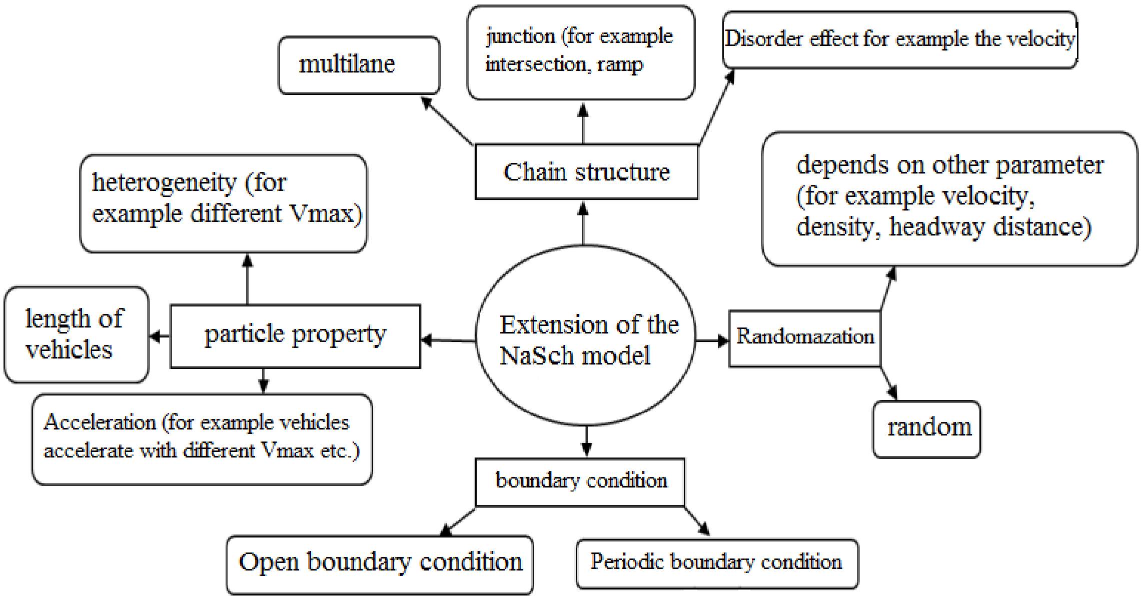


Figure 1.27: The Extension of the NaSch model

1.9.4.5.1. The Velocity-Dependent-Randomization Model

The NaSch model does not exhibit the metastability of traffic flow (Hysteresis) for intermediate densities. The phenomenon is widely observed in real traffic flow [31, 28, 40].

In order to reproduce the metastable state, a simple generalization exists, which is able to reproduce these effects. It is the so-called velocity dependent-randomization (VDR) model [43]. Here, in contrast to the original NaSch model, the randomization parameter depends on the velocity of the vehicle, $P = P(V(t))$. The rulesare supplemented by a new rule, given by:

$$P\big(V(t)\big) = \begin{cases} P_0 \; for \; V = 0 \\ P \; for \; V > 0 \end{cases}$$

With $P_0 > P$. This means that vehicles, which have been standing in the previous timestephave a higher probability P_0 of braking in the randomization step than the moving vehicles.

1.9.4.5.2. Fukui–Ishibashi Model

Fukui and Ishibashi [44] have introduced as a simplified version of the NaSch model. The main difference to the NaSch model is the absence of a velocity memory. All vehicles have an intrinsic velocity Vmax. In each time step, all drivers try to move at the maximum velocity

V_{max} (i.e., they accelerate to V_{max} instantaneously). The motion in this model is then defined by the following set of rules:

a) **Acceleration**:$V_n \rightarrow min(V_{max}, d_n)$, where $\{d_n = x_{n+1} - x_n - 1\}$
b) **Randomization**: If $V_n = V_{max}$, then $V_n \rightarrow V_{max} - 1$, with probability P.
c) **Vehicle motion**: $X_n \rightarrow X_n + V_n$.

As usual, X_n and V_n denote the position and speed, respectively, of the *n-th* vehicle.

The FI model differs from the NaSch model in two respects: (1) the increase of speed of the vehicles is not necessarily gradual and (2) the stochastic delay applies only to high-speed vehicles. Due to these modifications, no overreactions at braking occur and therefore the FI model does not exhibit spontaneous jamming.

1.9.4.5.3. Models with Anticipation

Usually "anticipation" means velocity anticipation, i.e., the estimation of the velocity of nearby vehicle in future time steps. In physics terminology, anticipation corresponds to next nearest or multiple particle interactions. Therefore, anticipation effects are an essential part of many models of three-phase traffic theory. Larraga et al. [45] have introduced an **anticipatory driving parameter** in the deceleration process to estimate the velocity of the preceding vehicle. This estimation, plus the real spatial distance to the leading vehicle, establishes a safe distance among vehicles. The dynamics of the model is then defined by the following rules:

a) Acceleration: $V(t+1) \rightarrow min(V_{max}, V(t) + 1)$.
b) Randomization: If$V(t) > 0$, $V(t+1) \rightarrow max(V(t) - 1, 0)$with probability P.
c) Deceleration: $V(t+1) \rightarrow min(V(t), d_{an})$.

Where $d_{an} = d + [(1-\alpha) \times V_{i+1} + \frac{1}{2}]$ and $0 \leq \alpha \leq 1$the velocity of car *n* is reduced to d_{an}. [x] denotes the integer part of x, i.e.$[x - \frac{1}{2}]$ corresponds to rounding x to the next integer value.

d) Vehicle motion: $X_n \rightarrow X_n + V_n$.

The order of the sub steps is different compared with the NaSch model because the randomization step is applied before Deceleration step. The deceleration step is the main modification to the original NaSch model. In this rule, the distances between the *i-th* and $(i +$

1)-*th* vehicles, and their corresponding velocities are considered. Knowledge of the preceding vehicle's velocity is incorporated through the anticipatory driving parameter α with range $0 \leq \alpha \leq 1$. Through a variation of the parameterα, different driving strategies can be modeled. For $\alpha = 1$, the speed of the precedingvehicle is not taken into account (no anticipation). For $\alpha = 0$, vehicle may move withthe same speed without additional safety distance. This case occurs with either a very aggressive driver or when vehicles can obtain information about the velocity of vehicles ahead.

1.9.4.5.4. Aggressive Driving Model

It is a model based on the nasal model where only the acceleration step of the NaSch model [46, 47] is changed to $V(t) = V_{max}$. i.e., all vehicles accelerate immediately to the maximum possible velocity V_{max}. This model is used to describe some aspects of intracellular transport.

1.10. Accident modeling

An important aspect of real traffic that is usually neglected in modeling approaches is the occurrence of accidents although these are responsible for a considerable fraction of jams, either directly or indirectly and it is associated with human life. Before describing the modeling approaches, firstly let's describe the car accident types:

1) ***Rear-end accident*** is between two vehicles evolving in the same lane and with the same direction, and it's based on the delayed reaction time of the successor vehicle and the unexpected abrupt deceleration of the predecessor vehicle (see Figure. 1.29).
2) ***Lane-changing accident*** is between an overtaking vehicle that want to return to its home lane and its following vehicle on same lane. An unexpected lane changing of a vehicle may lead to a collision; if the following vehicle cannot decelerate enough (see Figure 1.32).
3) ***Head-on accident*** is between two vehicles that evolve on the same lane and opposites directions (i.e. when vehicle try an unexpected lane changing in the bidirectional lane). This type of accident leads usually to fatal injuries (see Figure 1.31).
4) Junctions accident is between two competitors' vehicles at the same junction, this type of accidents occurs when one of the two vehicles doesn't respect the priority rules (i.e. right way, signal or road sign)

5) Vehicle/pedestrian accident is between a pedestrian or group of pedestrians and a vehicle, this type of accident occurs when a vehicle doesn't respect the pedestrian's priority on the crosswalks.

In principle, two types of accidents in real traffic can be distinguished, namely those due to careless drivers and those related to technical failures. The latter are difficult to implement explicitly in simple models and could be treated as random events. Careless and aggressive drivers, however, can be taken into account, e.g., by modification of the dynamical rules in CA models. Those modifications need to specify how to deal with these accidents if they occur in the simulations [57], however, in most investigations, accidents are only occurring virtually [56-62] which lead us to speak about dangerous situations instead of accidents. Therefore, quantities like the accident probability are calculated and it is closely related to the spatial headway distribution.

Among the studies that have tried to elucidate the importance of accidents in CA models and based on the NaSch model with a periodic boundary condition, boccara et al [58] calculated the accident probability per vehicle per time (Pac) with the following conditions:

i. $0 < d < V_{Max}$ The vehicle i can reach the position of the vehicle in front i+1 at the next time step t+1. (d is the gap distance between the vehicle i+1 and vehicle i)

ii. $V_{i+1}(t) > 0$The vehicle ahead is moving at time t,

iii. $V_{i+1}(t+1) = 0$ The vehicle in front i+1, it suddenly stopped at t+1.

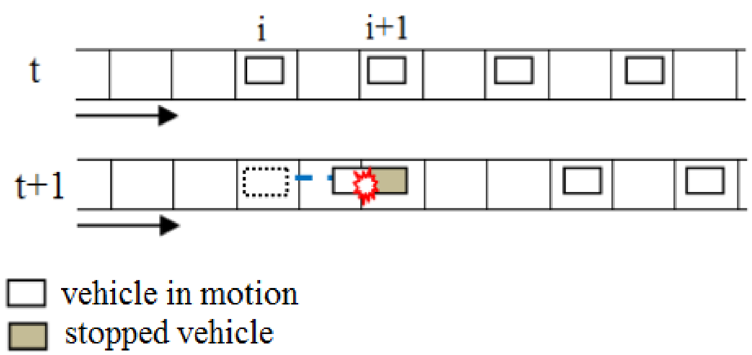


Figure 1.29: Schematically representation of the rear-end accident with Vmax=2

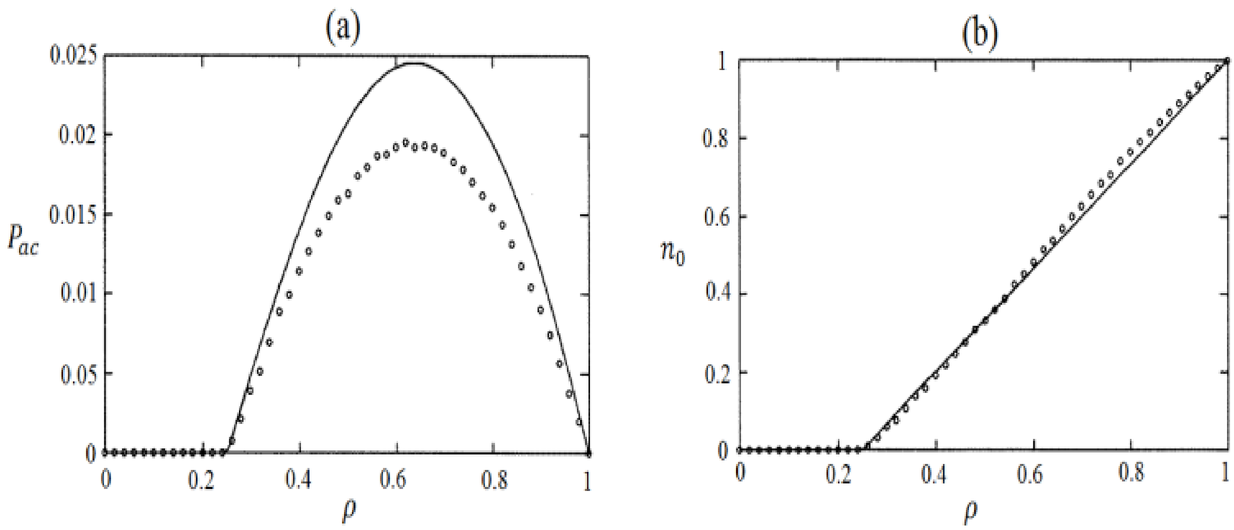


Figure 1.30: (a) Accident probability (b) number of stopped vehicles

Figure 1.29 show that When the car density, ρ, is less than the critical car density$\rho_c = \frac{1}{1+v_{max}}$, the average number of empty sites between two consecutive cars is larger than Vmax, the fraction, n_0, of stopped vehicles is zero and no accident can occur. If $\rho > \rho_c$, the average velocity is less than V_{max}, n_0 increases with ρ and careless driving will result in a number of accidents. The probability for a vehicle accident increases until it reaches a maximum for a vehicle's density, ρ, then decreases to zero for ρ=1, the latter case all the vehicles in the road are stopped.

On the other hand, in order to model other types of accidents, a simple modifications and improvements are needed for the NaSch model, for example Moussa [63] proposed new conditions to study the head on accidents and Lane-changing accidents in the bidirectional roads. Those conditions are given in the follow:

1) Head-on accidents
   - Vehicles are on the same lane with an opposite's direction
   - $\Delta t * V_i(t) > d_i(t) - V_{j+1}(t+1)$

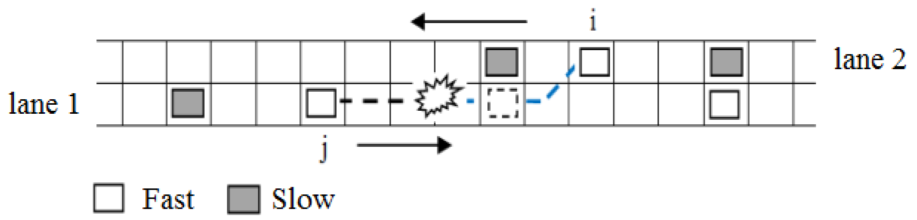


Figure 1.31: Schematically representation of Head-on accident

If the distance covered during the delayed reaction time Δt of the vehicle*i* is enough to reach the next time position of the vehicle j ahead in the opposite direction, fatal car accident happens most likely.

2) Lane-changing accidents

- The vehicle *i* doesn't takes her aimed place after overtaking.
- $\Delta t * V_i(t) > d_i(t) + V_{i+1}(t+1)$

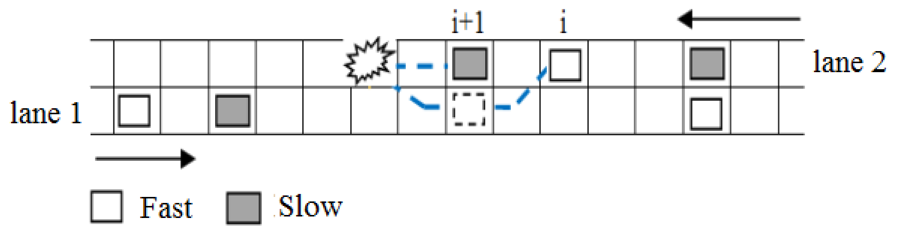


Figure 1.32: Schematically representation of Lane-changing accident

If the distance covered during the delayed reaction time Δt of the slowvehicle*i+1* on lane 2 is enough to reach the next time position of the fast vehicle *i* ahead that changed lanes 1, lane-changing crash happens most likely on lane 2.

The simulation results of those types of accidents show that dangerous situations are more important when the density of vehicles in one lane is small and that of the other lane is high enough. Also, the slow vehicles cause an important reduction of traffic flow which increases the risk of vehicle accident (i.e. Head on and lane changing accident).

1.11. Pedestrians

The complex nature of the mutual interactions between pedestrians gives rise to several self-organization phenomena, which are not observed in vehicular traffic. Modeling pedestrian dynamics is much more challenging than highway traffic because the motion of pedestrian have two-dimensional nature, however, we can considerate vehicular traffic is mostly one dimensional or quasi-one-dimensional. Therefore, only very few models exist, which can reproduce the empirically observed behavior precisely. The theory of pedestrian dynamics has to take into account three different levels of behavior [64, 65]

1) Strategic level, pedestrians plan their activities (shopping, going to work, etc.).
2) Tactical level, (short-term) decisions are made, e.g., choosing the precise route taking into account obstacles and density of pedestrians.
3) Operational level describes the actual walking behavior of pedestrians, including the interactions with others and collision avoidance.

However, models should be designed in such a way that they would easily allow to incorporate such information's.

As in highway traffic, the fundamental diagram [66] is an important quantity to characterize the collective properties of a group of pedestrians and their mutual interactions. However, it has to distinguish unidirectional from bidirectional fundamental diagrams, because the presence of counter-flow makes the interactions with the oncoming persons more relevant than the interactions with those walking in the same direction.

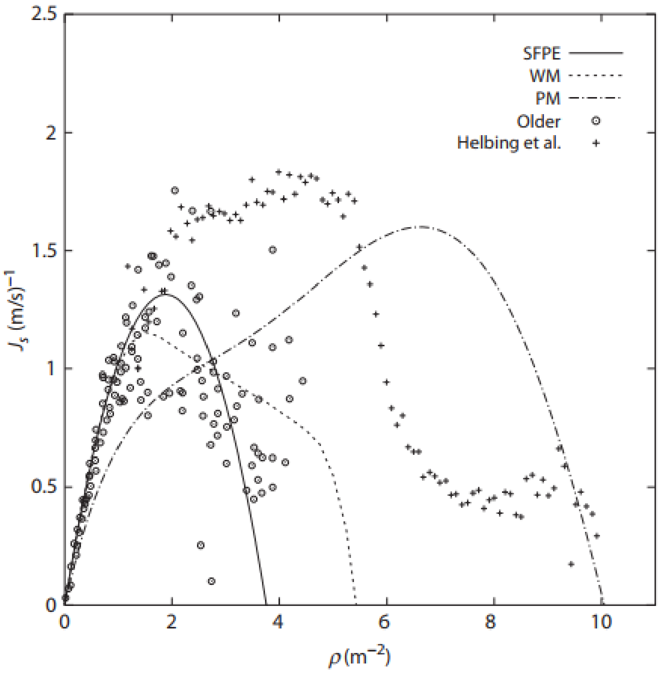


Figure 1.33: Fundamental diagrams for pedestrian movement in planar facilities. The lines refer to specifications according to planning guidelines (SFPE Handbook [67], Predtechenskii and Milinskii (PM) [69], Weidmann (WM) [70]). Data points give the range of experimental measurements (Older [68] and Helbing et al. [66]).

Figure 1.33shows various fundamental diagrams [66,70] used in planning guidelines and measurements of two selected empirical studies. Certain characteristics are shared by most fundamental diagrams, linear increases of the flow at low densities, a single maximum of the flow, and an asymmetry toward smaller densities. These features are similar to the characteristics of fundamental diagrams of highway traffic.

1.11.1. Vehicles-pedestrian's interaction

Generally vehicular traffic situation is more complex with the presence of pedestrian because interactions with other individuals (i.e. pedestrian which might cross the path of walking) in a certain range have to be taken into account. Vehicles and pedestrians are two important entities in traffic environments. They have inseparable relations and complex interactions in the real world. Accurately modeling the interaction between vehicles and pedestrians in transportation networks is important to traffic safety and future development of urban environments.

This important aspect has taking interest by a large community of physicist, echab et al [71,72] has investigated the interference between crossing pedestrians and vehicles at a roundabout and a T-intersection, and they found that pedestrians play an important role to defined the traffic flow characteristics, Li et al [73] investigated pedestrian conflicts with vehicles in crosswalk at signalized intersection.

Among the studies that have tried to elucidate the vehicles pedestrian's interactions in CA models, Xie et al [74] studied the characteristics of traffic flow for a road with a signalized crosswalk by NaSch model. The NaSch model was used to mimics the motion of vehicles, and the floor field model was used to describe the dynamics of pedestrians. Three types of pedestrians (i.e., careful pedestrians, normal pedestrians, and riskers) were considered to study the interactions between vehicles and pedestrians.

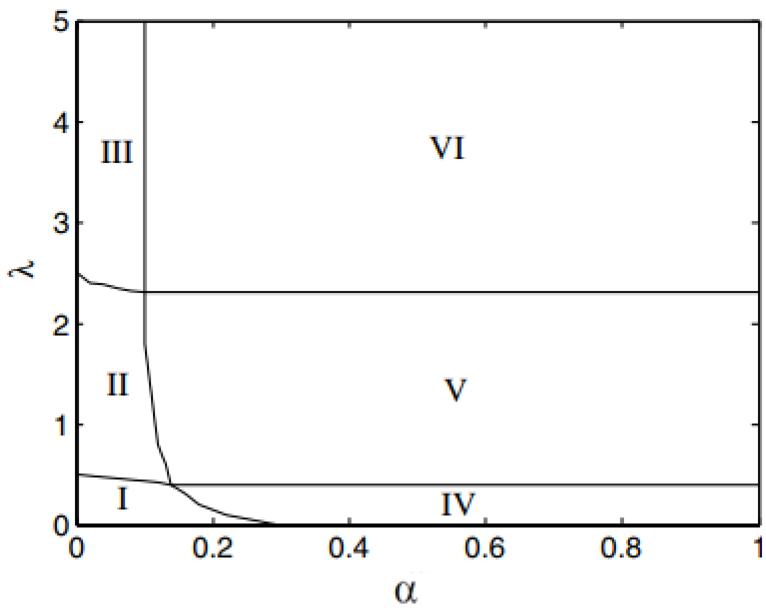


Figure 1.34: Phase diagram for $T = 120$s and $p_{nor} = 0.7$

Taking the pedestrians flow as an order parameter Fig 1.34 presentsthe phase diagram in space (α, λ) where α is the vehicles injection rate and λ is the number of arrival pedestrians which obeys the Poisson distribution. Six regions can be categorized depending on the number of pedestrian's arrivals λ. The results indicate that the interference between vehicles and pedestrians could affect the traffic situation in cities (i.e. safety and traffic flow).

We conclude from these studies that the interference between vehicles and pedestrians are very important ingredient in modeling traffic flow and ameliorate the security and the flow of the traffic in urban areas.

1.12. Simulation methods

Generally, interacting many-particle systems cannot be solved exactly. Therefore, one has to rely on approximations, preferably such that the error can be controlled. Apart from analytical approaches, numerical methods remain the most used successfully for the study of stochastic systems [53].

The most natural numerical approach for the investigation of stochastic systems is Monte Carlo (MC) simulations [54-56], which allow implementing the stochastic dynamics directly. Besides, computer simulations also numerical methods can be used to gain insights.

In figure we present the Monte Carlo simulation steps Figure 1.28 accordingly to NaSch model.

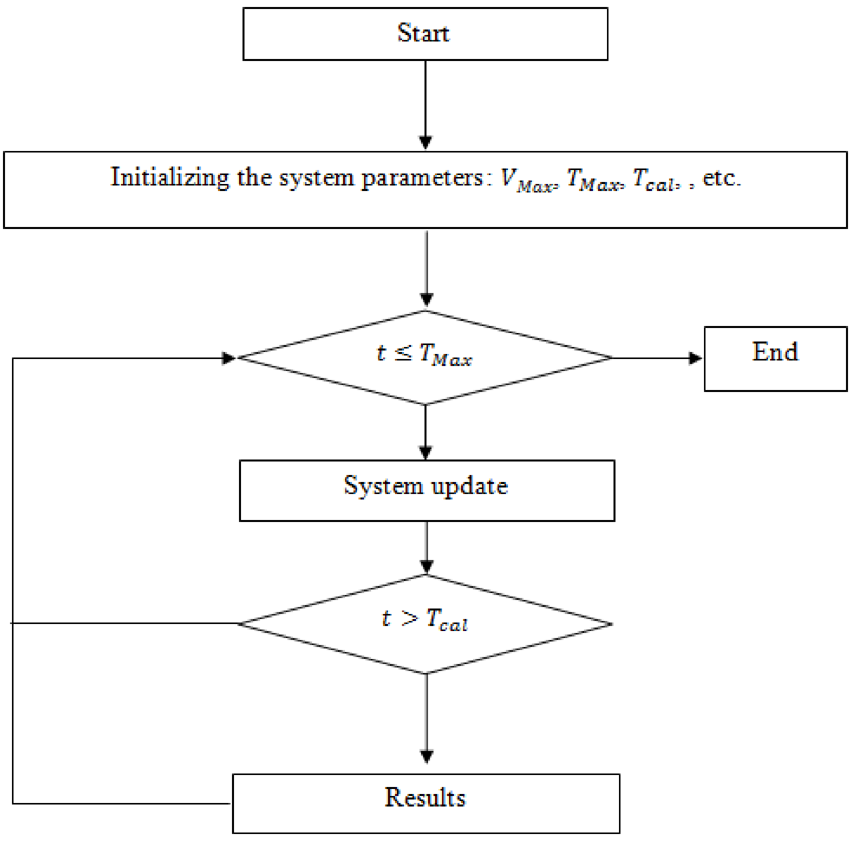


Figure 1.28: Monte Carlo steps

1.13. Conclusion

In this chapter, we presented some important basics issues used for studying the vehicular traffic. This chapter allowed us to underline the road networks, the traffic modeling models (i.e. macroscopic models, microscopic models and mesoscopic models), the traffic variables, the most used measuring instruments and some empirical results (fundamental diagram, phase diagram, etc.). The intersections and road classification were discussed, where we shed light on some basic concepts that will enable the reader to understand the following chapter.

In this context, we have put the action on the microscopic models because they allow us a fine study of the behavior of the vehicles also it has a great precision and a wealth of information that are likely to provide. Hence, we described NaSch model which is a CA model that would be useful for modeling some complex phenomena in real traffic such as phantom jam, the mutual blocking in traffic circle, etc. Therefore, this thesis adopted the NaSch model to describe the motion of vehicles in the three types of intersection studied here (i.e. traffic circle, roundabout, intersection without traffic lights). Although NaSch model is considered as a very simple model, however, keep the model as simple as possible will make us more understanding of the interaction between vehicles in those systems.

Chapter 2

The energy dissipation at a roundabout system

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The energy dissipation at roundabout system

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In this paper, we propose a cellular automata model to study the energy dissipation in the roundabout system. The energy dissipation and the phase diagram of the system in the space (α, β) are constructed. The energy dissipation profile $(\mathrm{SE}_d(i))$, and the effect of the rate γ (i.e., the rate of vehicles with no aimed exit point) and the probability P_{exit} of choosing the next exit point to leave the circulating lane on the energy dissipation are shown. The simulation results show that the energy dissipation explains the nature of the phases, the quasi-free-flow (Q-FF) phase take place on the free flow phase because some vehicles decelerate at the entry point. Likewise, the results also indicate that the energy dissipation takes small values with the increases of the two probability γ and P_{exit} which enhance the environmental statutes of the roundabout system.

Keywords: Cellular automata; roundabout; energy dissipation; phase diagram; energy dissipation profile.

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2.1. Introduction

Nowadays traffic congestion problems, environmental pollution and energy dissipation are one of the major fields studied by many scientists in the world. The complexity of traffic rise when two streams are meeting especially in the intersection which increases congestion and its associated problems. In order to mitigate of traffic problems a huge number of traffic flow models has been proposed. Among of those models NaSch [7] is widely investigated for the simulation of complex systems such as traffic circle, roundabouts and traffic city networks [83-87].In NaSch the mean speed and the current are usually used to understand the traffic phases, however, in some cases, it is hard to understand the interaction that generates the complex behavior, where the correlation between parameters (or other traffic parameters such as energy dissipation) is needed to more clarify the microscopic interactions between vehicles.

Recently, energy dissipation was used as a control parameter to understand the quality of traffic [88-91], Zhang et al. [88] investigated the energy dissipation in the NaSch model under the open boundary conditions. The results showed that dissipating energy rate depends on the vehicles density, and the initial configuration. Tian et al. [89] investigated the dependence of the energy dissipation on length of vehicles, the maximum velocity, and the rate of mixed traffic in the NaSch model. Wen et al. [90] investigated the energy dissipation in the mixed traffic flow based on the Fukui Ishibashi model [82]. Xue et al. [91] studied the influences of the injected probability and removed probability on the energy dissipation respectively through numerical simulation. Zhu [92], investigate the energy dissipation loss in traffic flow on a curved road. He found that the energy dissipation depends on the friction coefficient, the radii of curvature, the density and road length.

As knowing, roundabouts have become the major solution for traffic congestion in cities. Many researchers focused their investigations on the roundabout system in order to understand its complex interaction. Foulaadvand et al. [93] investigated the characteristic of traffic at an isolated roundabout in the framework of CA and car-following models. Huang [94] proposed a CA model to study the traffic Gridlock states at a roundabout system. Echab et al. [86] studied the phase diagram of a single lane roundabout. Lakouari et al. [87] studied the traffic flow behavior at a single lane roundabout as compared to traffic circle. Foulaadvand et al. [95] studied a model of traffic in a roundabout’s interior lane, where the dynamics of the system are described by the TASEP model [82]. In the previous studies, the current and the density were used as order parameters to understand the interaction between vehicles. Our aim in this chapter is to investigate the energy dissipation in a roundabout system which will be used to determine the traffic phases and understand the traffic interaction.

2.2. Model and method

2.2.1. Model

We consider the circulating lane as one-dimensional closed chain of L cells with N entry/exit points which are distributed equidistantly to each other respectively. Vehicles enter the circulating lane with velocity $V_{in} = 1$. In the circulating lane vehicles move counterclockwise and orderly Figure. 2.1(a) shows the sketch of the roundabout model. To describe the motion of a vehicle, we use the NaSch model [7]; where all vehicles are handled in parallel during one-time step for more detail see chapter 1 section 1.9.4.4

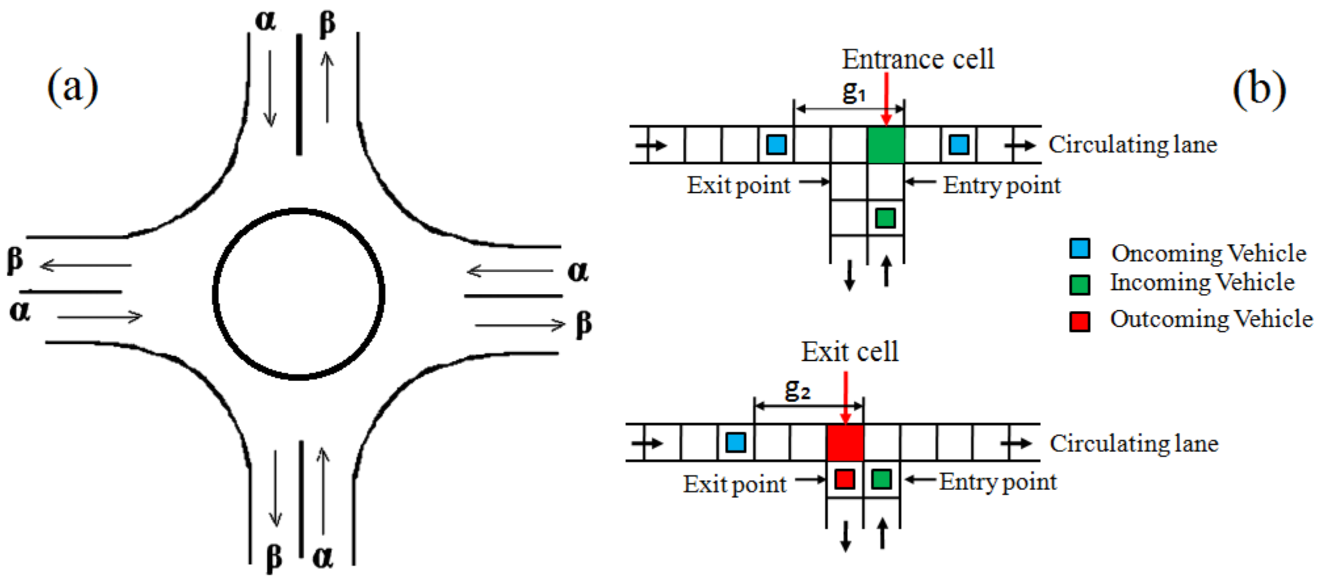

Figure 2.1: (a) Sketch of the roundabout, (b) the entry/exit rules.

2.2.2. Priority rules for vehicles entry/exit the Roundabout

The priority rules of the roundabout favor the circulating flow. To avoid conflict at the entrance, the entering vehicle (i.e. vehicle on the entry point) should yield to the vehicles in the circulating lane and reduce its velocity. The entering vehicles are injected in the circulating lane with probabilityα; if the entry cell Fig. 2.1(b) is empty and one of the following conditions is satisfied:

- The leading vehicle on the circulating lane (i.e. the oncoming vehicle), uses its indicator to signalize its wailing exit direction.
- Otherwise, the incoming vehicle inspects the number of empty cells (g_1) (i.e. the gap between the oncoming vehicles and the entry cells); If $g_1 > V_0 + 1$ vehicle at the entrance enter the circulating lane. This criterion ensures that the incoming vehicles respect and not disturb the oncoming.

Here V_0 denotes the velocity of the oncoming vehicle.

On the other hand, the oncoming vehicles can quit the circulating lane with probability β from its wailing exit, if the inspecting gapg_2 (i.e. distance between the oncoming vehicle and its desired exit point) are less than V_0 ($g_2 < V_0$), otherwise, with probability $1 - \beta$ the vehicle has to reduce its velocity and stop in the exit cell waiting for the exit point to be emptied so it can quit the circulating lane. The inclusion of the exit probability β can be related to the traffic status in the exit direction.

2.2.3. Energy dissipation and the energy dissipation profile.

The kinetic energy of the car moving with the velocity V is determined with the formula $\frac{mV^2}{2}$; where m is the mass of each car. Let E_d denotes energy dissipation rate per time step per car. For simplicity, all the others dissipation factors such as rolling and air drag dissipation, the energy needed to keep the motor running while the car is standing and moving are neglected. The dissipated energy of i-th car from time t-1 to t is defined by

$$e(i,t) = \begin{cases} 0 & for V(i,t) \geq V(i,t-1) \\ \frac{m}{2}[V^2(i,t-1) - V^2(i,t)] & for V(i,t) < V(i,t-1) \end{cases}, \quad (15)$$

V(i, t) and V(i, t−1) are the velocities of the i-th car at t and t−1 time respectively. Thus, the average energy dissipation rate is

$$E_d = \frac{1}{T}\frac{1}{N}\sum_{t=t_0+1}^{t_{0+T}}\sum_{i=1}^{N} e(i,t) \quad (16)$$

Where N is the number of cars in the system and t_0 is the relaxation time (i.e. taken as a long enough time for the system to reach a steady state).

The energy dissipation profile at each site from the lattice if this site is occupied by a vehicle, we calculate the difference of the kinetic energy of this vehicle between the time t and t-1 as follow

$$\mathrm{SEd(j)} = \frac{1}{\mathrm{T}} \sum_{\mathrm{t=t_0+1}}^{\mathrm{t_0+T}} \mathrm{e(j)} \tag{17}$$

Here T is the stationary time, and j is the site index.

2.3. Results and discussions

Simulations are conducted to examine the energy dissipation on a one single lane roundabout. The parameters L = 40, V_{max} = 3, P_b = 0 are used. The aimed direction is chosen on an equal probability. The results are averaged over 30 000 time steps after 5000 time steps for 80 different initial configurations.

2.3.1. Energy dissipation with different extraction rate

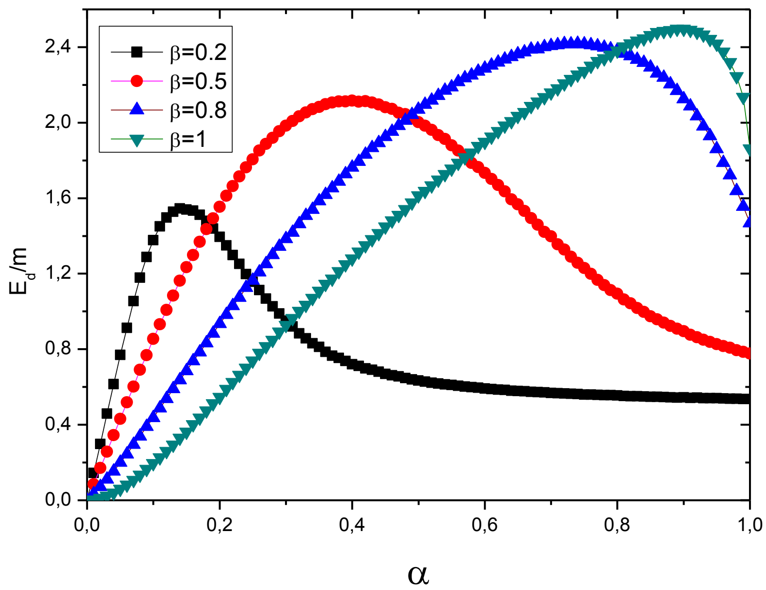

Figure 2.2: The energy dissipation E_d/m as function of the injection rate α with different values of β.

First, we study the effects of the boundary conditions on energy dissipation in the deterministic case where P_b = 0, Figure 2.2 shows the energy dissipation rate E_d as a function of the injection rate α with different values of the extinction rateβ. As shown in Figure 2.2 there is a critical value of the injection rate α below which the energy dissipation increases rapidly with the increase of the rate α, but above which the energy dissipation slightly decreases. There is a non-vanishing energy dissipation when$\alpha \gg \alpha_c$, which can be explained by the status of the traffic at the exit point. Considering that the order parameter is the energy dissipation, we plot the phase diagram in the plan (α, β) Fig 2.3,

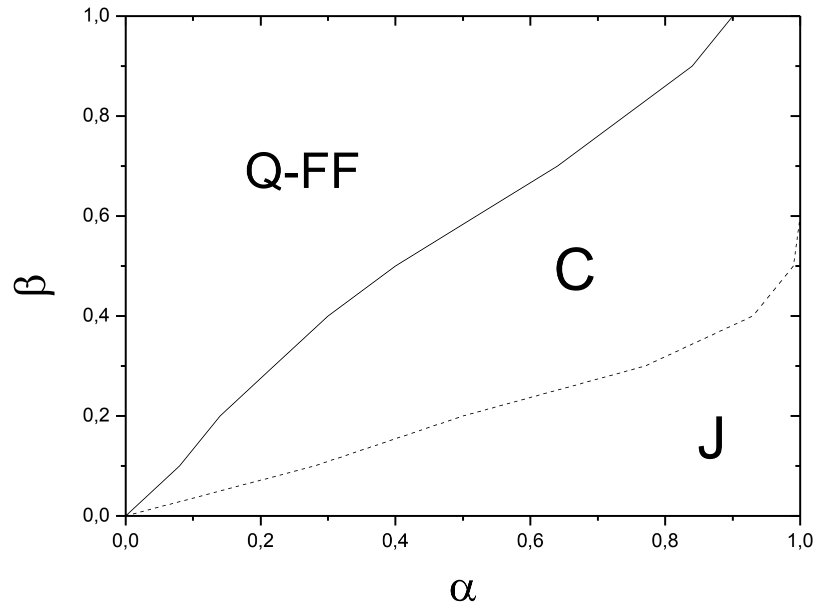

Figure 2.3: Phase diagram in the $(\boldsymbol{\alpha}, \boldsymbol{\beta})$ plane.

the phase diagram present three different phases. In the phase I, the free flow phase is reached, however, there is still energy dissipation while α is in the free-flow phase as referred in [86-87]. Therefore, we refer to this state as quasi-free-flow (Q-FF) phase, where vehicles interact between them without any backward moving jam. The vehicles interaction in the Q-FF phases results from the boundary condition and the priority rules (i.e. oncoming vehicles should yield the incoming vehicles). As we can see the energy dissipation increases while the extraction rate β increases, thus is related to the highest interaction between vehicles at the entrance cell i.e. if the entry rules are fulfilled the vehicles are injected with probability α and velocity V_{in} = 1, which lead to an accelerating for the incoming vehicles and decelerating for the oncoming vehicles. However, in the phase II, the congestion phase is obtained, here the energy dissipation decreases and each exit point generating a cluster of standing vehicles. In phase III the jammed phase is reached, and vehicles are in the extreme jam.

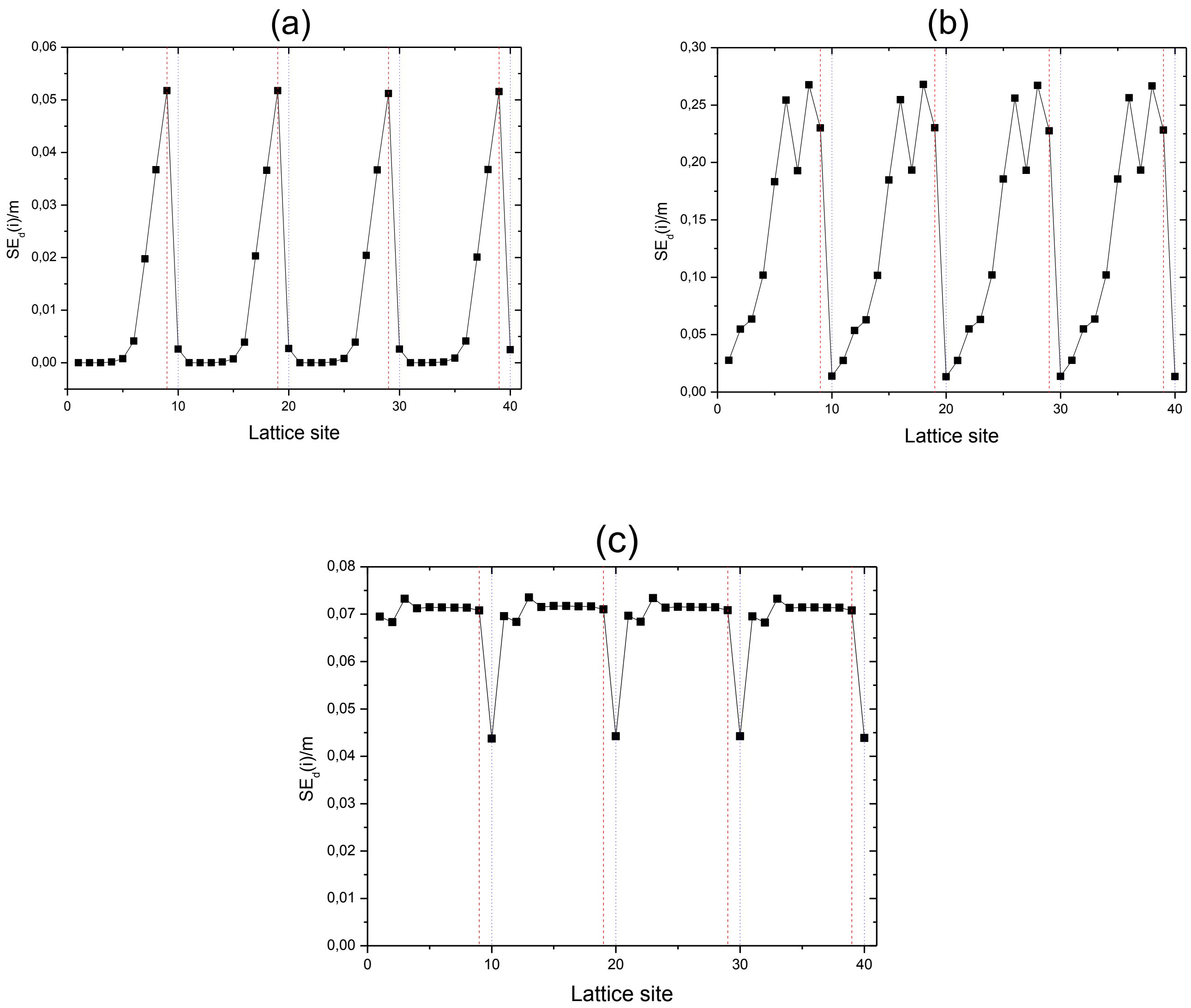

Figure 2.4: Energy dissipation profile $SE_d(i)/m$ as a function of site number i, where (a) ($\beta = 0.8, \alpha = 0.05$), (b) ($\beta = 0.8, \alpha = 0.8$) and (c) ($\beta = 0.2, \alpha = 0.8$). Red dashed (resp. bleu dotted) line presentsthe entry (resp. exit) point.

For a better insight, Figure 2.4 presents the energy dissipation profile in the quasi-free-flow (Q-FF), congestion and jammed phase. In Figure 2.4(a) the energy dissipation rate $SE_d(i)$(i.e. $SE_d(i)$ energy dissipation rate per site per time) shows a flat profile($SE_d(i)=0$) before each exit point, here vehicles move with their maximal velocity, but at the exit cell we can find that the $SE_d(i)$ increases which mean that vehicles decelerate at the boundary without any backward moving jam, and they accelerate at the entry point i.e. vehicles are injected with V_{in}= 1. At the congestion phase (Figure 2.4(b)) $SE_d(i)>0$, the oscillations are presented and it becomes stronger as we get closer to the exit point i.e. vehicles switch their status between decelerating and accelerating, which result a cluster of standing vehicles are formed. At the jammed (Figure 2.4(c)) phase $SE_d(i)>>0$, the oscillations back to disappear, while the energy dissipation is higher, which assumes that vehicles decelerate and a backward jam takes place. For the rest of this work we fixed the extraction rate at $\beta = 0.5$.

2.3.2. Turning vehicles effect

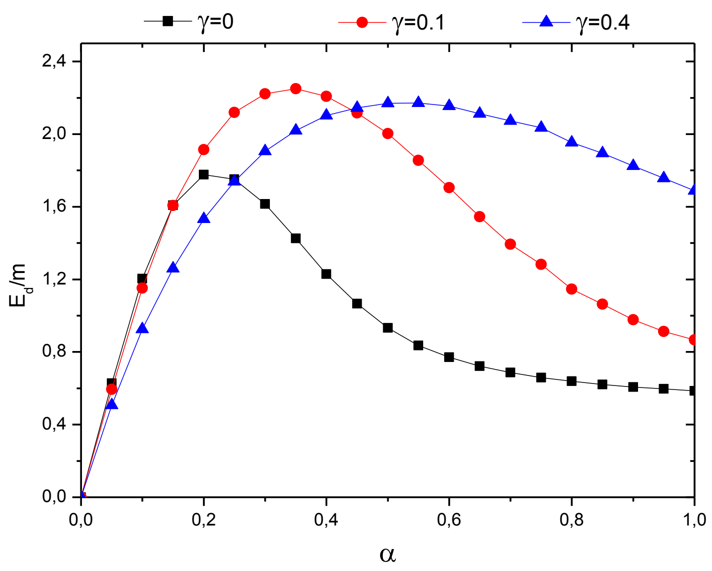

Figure 2.5: The energy dissipation E_d/m as function of the injection rate α with $P_{exit} = 0.1$ and different values of γ.

Until now, we have considered that each vehicle on the road has an intended destination or a desired exit at the entrance of the circulating lane. Next, we are going to study the rate of entering vehicles with no aimed exit point (γ) (i.e. vehicles that keep turning in the circulating lane) and the probability (P_{exit}) of choosing the nearest exit point to leave the circulating lane. Fig 2.5present the dissipating energy as function of the injection rate α with $P_{exit} = 0.1$ and different values of γ, as γ increases the number of vehicles that circle around in the roundabout without a desired exit increase, which reduce the number of entering vehicles to the circulating lane. Thus, the circulating lane is dominated by the turning vehicles, which reduces the interaction between vehicles, as a consequence, the energy dissipation decreases. However, as α increases (i.e. > 0.45), inasmuch as β=0.5 which block vehicles to reach there aimed exit or to keep turning as result the number of entering vehicles increases where the dissipation energy augments.

2.3.3. Choosing the next exit point probability

Next, we examine the effect of the probability P_{exit} on the circulating lane with$\gamma = 0.1$. As shown in Figure2.6 the dissipating energy increases as P_{exit} increases, evidently, increasing P_{exit} means low interaction between entering vehicles and circulating flow because vehicles choses the nearest exit point to leave the circulating lane which reduce the energy dissipation, another way to understand this effect is that when P_{exit} increase the system becomes decoupled it means that the roundabout system could be seen like four parts of road separated by in and out point,in that case the interaction reduced because vehicle enter from the in-point and get out from the nearest out point without passing by another part of road.

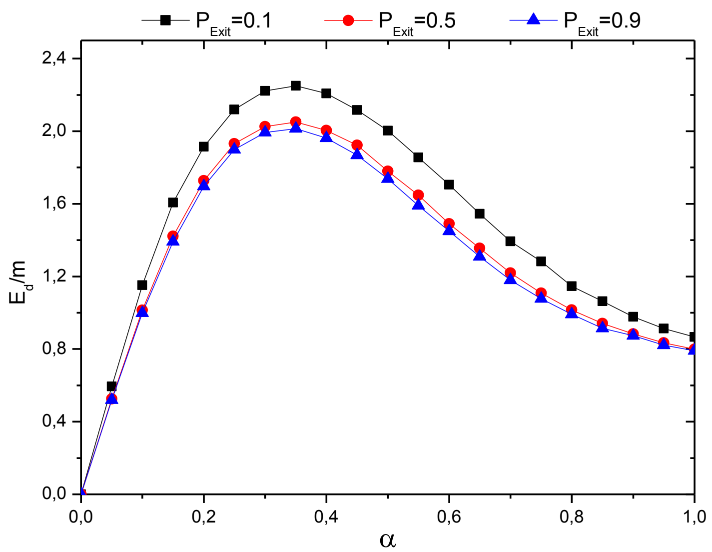

Figure 2.6: The energy dissipation E_d/m as function of the injection rate α with $\gamma = 0.1$ and different values ofP_{exit}.

2.4. Conclusion

In this chapter the energy dissipation in a single lane roundabout was studied. The energy dissipation and the phase diagram of the system in the space (α, β) space are constructed, in which the energy dissipation display tree phases the quasi free flow phase (QFF), congestion phase and jammed phase, we also plan the energy dissipation profile (SEd(i)), which explain the presence of the QFF phase and no free flow phase. Moreover, we have investigated the effect of the rate of vehicles with no aimed exit point $\gamma$and the probability that vehicles with no aimed exit point chose the nearest exit point P_{exit} on the energy dissipation. Likewise, the results also indicate that the dissipating energy decreases with the increases of the two probabilities γ and P_{exit} which enhance the environmental statues of the roundabout. To reduce the dissipation energy in the circulating lane controlling light should be used to reduce the interaction between vehicles; this study can be used to improve the traffic quality in the roundabout system.

Chapter 3

Traffic flow behavior at a single lane traffic circle

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Traffic flow behavior at a single lane traffic circle

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In this paper, we propose a stochastic cellular automata (CA) model to study traffic dynamic at a single-lane traffic circle of N entry/exit points. The boundaries are controlled by the injecting rates α_1, α_2 and the extracting rate β. Both the cases with and without the splitter islands of width L_{sp} are considered. The phase diagrams in the space $(\alpha_1\beta)$ are constructed and the density profiles are also investigated. The variation of the phase diagram with the traffic circle size (L), the number of entry point (N), and the time needed for drivers to change their exit willingly (T_{exit}) is studied. The results show that the phase diagram in both cases consists essentially of three phases namely free flow, congestion and gridlock. However, the large sized traffic circle shows better performance in the free flow phase, in contrary, the increase of N enlarges the congestion and the gridlock phases. We have also found that the decrease of T_{exit} enhances the traffic flow situation in the traffic circle. Furthermore, as the L_{sp} increases, the free flow phase enlarges while the congestion and gridlock ones shrink.

Keywords: Cellular automata; traffic circle; phase diagram; gridlock; density profiles.

1. Introduction

Research fields in traffic congestion problems have gained a big part of interest by different scientific groups, many scientists have come out with many studies with different models such as car following, fluid-dynamical method and cellular automaton (CA).[1–7] The CA model developed by Nagel and Schreckenberg (NS) is an intuitive and a stochastic model that can simulate the complicated phenomenon observed in traffic flow, due to its simplicity, flexibility, and its fast performance in simulations.[5–7]

Obviously, since more congestion problems occur in urban systems, especially, at intersections such as traffic circle, roundabout, T-intersection, Y-intersection, X-intersection, etc. To overcome these problems, more attention has been paid

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3.1. Introduction

Since more congestion problems occur in urban systems, especially, at intersections (traffic circle, roundabout, T-intersection, Y intersection, X-intersection, etc.). More attention has been paid to investigate traffic issue at intersections [96-97]. In particular, circular intersection (roundabout and traffic circle) has been extensively studied [86][93-95][98-99].

Typically, roundabouts are distinguished from traffic circles by their priority rules (i.e. roundabout gives priority to circulating traffic, in contrary traffic circle gives priority to incoming vehicles), and their uniform characteristics in design [100]. Compared with great research interests in roundabouts, traffic circles, however, have not attracted enough attention [101-104]; Jin et al. [101] studied the traffic circle administration based on circuit principles and marginal benefit theory. Ray and Bhattacharyya [102] studied the formation of density waves in traffic flow through intersecting roads. Caliskanelli et al [103] compared different capacity models for traffic circles. Lakouari et al [104] studied the traffic flow behavior at a single lane roundabout as compared to traffic circle; the results indicate that in low-volume situations, traffic circle shows better performance; whereas, in high-volume traffic, one has to use roundabout. The successes of both systems have motivated the development of scientific investigations that concern the performance provided by these systems, especially roundabout. Nevertheless, the traffic circle's performance is seldom studied. Our aim in this chapter is to explore and analyze some characteristics of traffic circle system, such as flux and capacity, in order to better understand of traffic interaction.

In this chapter, we investigate the traffic behaviors on a single-lane traffic circle with and without Splitter Islands. This latter is presented in reality as a painted or raised area between two successive exit and entry points, used to separate exiting from entering traffic, slow and deflect incoming vehicles, and provide the opportunity for pedestrians crossing the road in two stages. Furthermore, the effects of the system size, the injecting rates (α_1, α_2), the extracting rateβ, and the probability of changing the preferential exit will be studied.

3.2. Model and method

3.2.1. Model

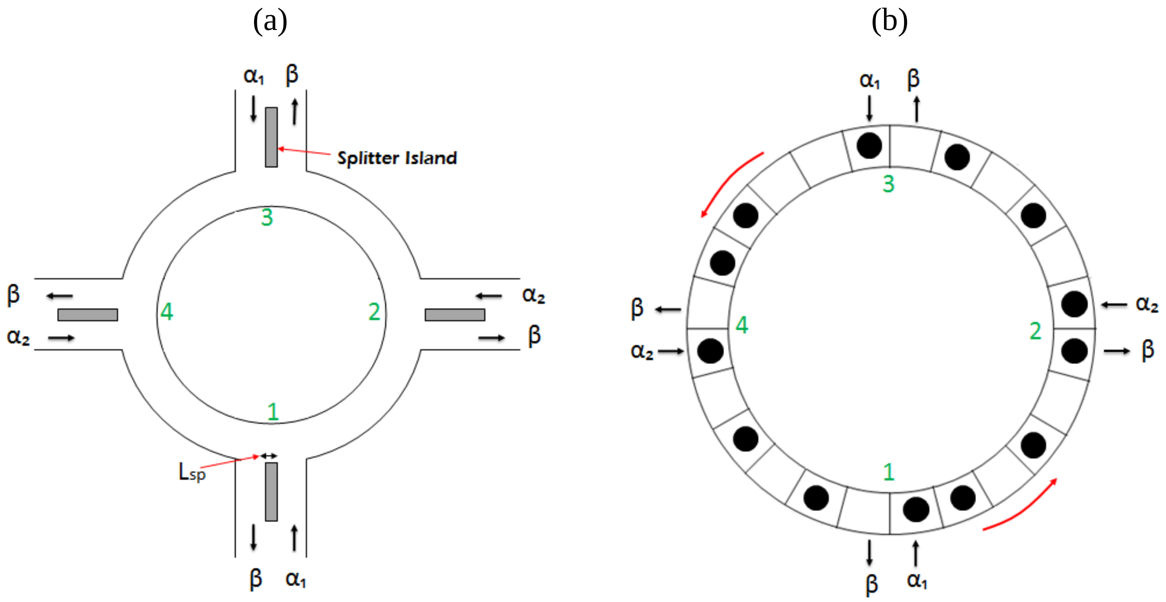


Figure 3.1: (a) Sketch of the roundabout, (b) Sketch of the circulating lane

The circulating lane is considered as one-dimensional closed chain, discretized into L cells, including four entry/exit points which are equidistantly located respect to each other. The splitter island of widthL_{sp} is designed between each exit and entry points. Vehicles move orderly and counter clockwise. Fig 3.1 (a)-(b) Show the sketch of the traffic circle model. The vehicles follow the updating rules of NaSch model [7]; where all vehicles are handled in parallel during one-time step for more detail see chapter 1 section 1.9.4.4

3.2.2. Priority rules for vehicles entry/exit the traffic circle

The entry rules of the traffic circle give priority to the incoming vehicles (i.e. vehicle on the entry point) according to the following rules:

i. The incoming vehicle (i.e. vehicle on the entry point) has the priority to enter the circulating lane with probability α_1 (resp. α_2) if the entrance cell (i.e. the cell connecting the entry point and the circulating lane Fig.3.2) is empty with a velocity$V_{in} = V_{max}$. Here, the oncoming vehicle should yield to incoming one and adjusts its velocity according to the gap g_1 , where g_1 is the gap between the oncoming vehicle and the entry point.

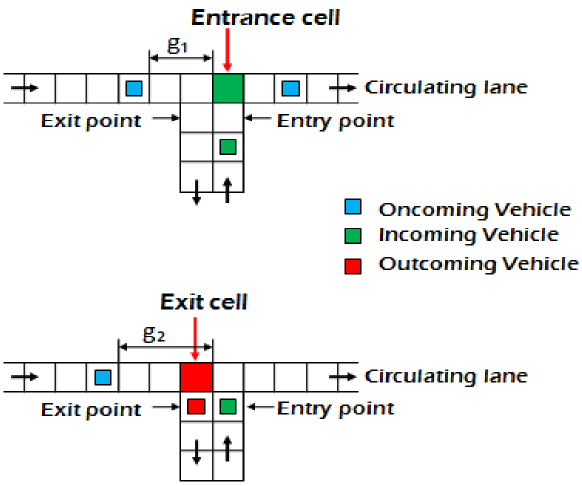


Figure 3.2: (c) entry\exit rule

The exit rules are giving by:

ii. The oncoming vehicle inspects the gap g_2 between the aimed exit and its position, if $g_2 < V_0$ the vehicle leaves the circulating lane with probabilityβ, here V_0 designates the velocity of the oncoming vehicle. Otherwise, with probability $(1-\beta)$ the vehicle slows down and stops in the exit cell (i.e. the cell connecting the exit point and the circulating lane). The inclusion of the exit probability β can be related to the traffic status in the exit direction.

We note that the exit point is selected for each vehicle with probability P_{out} upon entrance to the circulating lane.

3.2.3. Changing the Exit point

We know that in real traffic situation drivers get to think always about looking for any solution to escape congestion delay, which means that there are some drivers of oncoming vehicles changes their willing exit to save time and to avoid being trapped in the gridlock state. For this purpose, we assume that when an oncoming vehicle cannot reach its aimed exit during a period of time T_{exit} (i.e. vehicle is blocked in cluster), it can leave the circulating lane from the first exit point (with probabilityP_{Ch}).

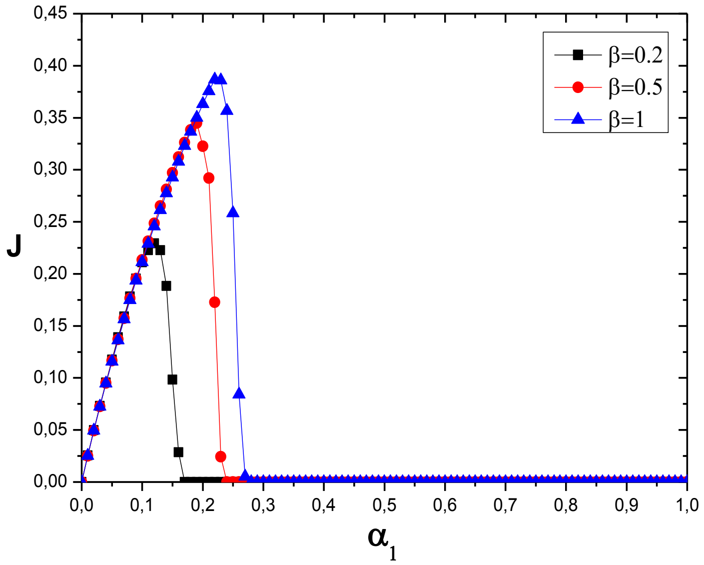
3.3. Results and discussions

The simulation results are presented. The circulating lane length is assumed to$L = 40$, the entry/exit point number is set to $N = 4$, the maximum velocity $V_{max} = 2$, and the braking probability $P_b = 0$ are used. The exit points are selected on an equal probability$P_{out} = 1/4$. The results are averaged over 50 000-time steps after 4000 time steps for 50 independent runs.

First, we examine the case where no splitter island is used (i.e. $L_{sp} = 0$), also we assume that$\alpha_1 = \alpha_2$

3.3.1. $\boldsymbol{\alpha_1 = \alpha_2}$

(a)



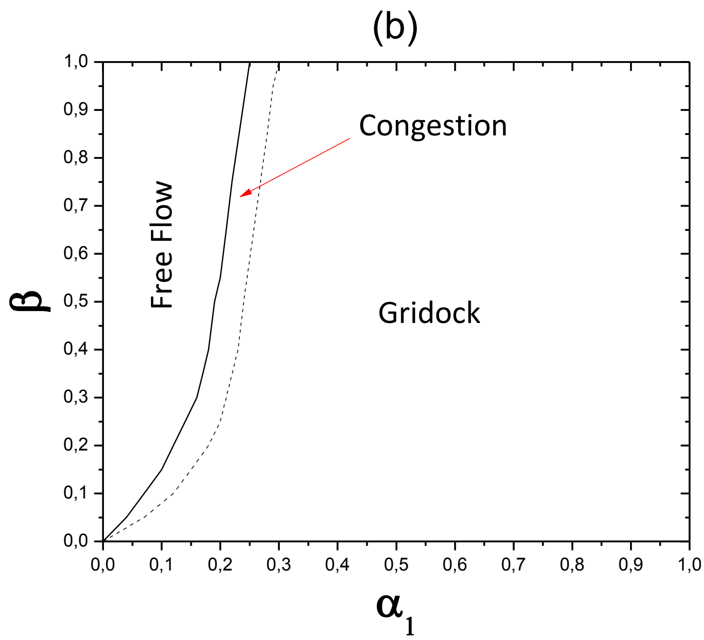
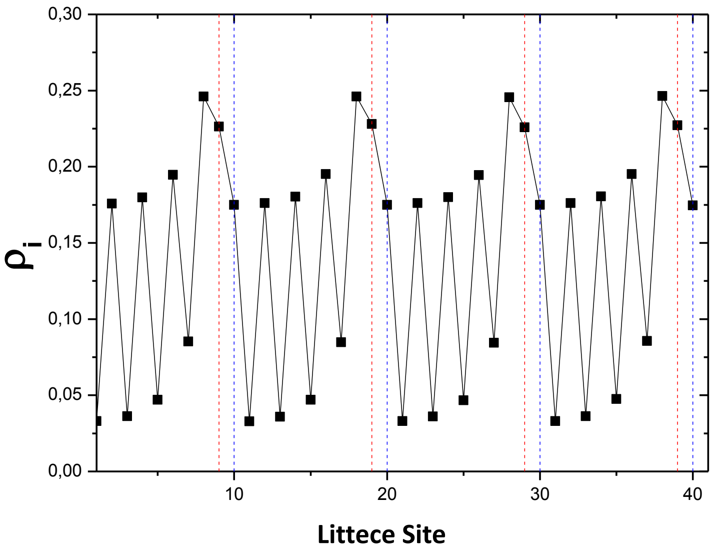


Figure 3.3: (a) Current as function of α_1 for differentβ, where$\alpha_1 = \alpha_2$, (b) Phase diagram in the (α_1, β).

Using the rotary flow J as an order parameter (Figure 3.3(a)); the phase diagram (α_1, β) is presented (see Figure 3.3(b)). Three different phases can be observed: the free flow phase, the congestion phase, and the gridlock phase. The free flow phase takes place when α_1 is very low thanβ, the flow in the circulating lane increases proportionally to α_1 andβ, here vehicles move freely in and out of the circulating lane. In the case of the congestion phase, the current in the circulating lane decreases because the rotary is dominated by clusters generated just before entry points (i.e. vehicles stopped by the priority rule). In the gridlock phase all vehicles in the circulating lane come to stop; the flow in the rotary$J$is set to zero, here no vehicle can enter to or exit from the circulating lane. The gridlock phase is larger than the free flow phase and the congested ones. Note that both transitions (i.e. from the free flow to congestion phase and from the congestion phase to gridlock one) are second-order transitions because the current is a continuous function of the injecting rate α_1 for a fixed rate β.

In order to get better insights into the traffic dynamics in those different phases, we presented the density profiles of the system with $\alpha_1 = \alpha_2$ (see Figure3.4).

(a)


0,30
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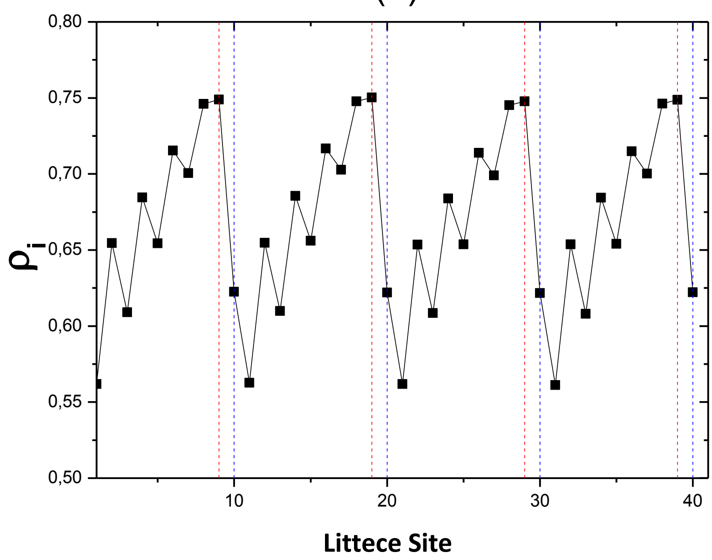
(b)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ρi
10
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30
40
Littece Site

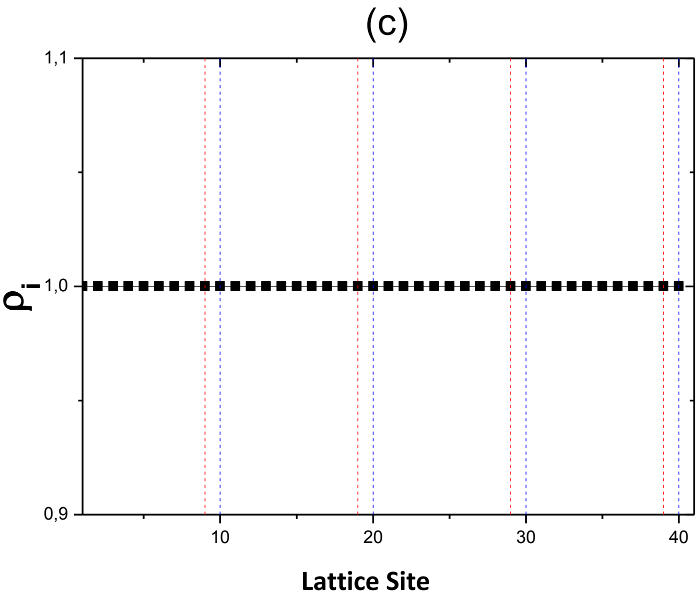


Figure 3.4: Density profile ρ_i as a function of the lattice site i, where$\beta = 0,4$ and$L_{sp} = 0$, (a)$\alpha_1 = \alpha_2 = 0,1$, (b)$\alpha_1 = \alpha_2 = 0,2$, (c)$\alpha_1 = \alpha_2 = 0,6$. Red dashed (resp. bleu dashed) line presents the exit (resp. entry) point.

In the free flow phase (Fig 3.4 (a)) the oscillations can be observed throughout the system. Vehicles move freely, and the interactions between them are extremely weak, vehicles can enter and exit to/from the circulating lane smoothly. According to the priority rules the average density will increase as we approach the entry point. In the congestion phase (Fig3.4 (b)) the oscillations are presented but it become weaker as we approach to the entry points because vehicles already in the rotary should give priority to the incoming vehicles which block temporary the exit points, as a consequence oncoming vehicle takes more time to reach its aimed exit. However, in the gridlock phase (Fig 3.4(c)) a flat profile is observed; the extreme congestion takes place. As the injecting rates increase as the priority rules provoke more delay to the oncoming vehicles which give rise to long clusters that emerge backward, this situation blocks the exit points. Thus, confirm the result of Ray and Bhattacharyya [102] where the congestion becomes confined to the traffic circle.

3.3.2. $\alpha_1 \neq \alpha_2$

Next, we study the phase diagram with$\alpha_1 \neq \alpha_2$ (Fig 3.5); the results show qualitatively the same phases obtained above (see Fig. 3.3). Therefore, with the increasing of α_2 the gridlock phase expands while both the free and jammed ones are shrunk. Evidently, when$\alpha_2 = 0$, only two entry points operate which increases the current and reduces the interactions between vehicles. However, by increasingα_2, the incoming flow increases, which only make the traffic more congested in the circulating lane and explain the enlargement of the gridlock phase. It can be concluded that by controlling the injection probabilities we can improve the traffic situation in the traffic circle.

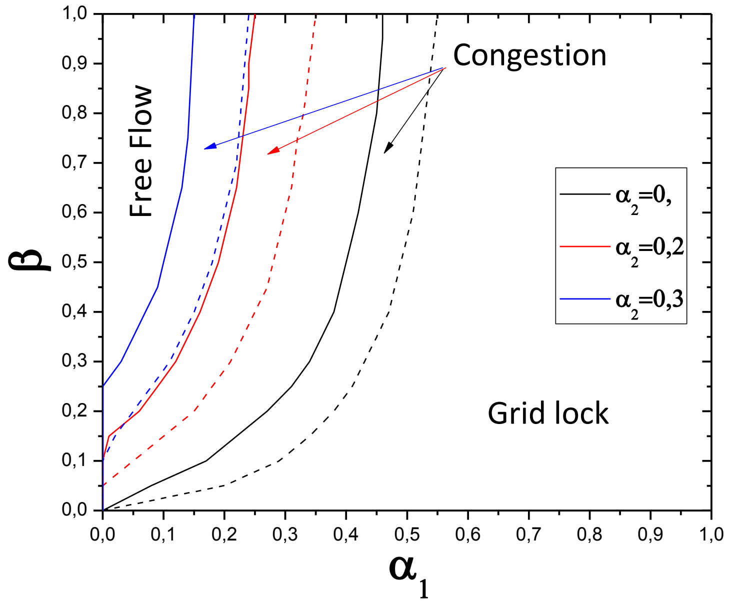


Figure 3.5: Phase diagram in the (α_1, β) plane for$\alpha_1 \neq \alpha_2$.

3.3.3. Circulating lane length

At the following we assume that$(\alpha_1 = \alpha_2)$, and then we investigate the relation between the traffic circle size and its performance. The results are shown in Fig 3.6. It can be found that with the increase of L, the free flow phase enlarges apparently while the jammed and gridlock phases shrink (see Fig 3.6 (a)). Here, the large size shows a better performance, this is because the oncoming vehicles move freely by using a lengthy weaving distance, which increase the probability for an oncoming vehicle finding distance headway to reach its aimed exit before been stopped by the entry traffic. However, decreasing the size of the circulating widen the jammed and the gridlock phases, because the capacity of short-sized traffic circle drops rapidly with the increasing of the incoming traffic Fig 3.6 (b).

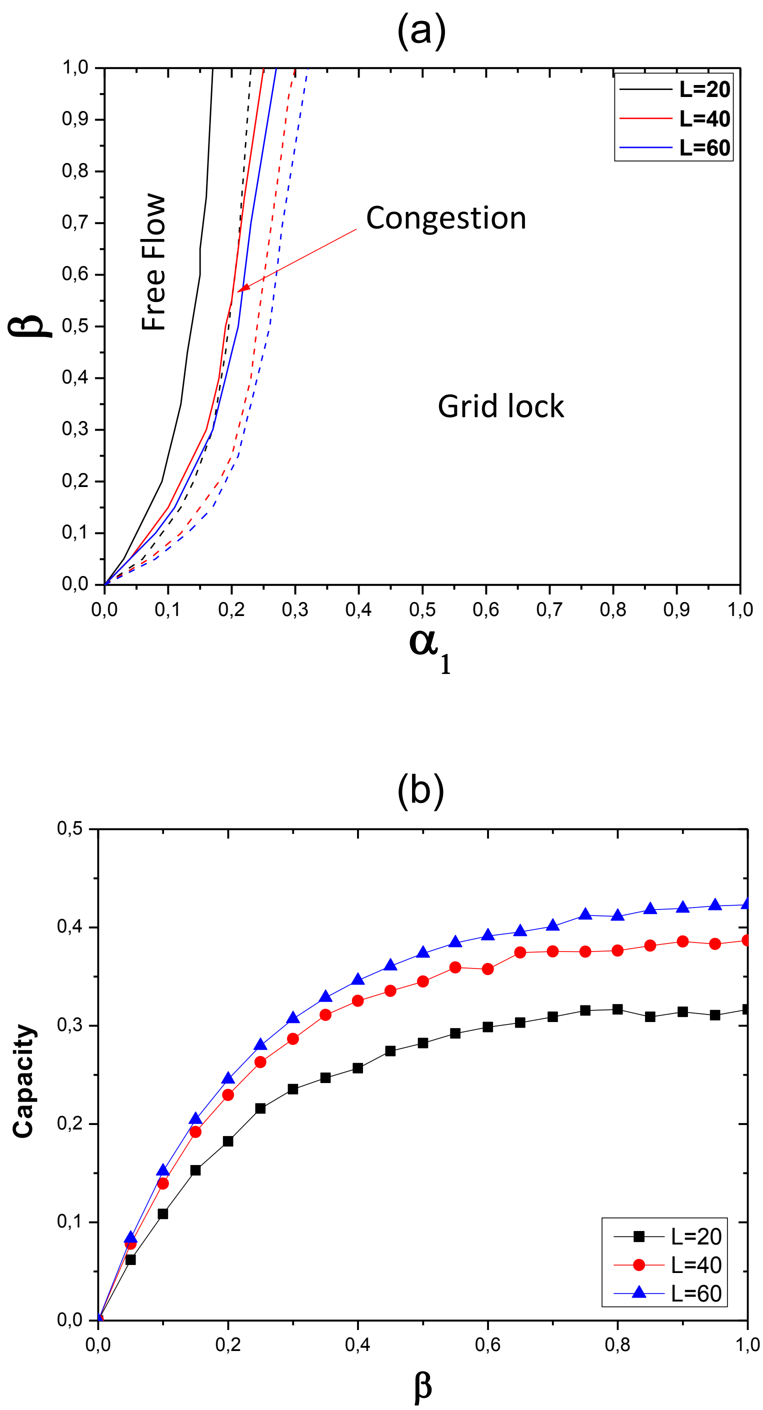


Figure 3.6: (a) Phase diagram in the (α_1, β)plane, (b) the capacity as function of rate β for different L where$\alpha_1 = \alpha_2$ and$L_{sp} = 0$.

3.3.4. The number of entry/exit points

In reality the intersection or the roundabout has more than four or three entry/exit point. Next, we study the effect of increasing the number of entry/exit points$N$ on the performance of the rotary traffic (with $L_{sp} = 0$).

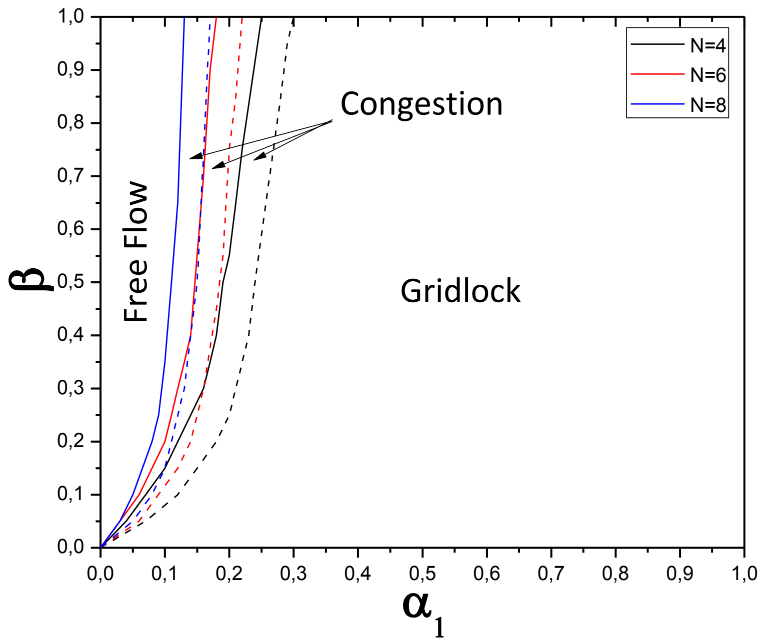


Figure 3.7: Phase diagram in the (α_1, β) plane for different N where$\alpha_1 = \alpha_2$ and $L_{sp} = 0$

Fig 3.7 depicts the phase diagrams for various values of N, as shown in Fig.3.7 the free flow and the congestion phase shrink, while the gridlock phase enlarges. Obviously, with the increases of$N$the weaving distances decreases and the traffic flow decrease. This leads to an increase of vehicles density at the circulating lane, as a consequence lengthy clusters of standing vehicles will be generated and blocks the traffic at the circulating lane to reach its aimed exit, thus the gridlock phase enlarges.

3.3.5. Splitter island effect

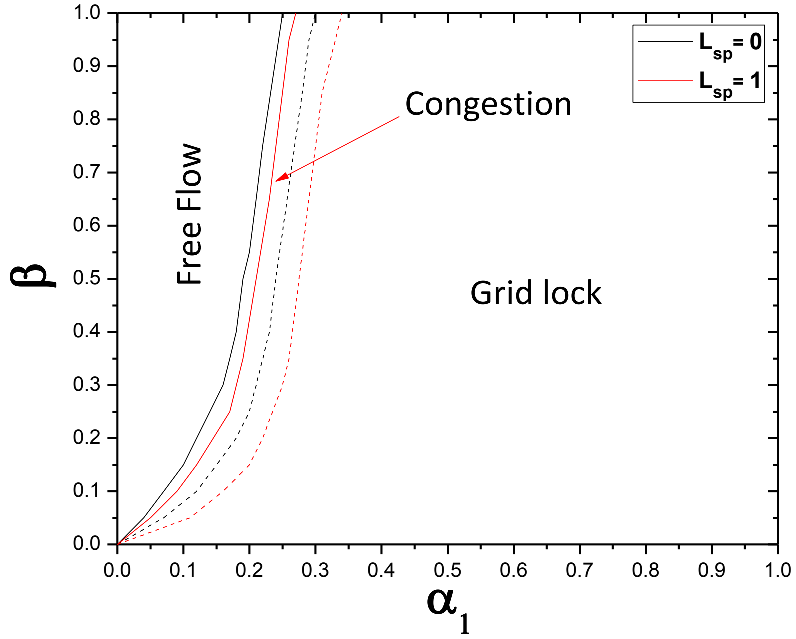
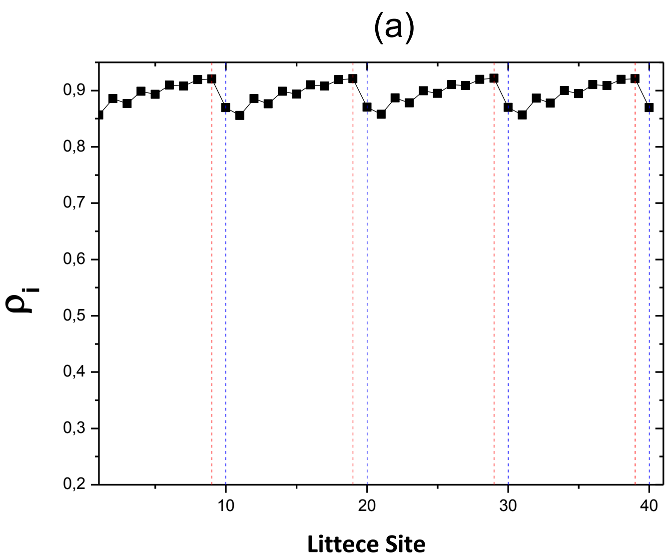


Figure 3.8: Phase diagram in the (α_1, β) plane for differentL_{sp}.

Here after, we study the effect of the Splitter islands (i.e. area that separate the exiting from the entering traffic Fig 3.1 (a)) on the system performance. In this way, we consider a raising area of width $L_{sp}$to create a separation between two successive exit and entry points. Fig 3.8 shows the phase diagram (α_1, β) for different values of L_{sp} .One can be found that by increasingL_{sp}, both the free flow and the jammed phase enlarge while the gridlock phase shrinks.



(b)

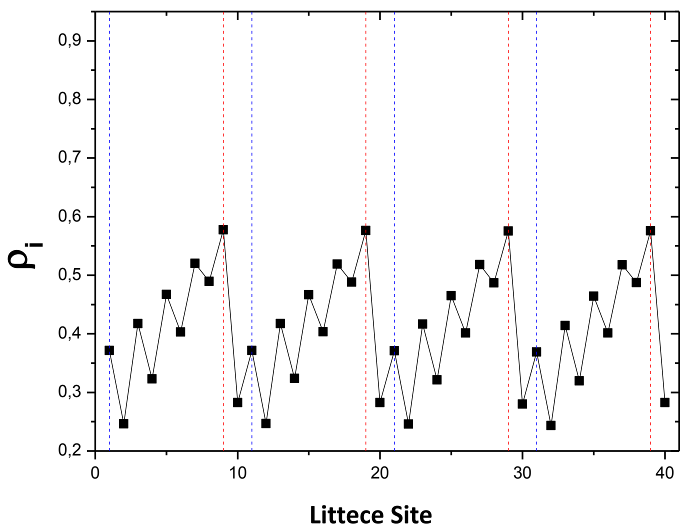


Figure 3.9 : Density profile ρ_i as a function of site number i, where$\alpha_1 = \alpha_2 = 0,2$ and$\beta = 0,35$, (a)$L_{sp} = 0$, (b)$L_{sp} = 1$. Red dashed (resp. bleu dashed) lines present the exit (resp. entry) points.

To better understand the traffic dynamics in this situation, we presented the density profile in both cases (i.e. with and without the splitter islands Fig 3.9), we note that the sites$j = 9, 19, 29, 39$ present the exit points in both cases, while $j = 10, 20, 30, 40$ (resp. $j = 11, 21, 31, 1$) show the entry points without (resp. with) Splitter Islands. The results show the presence of the oscillation in the system, and it's weaker in the case where$L_{sp} = 0$ (i.e. without the Splitter Islands Fig 3.9 (a)), the splitter island Fig 3.9 (b) provide an expanded site before entering point which can be used by the vehicle that yield to the entering vehicle ,thus reduce the blocking of the exit point. In this situation increasing the distanceL_{sp} reduce the probability of a yielding vehicle to block the out points which enhance the traffic situation in the circulation lane.

3.3.6. Changing direction decision time

Globally, we have investigated the traffic circle under many circumstances. The results show that the incoming traffic blocks the oncoming traffic which makes the traffic situation worst. And so, in times of heavy traffic (i.e. with higher values of the injection probabilitiesα_1, α_2) a gridlock is often to be expected. The congestion delay promotes some drivers to seek solutions (i.e. changing road destination which means in our case changing their willing exit).

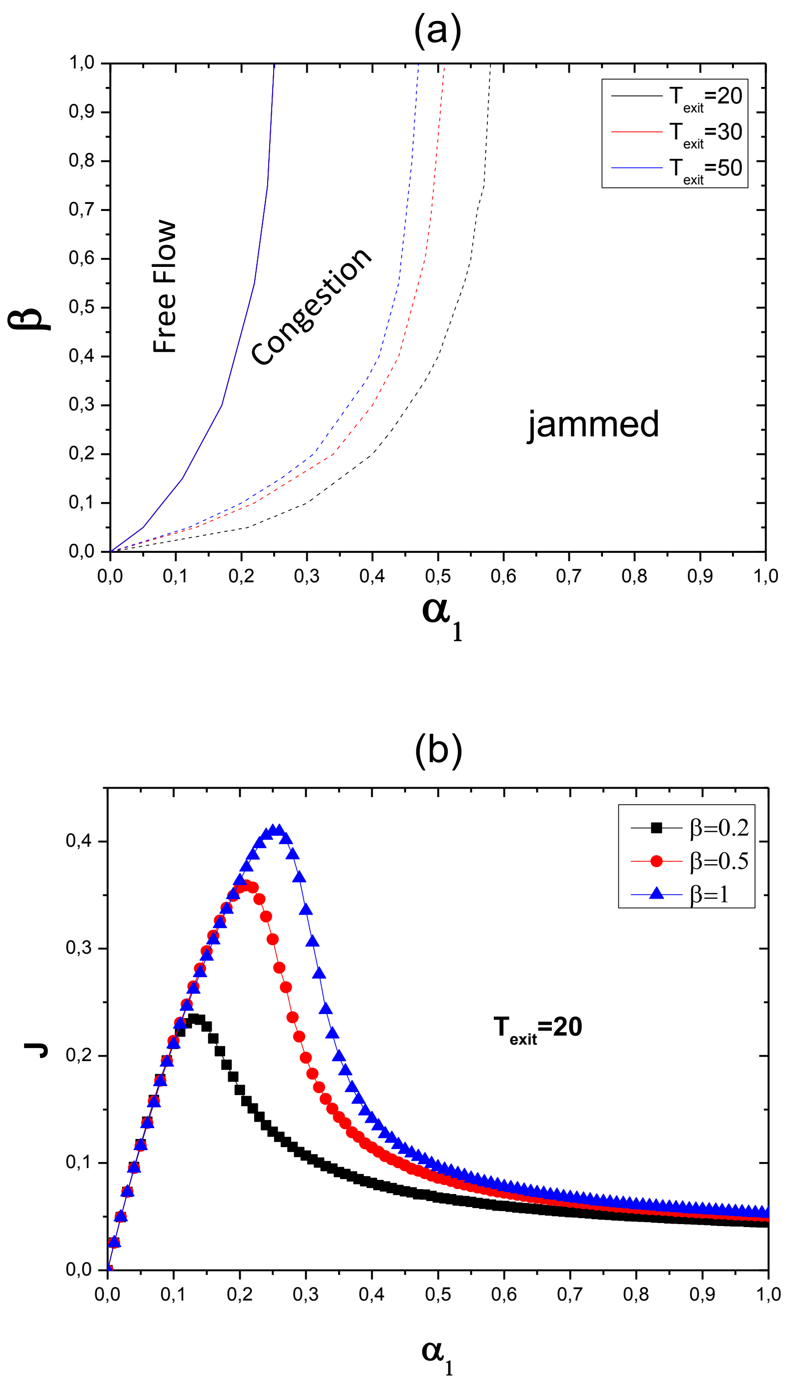
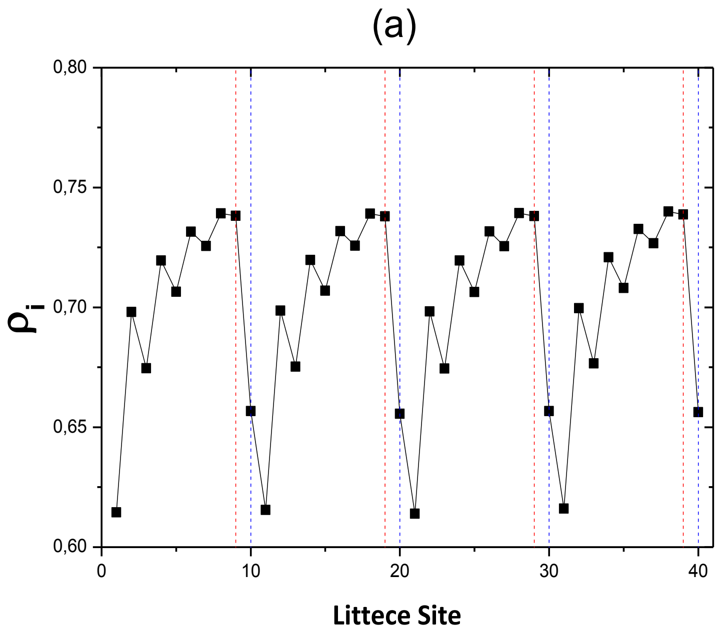


Figure 3.10: (a) Phase diagram in the (α_1, β) plane for different T_{exit} (b) Current as function of α_1 for different β, where $\alpha_1 = \alpha_2$ and $T_{exit} = 20$.

Next, we investigate the time (T_{exit})for a driver to change his willing exit. As shown in Fig 3.10, the free flow and the congestion phases are presented while the gridlock phase is vanished and it becomes a jammed phase where the oncoming vehicles change their willing exit to save time and to avoid being trapped in the gridlock state (see Fig 3.10(a)).With the increase of T_{exit} the free flow phase remains unchanged,while the congestion phase shrinks, hence the jammed phase enlarges. Once the timeT_{exit} condition is fulfilled vehicles at the exit point will change their willing exit and take the nearest exit point; which explains the vanishing of the gridlock phase.



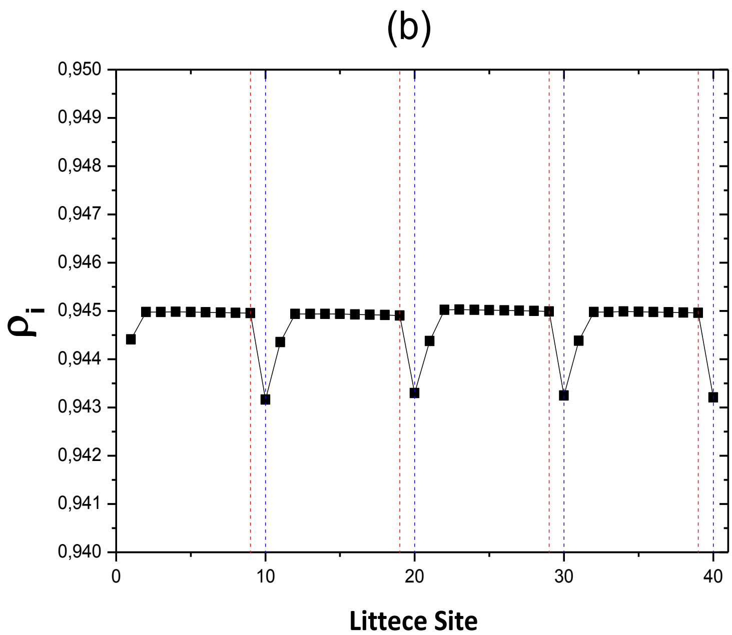


Figure 3.11: Density profile ρ_i as a function of site number i, where$\beta = 0,5$ and$L_{sp} = 0$, (a)$\alpha_1 = \alpha_2 = 0,3$, (b)$\alpha_1 = \alpha_2 = 0,8$. Red dashed (resp. bleu dashed) line presents the exit (resp. entry) point.

To better understand the traffic dynamics in both phases; the congestion and the jammed phase, we present the density profile Fig 3.11. In the congestion phase (Fig 3.11 (a)) the results are qualitatively the same with the case where drivers keep waiting; the oscillations are presented but they become weak and the density goes up as one approach to the entry point due to the high interference between incoming and oncoming vehicles. This situation indicates that vehicles cannot exit from the circulating lane smoothly, at the jammed phase (Fig 3.11 (b)) the density on the circulating lane takes a higher value due to the jam caused by the priority rules at then try points which it emerge backward in its left side. Here the circulating lane is dominated by clusters generated at the entry point. As a consequence, the capacity (i.e. the maximum traffic flow on the circulating lane) decreases.

3.4. Conclusion

In this chapter we investigated a single lane traffic circle system using NaSch model. The open boundary conditions are selected, the entry points are controlled by the injecting ratesα_1,α_2 and the exit points by extracting rateβ. We considered both cases with and without the splitter islands (i.e. the separation distance (L_{sp}) between two successive exit and entry points). Phase diagram in the space (α_1, β) are presented, the effects of the traffic circle size (L), the number of entry point (N), and the time needed for drivers to change their willing exit (T_{exit}) are discussed. The results show that the phase diagram in both cases is characterized by the presence of three phases: free flow, congested and gridlock. Furthermore, the large sized traffic circle shows better performance in the free flow phase. In contrary, increasing the number of the entry/exit point$N$ promotes and enlarges the congested and gridlock phases. Hence, we tried to enhance traffic at the system by controlling the timeT_{exit}, the results show that the gridlock phase has become a jammed one. Finally, we investigated the effect splitter island, as L_{sp} increases the free flow and the congested phases enlarge while the gridlock one shrinks.

Chapter 4

Traffic flow behavior at un-signalized intersection with crossing pedestrians

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Traffic flow behavior at un-signalized intersection with crossings pedestrians

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ABSTRACT

Mixed traffic flux composed of crossing pedestrians and vehicles extensively exists in cities. To study the characteristics of the interference traffic flux, we develop a pedestrian-vehicle cellular automata model to present the interaction behaviors on a simple cross road. By realizing the fundamental parameters (i.e. injecting rates α_1, α_2, the extracting rate β and the pedestrian arrival rate α_P), simulations are carried out. The vehicular traffic flux is calculated in terms of rates. The effect of the crosswalk can be regarded as a dynamic impurity. The system phase diagrams in the (α_1, α_P) plane are built. It is found that the phase diagrams consist essentially of four phases namely Free Flow, Congested, Maximal Current and Gridlock. The value of the Maximal current phase depends on the extracting rate β, while the Gridlock phase is achieved only when the pedestrians generating rate is higher than a critical value. Furthermore, the effect of vehicles changing lane (P_{ch1}, P_{ch2}) and the location of the crosswalk X_P on the dynamic characteristics of vehicles flow are investigated. It is found that traffic situation in the system is slightly enhanced if the location of the crosswalks X_P is far from the intersection. However, when P_{ch1}, P_{ch2} increase, the traffic becomes congested and the Gridlock phase enlarges.

1. Introduction

With the rapid development of the cities, the traffic congestion problems have attracted much attention of researchers. The city's traffic system is composed of streets, vehicles, pedestrians. Physicists have notably attempted to simulate traffic flow at intersections and other city traffic designations [1–12].

In the city traffic the dynamics is not only controlled by the interaction between vehicles, but is also influenced by crossings pedestrians. Pedestrian movement has taken a lot of interest by researchers [13–17].

Currently, more and more concerns have been focused on the studies of interaction between pedestrians and vehicles, several models have been proposed [18–22], among them; cellular automata (CA) is widely used to understand the interference processes between vehicles and pedestrians [23–29]. Sucha et al. [24] described pedestrian-driver encounters and decision strategies at marked un-signalized crossings in urban areas in the Czech Republic. Murphy et al. [26] evaluated the Safety in Numbers effect for pedestrians at urban intersections. Ranjit Prasad Godavarthy and Eugene R. Russell [23] studied of pedestrian hybrid beacon's effectiveness for motorists at midblock pedestrian crossings. Obeid et al. [25] analyzed driver-pedestrian interaction in a mixed-street environment using a driving simulator. Feng et al. [27] proposed a cellular automata (CA) model to simulate the process of pedestrians crossing a street. Zhou et al. [28] investigated the effects of age, gender and conformity tendency on Chinese pedestrian's intention to cross the road in potentially dangerous situations. Zhuang and Wu [29] developed a model of pedestrian crossing paths at unmarked roadways for a better understanding of pedestrian behaviors. Furthermore, some studies have considered the interactions of vehicles and pedestrians at a single crossing point [30,31]. Jin et al. [30] proposed an improved car flowing model to represent the interaction between vehicles and pedestrians in a simulated single-lane pedestrian crossing situation. Xin et al. [31] introduced a pedestrian-vehicle CA model to study the characteristics of mixed traffic at an un-signalized mid-block crosswalk. Jiang et al. [32] proposed a simplified CA model to describe the traffic flow when there are pedestrians traversing the road. Chen and Wang [33] studied the interaction of vehicle flows and crossings pedestrian on uncontrolled low-grade roads or branch roads without separating barriers in cities where pedestrians may cross randomly from any location on both sides of the road. Liu et al. [34] studied the dynamic analysis of pedestrian crossing behaviors on traffic flow

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4.1. Introduction

Pedestrians in cities are a crucial part of traffic, which influence the quality of vehicular traffic especially near to the intersections. Currently, more and more concerns have been focused on the studies of interaction between pedestrians and vehicles, several models have been proposed [112-116], among them; CA is widely used to understand the interference processes between vehicles and pedestrians [117-123]. Sucha et al [117] described pedestrian-driver encounters and decision strategies at marked un-signalized crossings in urban areas in the Czech Republic. Murphy et al [118] evaluated the safety in numbers effect for pedestrians at urban intersections. Godavarthy and Russell [119] studied of pedestrian hybrid beacon's effectiveness for motorists at midblock pedestrian crossings. Obeid et al. [120] analyzed driver-pedestrian interaction in a mixed-street environment using a driving simulator. Feng et al. [121] proposed a CA model to simulate the process of pedestrians crossing a street. Zhou et al. [122] investigated the effects of age, gender and conformity tendency on Chinese pedestrian's intention to cross the road in potentially dangerous situations. Zhuang and Wu [123] developed a model of pedestrian crossing paths at unmarked roadways for a better understanding of pedestrian behaviors. Furthermore, some studies have considered the interactions of vehicles and pedestrians at a single crossing point [124-125]. Jinet al. [124] proposed an improved car flowing model to represent the interaction between vehicles and pedestrians in a simulated single-lane pedestrian crossing situation. Xin et al [125] introduced a pedestrian-vehicle CA model to study the characteristics of mixed traffic at an un-signalized mid-block crosswalk. Jiang et al. [126] proposed a simplified CA model to describe the traffic flow when there are pedestrians traversing the road. Chen and Wang [127] studied the interaction of vehicle flows and crossings pedestrian on uncontrolled low-grade roads or branch roads without separating barriers in cities where pedestrians may cross randomly from any location on both sides of the road. Gang et al. [128] studied the dynamic analysis of pedestrian crossing behaviors on traffic flow at un-signalized mid-block crosswalks. Han-Tao et al [129] established two traffic flow CA models of urban two-lane road concerning pedestrians crossing streets at crosswalks without signal control and uncontrolled sections without specific crossing facility. However, seldom researches have focused on the effect of the pedestrian crossing on the traffic flow at an un-signalized. Therefore, this chapter is devoted to studying the interaction between two important components of traffic in cities(i.e. vehicles and pedestrians).

4.2. Model and methods

In this subsection we are going to describe all parameters used in the modeling and simulation in this chapter.

4.2.1. System Model

The system consists of two lanes of length L connected to each other in the middle at position $L_{1,2}$ (i.e. intersection), the length of each cell of the lane is taken as 7.5m (this corresponds to the typical space occupied by one vehicle in a dense jam (i.e. the vehicle length plus the distance to the preceding vehicle) and the width is set to 3.6m. All chains are single lane and one-way. Also, each chain is designed with two crosswalks (Fig 4.1 (a)). We note that the movement in the road 1 (resp. road 2) is from left (resp. the bottom) to right (resp. to the up). Also, vehicles in the road 1 (resp. road 2) can turn only to the left (resp. right).

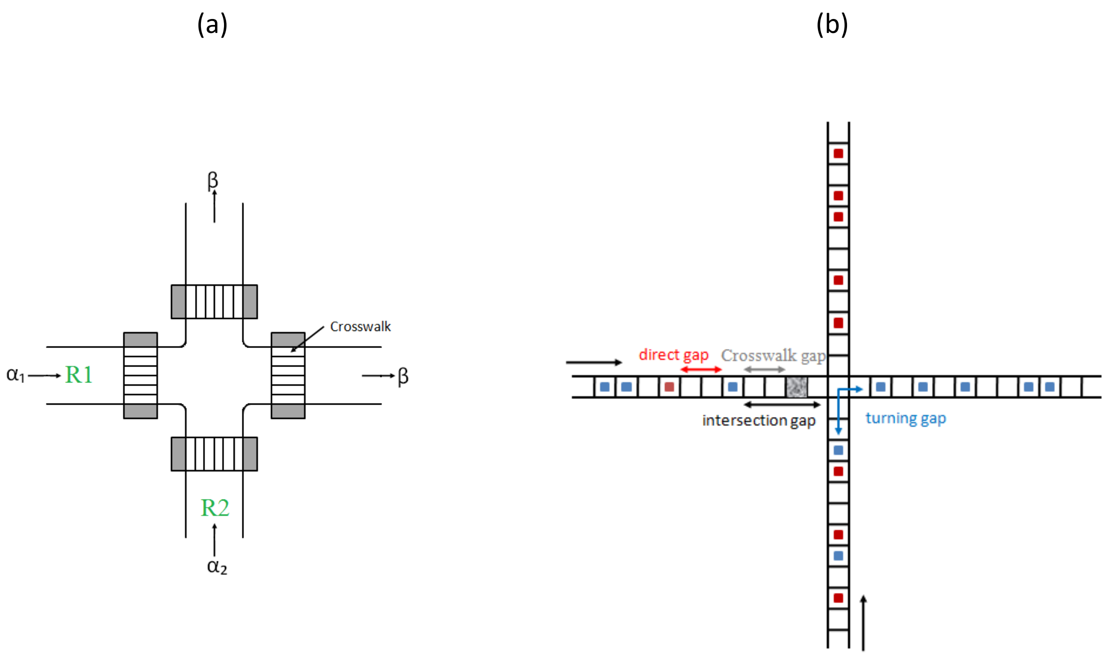


Figure 4.1: (a) Sketch of the intersection, (b) Intersection of two uni-directional single-lane streets with possibility of vehicle turning at the intersection

4.2.2. Crosswalk

In this model, we introduce two crosswalks at each road (i.e. before and after the intersection) for accommodate crossings pedestrians (see Figure 4.2).Here, the crosswalk is defined on a discrete $L_C * W_C$ small site grid in a part of one cell of the road and it is located N_c cells upstream/downstream of the intersection, this situation increases the pedestrian safety and does not incur large delays to traffic. L_C and W_C are the crosswalk's length and width, respectively. Furthermore, pedestrians are generated at a waiting zone Fig 4.2 (i.e. gray area) with rate α_P then a pedestrian makes his/her choice to begging to cross or not according to the situation of the first sites of the lane empty or occupied/ it accommodates entering or existing pedestrian (i.e. If there are several possibilities, only one site will be selected randomly with an equal probability P_a=0.25).

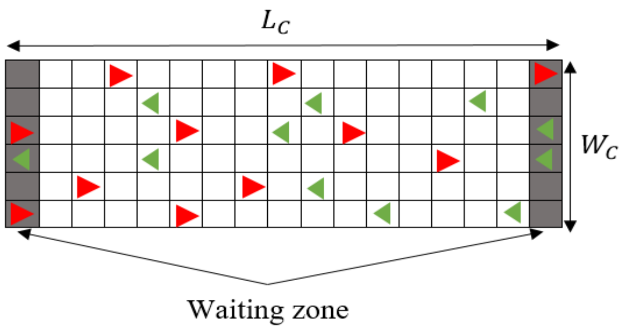


Figure 4.2: Sketch of the crosswalk,

According to HCM [130], the static thickness is 0.3m and the dynamic space (i.e. space that contains only one moving pedestrian) is among 0.6 m and 0.8 m, we take 0.6 m as the dynamic space. In our model the dimensions of the crosswalk at each road side are: $L_C = n * 0.6$ sites and $W_C = k * 0.6$ sites. Here, n is the number of sites for one road side, k is the number of pedestrian crossing lane. Indeed, the total space uses by crossing pedestrians is just: $L_C * W_C$. Furthermore, in reality the dimensions of a crosswalk at single lane road are: the length $L_C = 3{,}6$ m and the width $W_C = 2{,}5$ m. So, $n = \left\lceil \frac{3.6}{0{,}6} \right\rceil = 6$ and $k = \left\lceil \frac{2.5}{0{,}6} \right\rceil = 4$, where$\lceil \quad \rceil$denotes the Ceiling function.

4.2.3. Pedestrian dynamic

For foolproof crossing each pedestrian examines the available headway between the nearest vehicle and the crosswalk g_1 (see Fig 4.3 (b)), then she/he decides whether begin to cross or not, in other words, if the headway between the crosswalk and the vehicle is larger than a critical value gap acceptance G_{ac}, the pedestrian starts crossing. Else, she/he will stay at the sidewalk and wait. According to Ref. [131], the critical gap is calculated as : $G_{ac} = \text{round}\left(\frac{L_c}{V_{Pi}}\right) + \tau_{sf}$, where$\tau_{sf}$ presents if the pedestrian is aggressive or prudent, i.e., the larger τ_{sf} reflects that the pedestrian is more prudent and vice versa.

(a) (b)

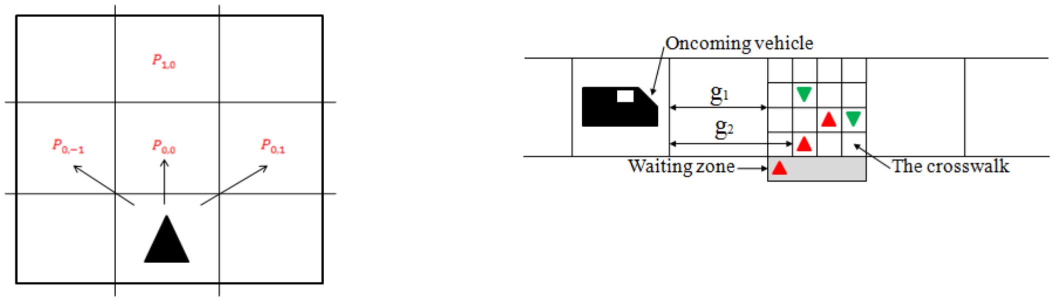


Figure 4.3 :(a) The movement field, and the associated matrix of probability for his or her possible choices of action, (b) the two-headway gap between vehicle and crosswalk/pedestrians.

We note that on the crosswalk, if the pedestrians begin crossing the road, they have the priority over vehicles, i.e., the nearest vehicle should stop until he/she has finished crossing. On the other hand, the pedestrians' movement at crosswalk is related to their neighborhood (i.e. surrounding environment) where pedestrians can move to one of the three sites in front of them or wait with probability $P_{i,j}$ (see Fig 4.3 (a)) where i, j= {-1,0,1},i.e., i presents the line position while j reflects column position (left -1, middle 0, right 1), here the corresponding site is selected by the higher $P_{i,j}$.

$$P_{i,j} = \begin{cases} 1 & \text{if the site (i, j)will be empty at the next time step} \\ 0 & else \end{cases}$$

If there are several possibilities (i.e. two sites or more have the same probability), the forward-movement is selected firstly. Otherwise, only one site will be selected randomly with equal probability. To describe the motion of a pedestrian, we propose a cellular automata model; where whole walkers are treated in parallel over one-time stage by virtue of the three rules:

1. Acceleration:$V_{Pi} \leftarrow Min\ (V_{Pi} + 1;\ V_{Pmax})$
2. Deceleration:$V_{Pi} \leftarrow Min\ (V_{Pi};\ d_{Pi})$
3. Movement:$x_{Pij} \leftarrow x_{Pij} + V_{Pi}$

Where x_{Pij} and V_{Pi} present the location and speed of the pedestrian i, respectively. The maximum velocity and the gap between walkers are designated as V_{Pmax} and d_{Pi}, respectively.

According to Ref. [132], the pedestrian maximum speed under easy mind is no more than 1.4 m/s (i.e. $V_{Pmax} = \left\lceil \frac{1,4}{0,6} \right\rceil = 3$).

4.2.4. Vehicles movement rules

To describe the motion of a vehicle we use the NaSch model (see Chapter 1 section 1.9.4.4).

Vehicles near the crosswalks must decelerate and adapt their velocities according to the distanced_i as presented:

$$d_i = \begin{cases} X_{i+1}(t) - X_i(t) - 1 & \text{if the crosswalk is empty} \\ X_P - X_i(t) - 1 & else \end{cases} \tag{18}$$

Where, $L_{1,2}$ is the location of the intersection, N_c is the number of cells between the intersection and the crosswalk, and $X_P = L_{1,2} - N_c$ is the crosswalk position.

4.2.5. Priority to occupy the intersections and the turning rules

Upon entrance each vehicle selects its direction with a finite likelihood P_{ch} and it remains unchanged. Furthermore, if a vehicle intends to turn right or left should use its indicator to acquaint the others of its direction andadjust its speed as it bears up the intersection cell, in other words, if $L_{1,2} - X_i \leq V_{max}$ the turning speed update rule is $V_i = \text{Min}(V_{max}, V_i + 1, gt)$. Here, $L_{1,2}$ designate the position of the intersection position, and gt is the turning gap (i.e. the gap between the vehicle i and the first vehicle in the perpendicular direction which has already passed the intersection see Fig 4.1(b)). This rule mimics the vehicle's preparation turning. After that the priority rules to occupy the intersection is applied. Thus, the priority rules at the intersection are given as follows:

(i) The vehicle in the intersection cell goes first
(ii) If the intersection is empty, then the nearest vehicle to the intersection goes first.
(iii) If the vehicles have the same distance $(G_1 = G_2)$to the intersection, the priority is given to the vehiclewhich is going to reach the intersection with less time.
(iv) If the vehicles can reach the intersection at the same time and they have equal distance to the intersection, then the priority is giving to one of them randomly with probability P_P.

Otherwise, if the vehicle has not fluffed the rules of turning, the approaching vehicle gap is adjusted appropriately via the intersection position (see Fig 4.1(b)) the vehicle should decelerate via $V_i = \text{Max}\,(0, L_{1,2} - X_i - 1)$.

4.2.6. Boundary conditions

We adopt the open boundary condition proposed by Barlovic et al [127] for more detailed information see chapter 1 section 1.9.4.3.2 and 1.9.4.4

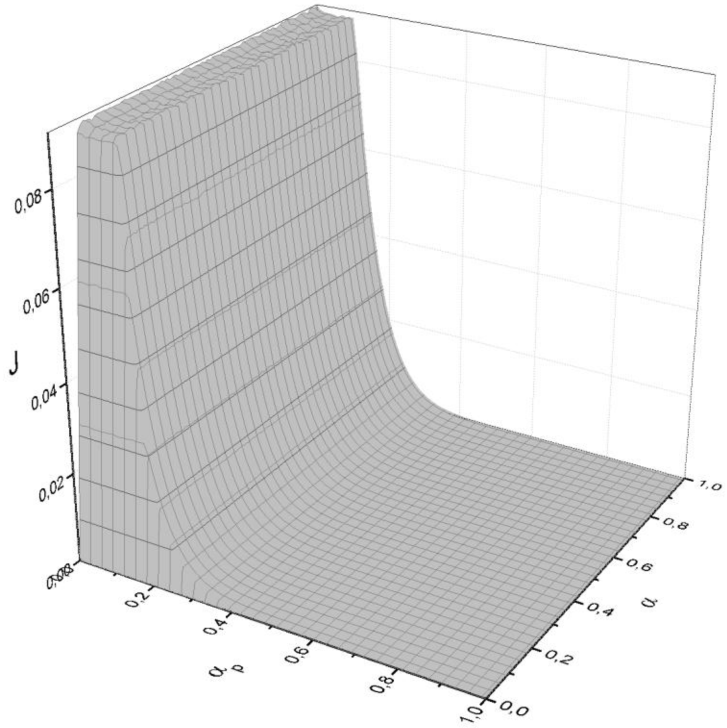
4.3. Results of the simulation and discussions

In this section, the simulation results are presented. The parameters used are: $V_{max} = 2,\ L = 100, L_{1,2} = 50$, $P_p = 0{,}5$, $N_c = 3m' = 4$and $V_{Pmax} = 3$. The results are averaged over 60 000 time steps after 10 000 time steps for 50 independent runs. We denote the total current at the system by J, where $J = (J_1 + J_2)/2$ (J_1 and J_2 are the current on the road R1 and R2 respectively).

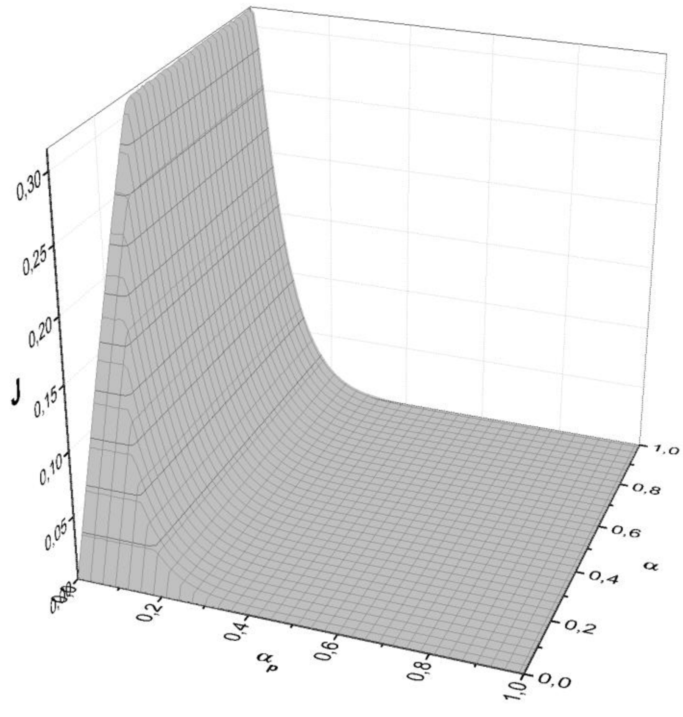
4.3.1. $\boldsymbol{\alpha_1 = \alpha_2}$

Firstly, we are going to take the case where vehicles cannot change their direction (i.e., $P_{ch\,1} = P_{ch\,2} = 0$) and for the sake of simplicity we assume that$\alpha = \alpha_1 = \alpha_2$. We study the global current in the system J as functions of the probabilities α_1 and α_p for several values of β. As we can see from Fig 4.4, the current in the system depend strongly on the parameters α_1, α_p and β. Based on the current in each road as an order parameter, Fig 4.5 presents the phases diagrams of the system in(α, α_P) plane for several values ofβ. The first phase diagram ($\beta = 0.1$), Fig 4.5(a), presents four different phases.

(a)


0,08
0,06
J
0,04
0,02
0,2
0,4
0,6
0,8
1,0
α_p
0,0
0,2
0,4
0,6
0,8
1,0
α

(b)


0,30
0,25
0,20
J
0,15
0,10
0,05
0,2
0,4
0,6
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α_p
0,0
0,2
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0,6
0,8
1,0
α

(c)

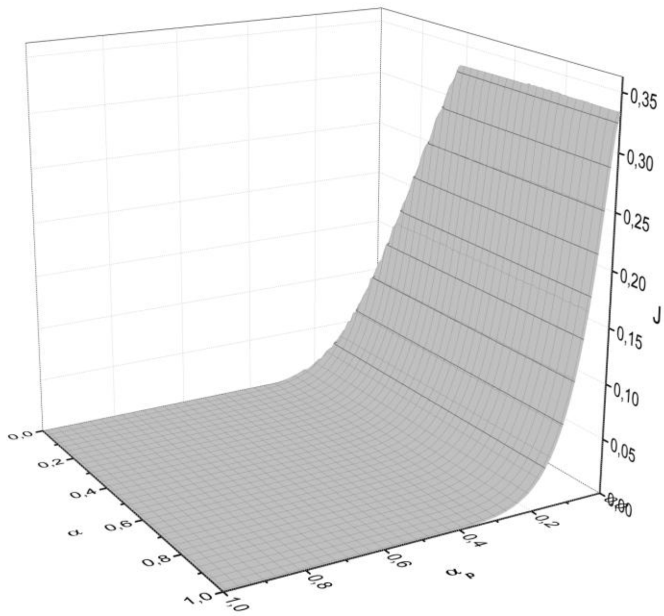
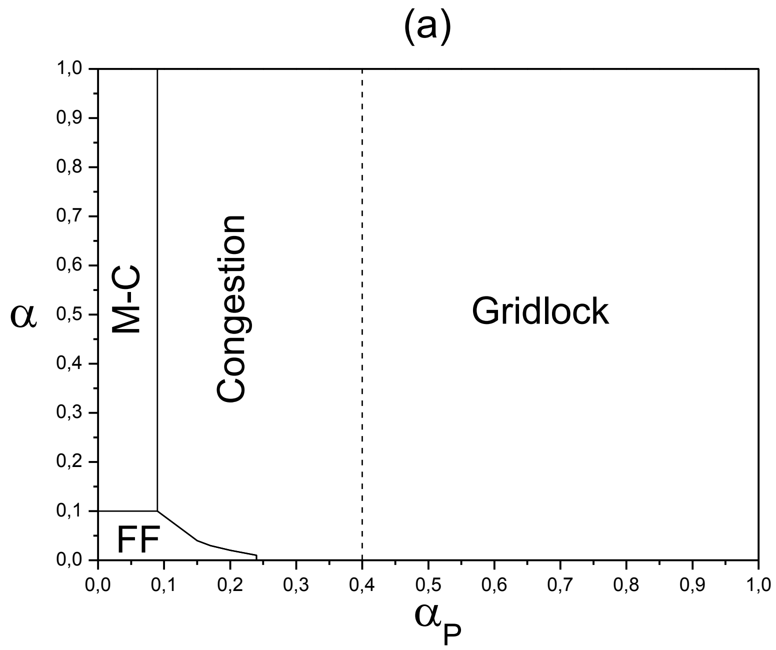
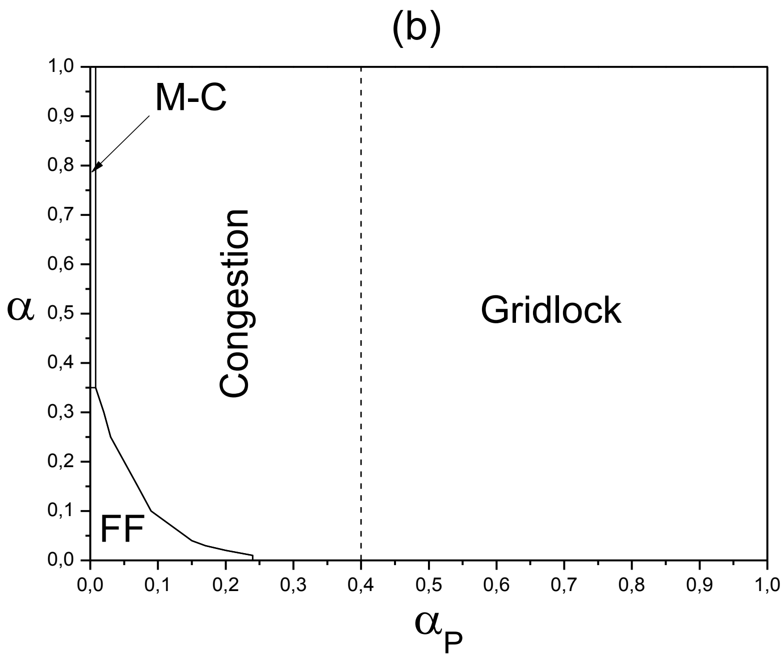


Figure 4.4: Variation of vehicle flux under different α and α_P for $X_P = 3$, (a) β=0.1, (b) β=0.4, (c) β=1

In phase I, the Free Flow is reached; vehicles can move freely and the pedestrian doesn't influence the vehicular traffic. Phase II, the congested state is obtained, vehicular flow is mostly influenced by pedestrians at the crosswalks, the interaction between pedestrians and vehicles are increased. In phase III, the Gridlock phase is reached. Here, the interactions are higher; pedestrian blocks the vehicles at the crosswalks, in other word the crosswalk is occupied by crossing pedestrian. In this respect, we can say that the Gridlock phase is shown by increasing the generating probability of pedestrians, and this finding agrees well with Ref [105]; where the case of a roundabout with pedestrian crossing was studied. In phase IV, the Maximal current phase is reached (the current in this case is J=0.09) and it's depends on the extraction rateβ. As β increased (see Fig 4.5(b) and (c)) the Free Flow and the Congestion phases are extended while the Maximal current phase is decreasing (for $\beta = 0.4$; J =0, 34 and for $\beta = 1$; J =0, 38), while the Gridlock phase remains unchanged. Here the system is affected by two types of local defect (i.e. the intersection and the other are the cross walking of pedestrians). Note that, the local defects appear as a defective cell which affects the low dimensional non-equilibrium systems on a global scale [134-136]. Nevertheless, in both cases from the free flow to the congestion and from the MC to the congestion we found a first-order phase transition; the current change is discontinuous at the transition point. However, the phase transition between the congestion and the gridlock is continuous which means that the transition here is second-order. While, from free flow to MC first-order phase transition occurs is first order because the current change is discontinuous.





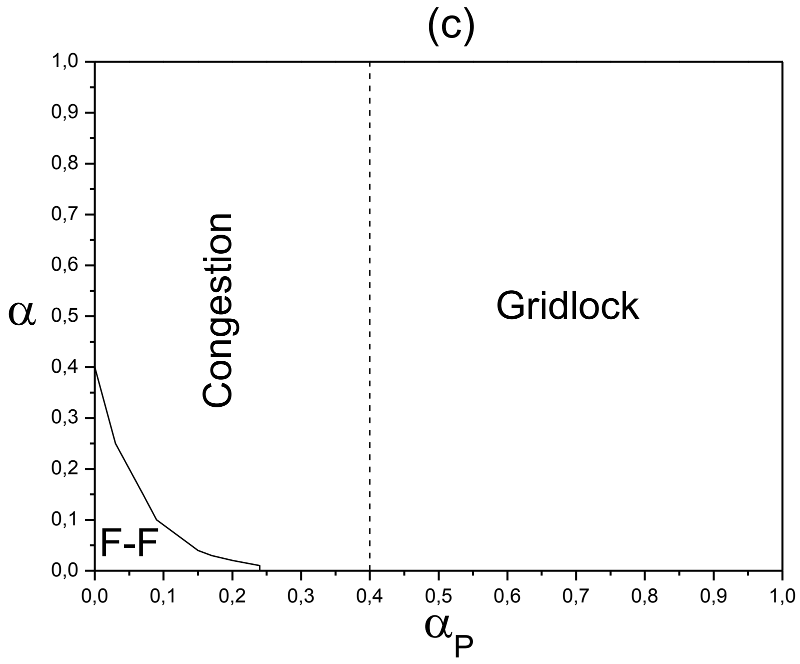
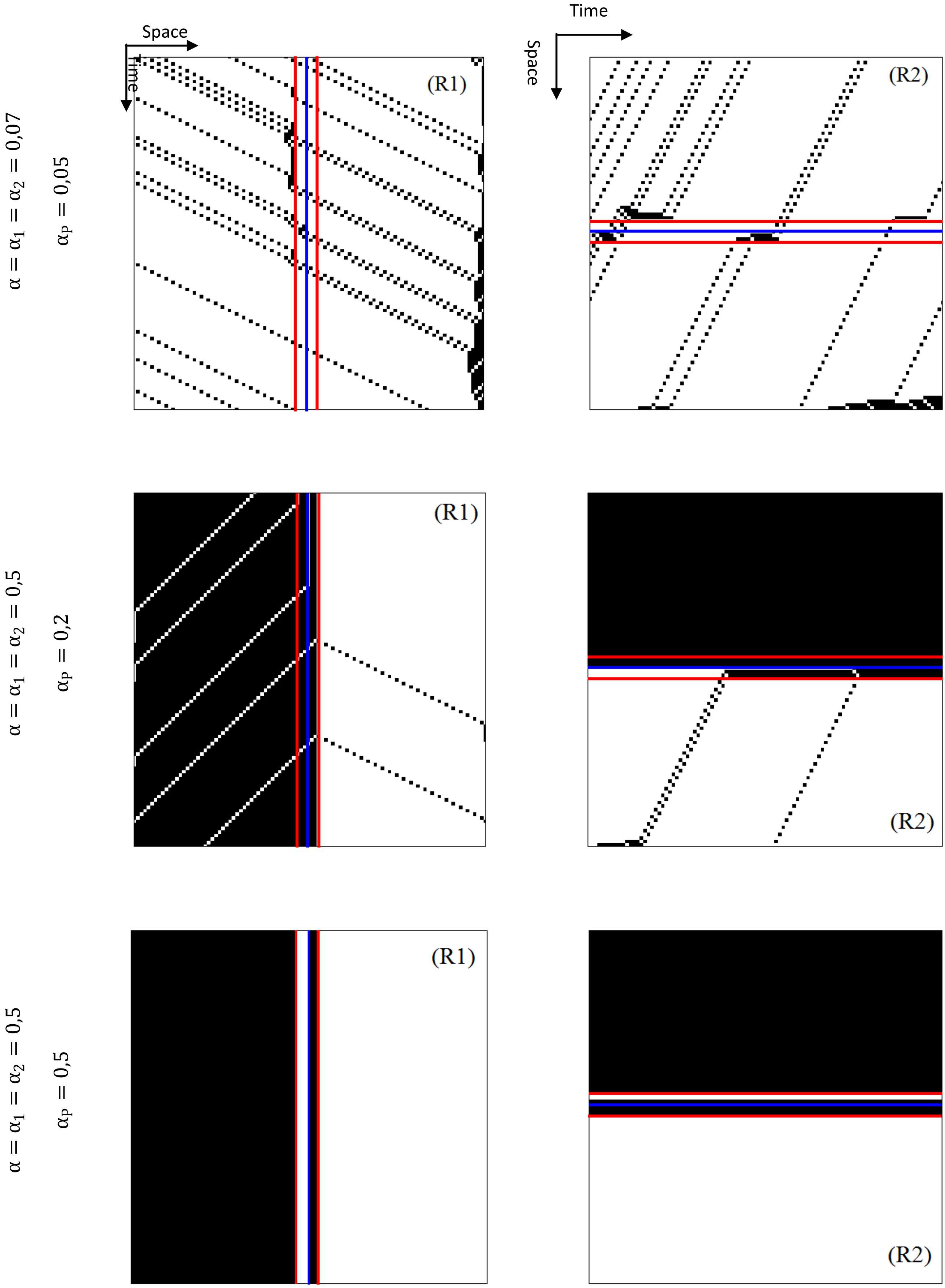


Figure 4.5: Phase diagram in the (α_P, α) space for $X_P = 3$, (a) β=0.1, (b) β=0.4, (c) β=1.

In order to have a deep insight into the traffic dynamics, we plot the spaces times of each phase (see Fig 4.6). In the Free Flow phase vehicles can move almost freely except near the intersection and the rights boundaries (i.e. β<1 provokes some clusters of standing vehicles waiting to be removed); also, we see that the crosswalk has a slight effect on the vehicles motion. However, in the Congestion phase, we can see a phase separation because vehicles are hindered by the cross walking. In the case of the Gridlock phase the vehicles are totally blocked because α_P is greater than α_{Pc}. Here, the pedestrian may hinder vehicles which increase the waiting time thereby a long cluster of standing vehicles. As result the intersection is blocked thus provoke the emergence of Gridlock phase. In the Maximal current phase traffic situation are congested. Here, the intersection affects the traffic in both roads, i.e. the priority rules increase the breaking near the intersection (i.e. the intersection act as an impurity cell), which reduce the effect of rates α and α_P on traffic flow.


Space
Time
(R1)
Time
Space
(R2)
α = α1 = α2 = 0,07
αP = 0,05
(R1)
(R2)
α = α1 = α2 = 0,5
αP = 0,2
(R1)
(R2)
α = α1 = α2 = 0,5
αP = 0,5

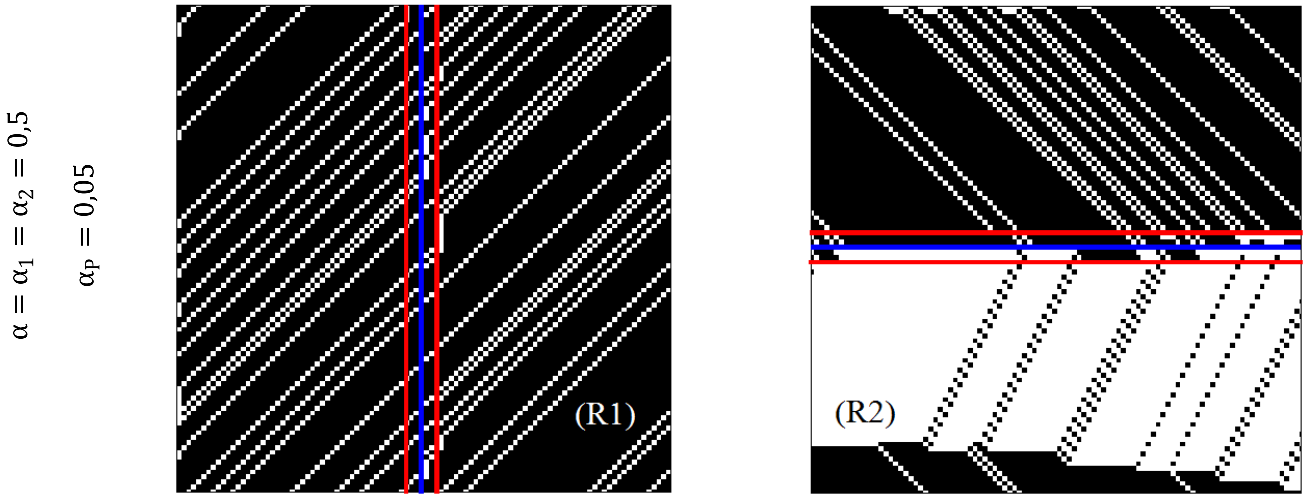


Figure 4.6: Space time of each road$X_P = 3$, $\alpha = 0.07$, $\alpha_P = 0.05$, $\alpha = 0.5$, $\alpha_P = 0.2$, $\alpha = 0.5$, $\alpha_P = 0.5$, $\alpha = 0.5$, $\alpha_P = 0.05$. The two red lines indicate the crosswalks positions and the blue one the intersection cell.

Furthermore, seen the resemblance between the Congestion phase and the Maximal current, and to get a better view into the traffic dynamics in those two phases, we present the density profiles Fig 4.7(i.e. density profile is the occupation rate of vehicles per cell). In the Congestion phase (Fig 4.7(a)); we can see a flat profile before the first crosswalk. The pedestrians block the vehicular traffic; thus, the density is almost equal to 1. After the first crosswalk vehicles are hindered again by the intersection as well the second crosswalk. Here after small oscillations are observed in the density profile because only few vehicles can pass the second crosswalk which reduces the probability of occupation. As we approach to the boundary the density increases due to the small value of the extraction rate. However, in the Maximal current phase (see Fig 4.7(b)), we have the same behavior before the intersection except the density is not that higher as in the Congestion phase because the pedestrian injection rateα_P takes small values. Afterthe second crosswalk the occupation rate increase until it reaches 0.9 because of the extraction rate ($\beta = 0.1$).

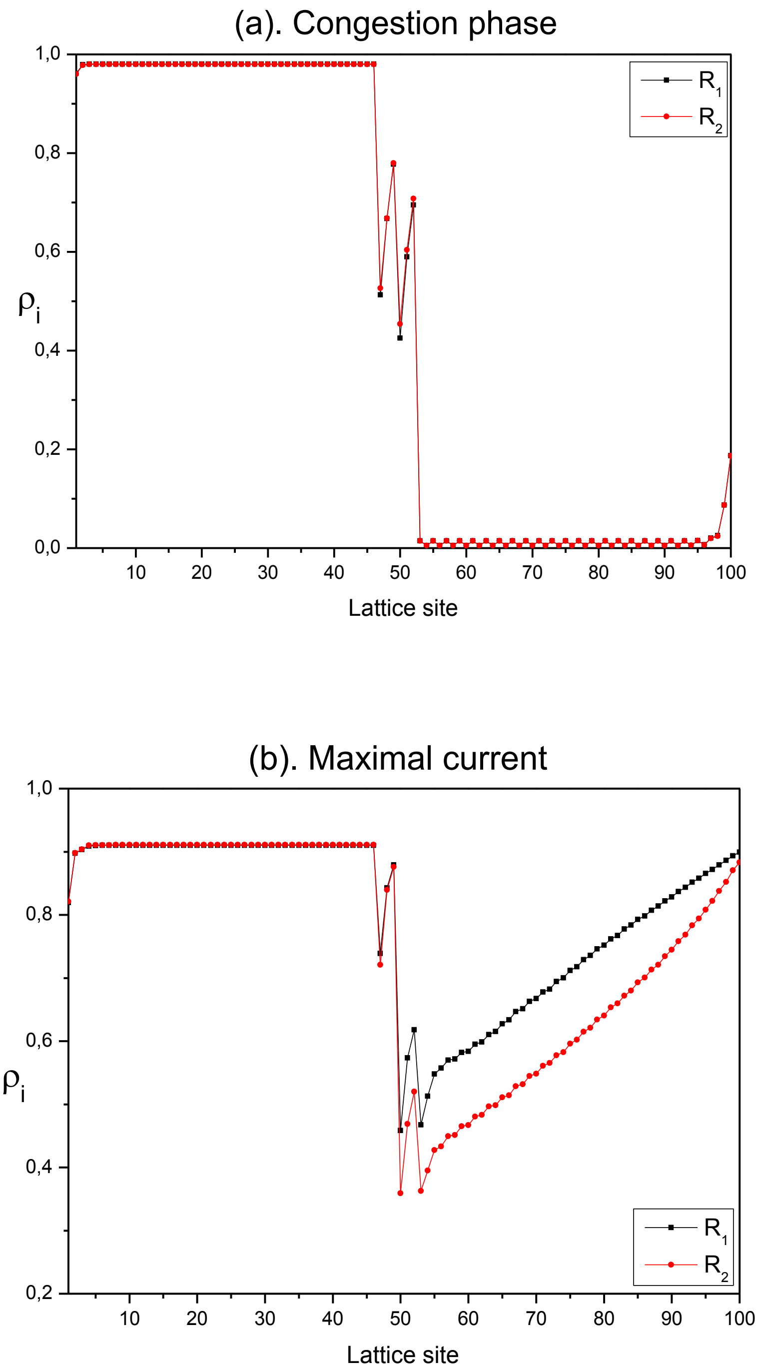


Figure 4.7: Density profile (ρ_i) of each road as function of cell number i at the Maximal current and the Congestion phase $X_P = 3$ (a)$\alpha = 0.5, \alpha_P = 0.2$, (b) $\alpha = 0.5, \alpha_P = 0.5$.

4.3.2. $\alpha_1 \neq \alpha_2$

For the rest of this chapter, we take $\alpha_1 \neq \alpha_2$ and$\beta = 1$. Fig 4.8 presents the phase diagram in the (α_1, α_P) plane. It has turned out that the results are similar with those obtained in Fig 4.5(c) where the three phases are shown. Furthermore, with increasing the injections rate$\alpha_2$the interactions vehicles-vehicles and vehicles-pedestrian raise which reduce the Free Flow phase to the low value of α_P until it disappears, while the congested phase is expanded.

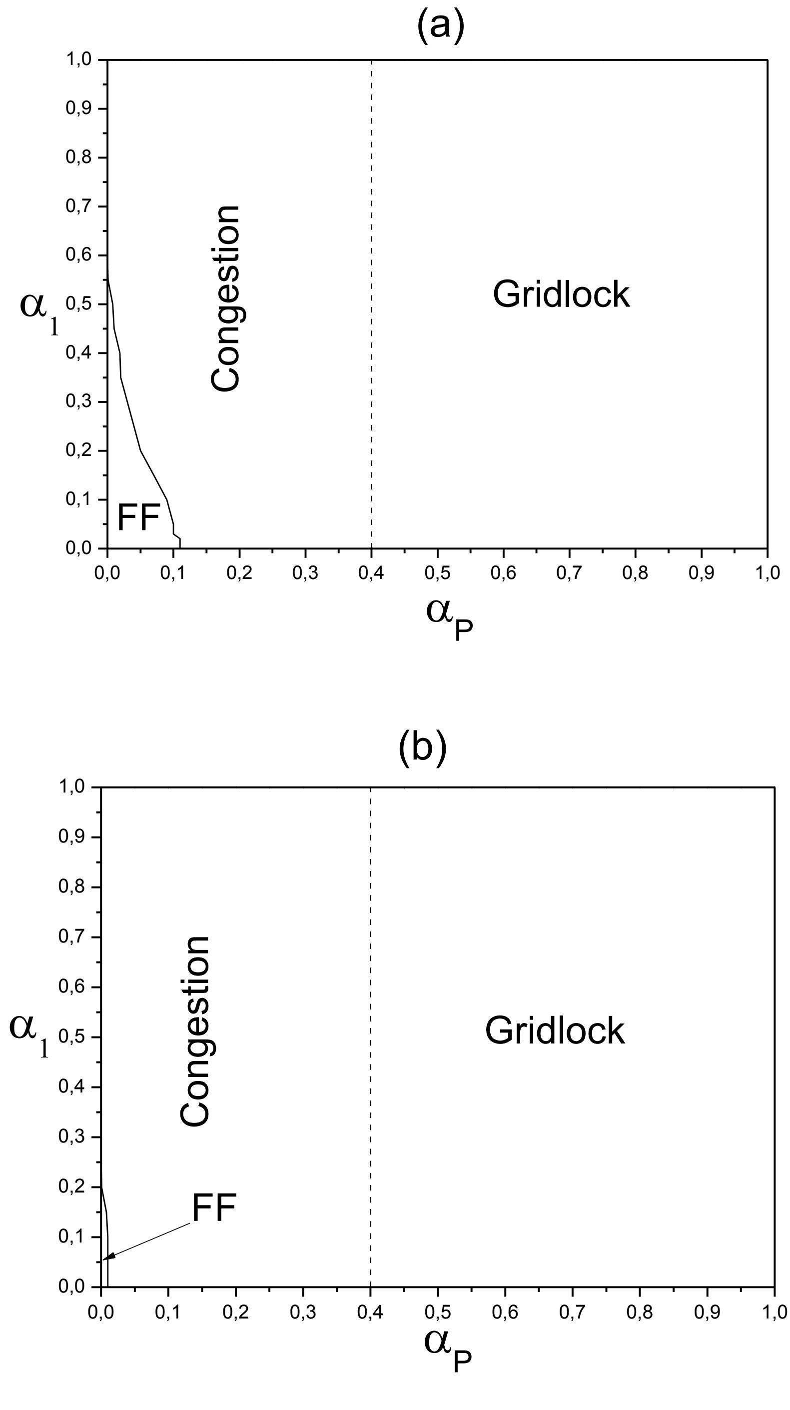


Figure 4.8: Phase diagram in the (α_1, α_P) space $X_P = 3$, (a) $\alpha_2 = 0.1$ and (b) $\alpha_2 = 0.5$

4.3.3. Changing direction probability

Besides, the traffic flow depends also on the possibility of changing direction at un-signalized intersection. However, in our system the interference between crossings pedestrian and vehicles flows can increase the interactions. Therefore, it is important to study the effect of changing direction on the traffic flow in the system. Fig 4.9 shows the phase diagram; the parameters are specified in the caption. The results show that the Gridlock phase enlarges while the congestion one shrinks. The increase of the probability of changing direction can provoke a further jamming which enlarge the queue length and thereby occupying the intersection cell causing a Gridlock in the system, which are the analogs of the jamming arises from the mutual blocking in the BML model [27].

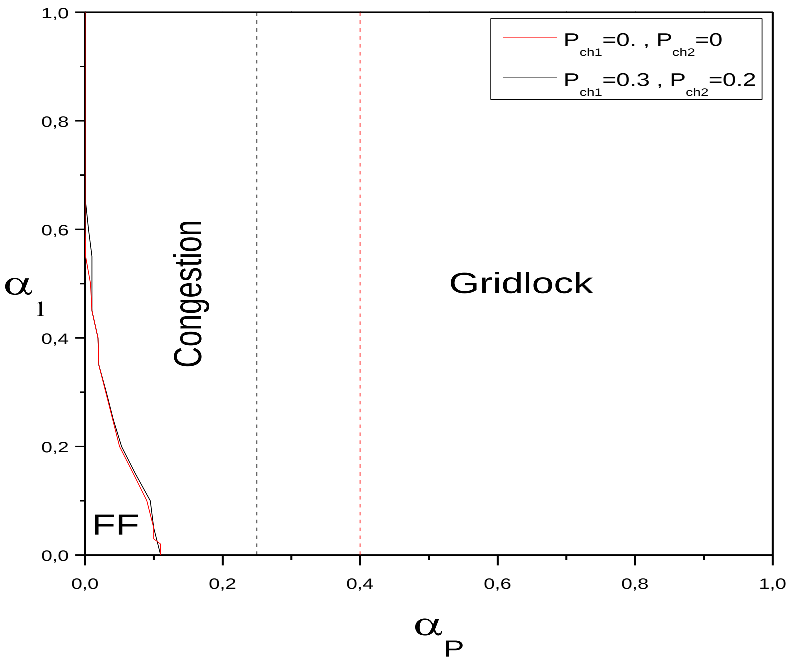


Figure 4.9: Phase diagram in the (α_1, α_P) space for $\alpha_2 = 0.1$and $X_P = 3$with several values of the probability of changing direction ($P_{ch1} = 0.3, P_{ch2} = 0.2$ and $P_{ch1} = 0, P_{ch2} = 0$)

4.3.4. Crosswalk location

Finally, we examine the effect of changing the location of the crosswalk from intersection X_P on the vehicular traffic flow. Fig 4.10 presents the phase diagram for different X_P. As we can see the three phases are presented, the congested shrink and the Free Flow phase extend while the Gridlock phase remains unchanged as X_P is far from the intersection. The interference pedestrian-vehicles can increase the braking near to the crosswalks which enlarge the queue length. Indeed, when the positions of the crosswalks are far from the intersection, traffic situation is enhanced.

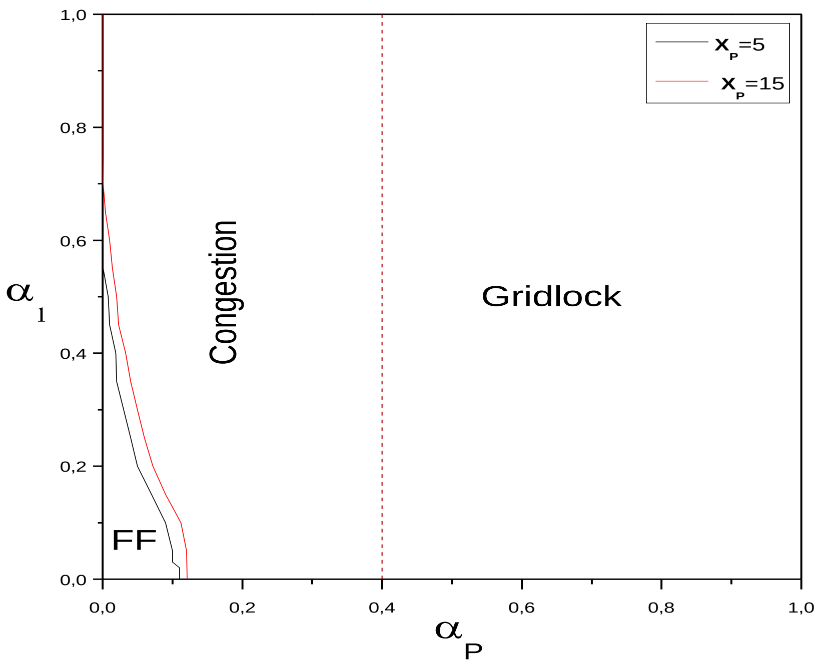


Figure 4.10: Phase diagram in the (α_1, α_P) space for $\alpha_2 = 0.1$ with several values of the crosswalk position X_P ($X_P = 3$, $X_P = 15$).

4.4. Vehicle-Vehicle and Pedestrians-Vehicle accidents

Studying car accidents is very important because it can help us to save human's life but preserving human's life doesn't mean to focus our researches just on vehicles accident models but it is also important to study the interference pedestrians-vehicles and their accidents. In this section we are going to study the probability for a vehicle-vehicle accident P_{ac} and pedestrians-vehicle $P_{ac}^{(p)}$ to occur. For this purpose, we distinguish two types of vehicles accidents: the accidents at the crosswalks (i.e. vehicles-pedestrian's accidents), and the rear-end accident.

4.4.1. Pedestrians-Vehicle accidents condition

The accident at the crosswalk is between the nearest vehicles on each road and the pedestrians at the crosswalks. For this purpose, we suggest a vehicle-pedestrian's accidents model. By studying the probability for a car accident to occur when drivers do not yield to the crossing pedestrians. More precisely, if at time t, the velocity $V_i(t)$ of the nearest vehicles to the crosswalk was positive, and $0 < G_i < V_i(t)$ (i.e. G_i is the gap between the crosswalk and the nearest vehicle). Next at time t+1 if $V_i(t+1) < V_i(t)$ the vehicle i, stopped by crossing pedestrians at t+1, and the crosswalk is not empty (i.e. pedestrians crossing road) then car i will cause an accident at time t + 1, with a probability$P_c^{(p)}$.

4.4.2. Vehicle-Vehicle

The rear-end accident is a vehicle collision with the vehicle ahead. We are going to use the conditions proposed by Boccara et al [58] in the first chapter section 1.11

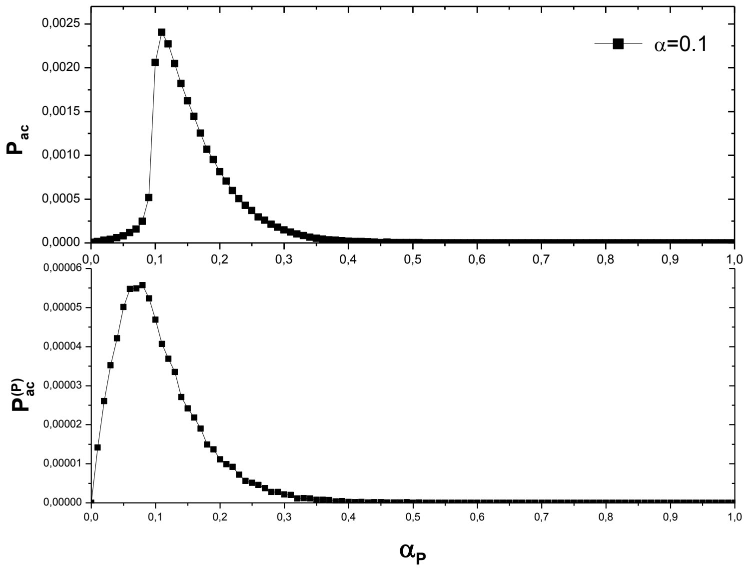


Figure 4.11: the vehicle/vehicle and vehicle/pedestrians' probability

Figure 4.11 shows the vehicle-vehicle P_{ac} and pedestrian-vehicle $P_{ac}^{(p)}$ accident probability as a function of the pedestrian injecting rate α_P with $\alpha = 0{,}1$. Increasing α_P, slightly increasesP_{ac} until it reaches its maximum at the critical point α_{Pc1}, this region coincides with the first district where the interaction between vehicles are lower (i.e. vehicles move with their own, and vehicles might have trapped by the intersection priority. When α_P continues to increase, P_{ac} decreases until it becomes null, this region presents the congestion phase, here the roads are dominated by clusters of standing vehicles, which decreases vehicles accident probability. $\alpha_P > \alpha_{Pc2}$ the road is in the gridlock phase, all the vehicles are blocked behind the crosswalks, thus accident probability is null.

4.5. Conclusion

Walking is a daily necessity for many people, especially in developing countries, and it's also good for one's health and the environment. Everyone has different preferences when it comes to transportation, but at one time or another everyone is a pedestrian. Fortunately, more than 270,000 pedestrians lose their lives on the world's roads each year, or 22% of the 1.24 million total road traffic deaths annually, according to World Health Organization (WHO). Preserving pedestrian’s safety has attracted a lot of interest by researchers, to understand the pedestrian movement/safety and to increases the fluidity of the road. The coexistence of the pedestrians in the urban traffic makes the prediction of the traffic accident and traffic quality in cities a complex task. In this chapter, we studied the interaction between vehicles and pedestrian crossings at an un-signalized intersection. To control the system boundary, we use the open condition with the injection rate α_1, α_2 and the extracting one β, while the pedestrians are generated with probability α_P at a waiting zone. We have shown that the Maximal current phase value decreases whit the raise of the extraction probability, whilst the Gridlock phase is obtained when the pedestrian injection rate α_P is higher than a critical value. Moreover, we have investigated the effect of vehicles changing lane $(P_{ch\,1}, P_{ch\,2})$ and the location of the crosswalk X_P on the vehicular traffic flow. It was shown that as $P_{ch\,1}, P_{ch\,2}$ increases as the interactions between vehicles become higher at the intersection and before the crosswalks, thus the traffic becomes congested and the Gridlock phase enlarges. On the contrary, traffic situation in the system is slightly enhanced if the location of the crosswalks X_P is far from the intersection. This finding can be used to understand the interactions vehicles/pedestrians at such intersection. Finally, we have studied the accident probability of vehicles/vehicles accidents and pedestrian/vehicle accidents, it was found that with the pedestrians’ crosswalks qualitatively affect the accident probability whether pedestrian/vehicle accidents or vehicle/vehicle accidents. This study shows that the pedestrians should take into consideration as an important factor in the future studies of vehicular traffic.

Conclusion general

Effective transportation systems for people and goods significantly contribute to improving the quality of life in modern societies. The increasing demands of transportation lead to a significant increase in the number of vehicles in and around big cities. In recent years, most industrialized societies have begun to see the limits of growth of traffic infrastructure, leading to recurrent and systematic traffic congestion. Solutions are now oriented to better management and control of existing transportation systems by designing techniques for dynamic management of traffic flows. Nevertheless, the design and implementation of such techniques require suitable models for a proper understanding of traffic dynamics on a local and global system level, and on the effect of the associated phenomena. This knowledge needs understanding the different traffic components and the different modeling approaches.

In this context, we presented in chapter I the basics parameters of the traffic field; the component of the road network, the aggregated data, and the different models' approach of traffic (i.e. microscopic models, macroscopic models and mesoscopic models) and we focused on the importance of computer simulation.

Computer simulations as a means for evaluating control and management strategies in traffic systems have gained considerable importance because of the possibility of taking into account the dynamical aspects of traffic. During a long time, the preferred method for traffic flow simulation was to derive macroscopic models that aggregate traffic variables in spatially discretized versions of highways and therefore to pay attention to the average value of the significant variables. Recently, there has been a trend to perform microscopic traffic simulations that focus on individual vehicles due to the rapid development of computer capacity. Microscopic models have become popular as they can reproduce a large variety of phenomena observed in traffic that cannot be captured by most macroscopic models. Among the microscopic models, cellular automata (CA) have been increasingly used in simulations of traffic flow on account of their simplicity and flexibility. As a matter of fact, the microscopic models are based on three laws: car following, lane changing and the gap acceptance. Using the gap acceptance law, we studied traffic flow in three types of intersections and some effective solutions were proposed to improve the traffic flow situation in terms of fluidity and security.

In the second chapter, we have used the NaSch model to study the energy dissipation (Ed) in the roundabout system, based on the Ed as an order parameter of traffic quality we have been able to explore much more feature of the traffic phases and we proved that the named free flow phase is just a quasi-free flow phase, where the vehicles decelerate at each entry point and dissipate energy. Also, we have studied the rate of vehicles with no aimed exit point and the probability that vehicles with no aimed exit point choose the nearest one. Indeed, the results also indicated that the dissipating energy decreases with the increases of the two probabilities which enhance the traffic situation of the roundabout.

Besides, roundabout or "modern roundabout" is a road junction where the priority is given to the circulating flow. According to history the first roundabout was built in United States, it was a huge rotary, where vehicles within the central circle had to yield to those entering the intersection and it called “traffic circle”. Those rotaries were the subject of our third chapter.

In the third chapter, we have shown that traffic circle presents a better performance in the low traffic flow situation, so to make it more credible we have examined some parameters of the traffic circle that changes the safety and performance of the systems. The simulation results show that the phase diagram in both cases consists essentially of three phases’ namely free flow, congestion and gridlock. However, the large sized traffic circle and the cases with splitter islands shows better performance and more fluidity of the flow, in contrast, traffic circle with a high number of entry/exit points make the fluidity worsen which reduce the capacity and lead to the gridlock in the system. By the end of this chapter, we have tried to overcome this gridlock situation by adding a new parameter (i.e. time for a driver to change his/her willing direction) that given the vehicles trapped by the gridlock the right to change their direction and to choose the next exit point to leave the circulating lane. We found that when the decision time is less, traffic flow mode improves in the traffic circle.

The fourth chapter is devoted to the study hybrid traffic at an un-signalized intersection, where we analyze the traffic conditions taking into account the interactions between the pedestrians and the vehicles, we ascend that the gridlock phase is more likely when the vehicles always give way to the pedestrian crossing. Our results suggest that controlling the vehicles (respectively pedestrians) traffic flow can improve the traffic situation and restore balance of power vehicles/pedestrians. Also, we found that changing direction at the intersection has a big effect in the choice of pedestrian crosswalk position, where it must allow the vehicles to leave the intersection, when it gives way to pedestrians. On the other hand, the crosswalk must not be too close or too far from the intersection. Too close, does not allow the vehicles of leave the intersection, too far, it forces the pedestrians to make an excessive trip.

Given the diversity of road traffic as a field of study, this thesis work presents a partial contribution to keep the uniqueness of the work. Knowing that they are still questions to be addressed and that will be treated in perspective:

- At the modeling level, it is necessary to better adapt the NaSch model to take into account the synchronization of velocities, thus enhance this model with an overtaking rule in order to treat the case of multi-lane roads.
- At the environmental level, further research needs to take into account more environmental impact data such as, fuel consumption and greenhouse gas emission.
- At the traffic control level, further research needs to generalize solutions over a more complex network. Indeed, the objective will be to study the correlation of traffic in a two-lane roundabout, as well as two adjacent intersections, roundabout, traffic circle or the mixed situation in order to develop a model that can deal with complex traffic situations.

List of publication

1. A. Khallouk, H. Binoua, N. Lakouari, H. Echab, R. Marzoug and H. Ez-Zahraouy "The energy dissipation at roundabout system" Int. J. Mod. Phys. B, Vol. 33 1950007 (2019).
2. A. Khallouk, N. Lakouari, H. Echab and H. Ez-Zahraouy. "Traffic flow behavior at a single lane traffic circle" Int. J. Mod. Phys. C Vol. 28, No. 7 1750093(2017).
3. A. Khallouk, H. Echab and H. Ez-Zahraouy, N. Lakouari "Traffic flow behavior at un-signalized intersection with crossing pedestrians" Phys Lett A 382, 566–573(2018).
4. R. Marzoug, N. Lakouari, O. Oubram, H. Ez-Zahraouy,A. Khallouk , M. Limon-Mendoza and J.G. Vera-Dimas "Impact of traffic lights on car accidents at intersections" Int. J. Mod. Phys. C Vol. 29, No. 121850121 (2018)

Articles in process

1. A. Khallouk, A. Karakhi, A. Laarej, N. Lakouari, H. Echab, and H. Ez-Zahraouy. "traffic flow behaviors in a tow connected roundabouts"
2. A. Khallouk, A. Laarej, A. Karakhi, N. Lakouari, H. Echab, and H. Ez-Zahraouy. "velocity-depend-randomization model for heterogeneous traffic"
3. A. Laarej, A. Khallouk, A. Karakhi, N. Lakouari, and H. Ez-Zahraouy "Dissipation energy in a heterogeneous tow lane traffic model"
4. A. Karakhi, A. Khallouk, A. Laarej, N. Lakouari, and H. Ez-Zahraouy "car accidents in a three phases cellule automata model"

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Abstract

Traffic networks are complex systems, and predicting traffic behavior is crucial for planning and operation purposes. Computer simulations have become important tools for evaluating control and management strategies in traffic systems, and among the various simulation models, Cellular Automata (CA) models have gained significant popularity due to their efficient performance in computer simulations. This thesis emphasizes the importance of CA models in describing and predicting traffic flow situations in intersections. The traffic flow situation was studied in three types of intersections: roundabout, traffic circle, and un-signalized intersection. The energy dissipation rate was studied in a roundabout system, and the study showed that the free flow phase is just a quasi-free flow where vehicles decelerate at each entry point of the rotary. Additionally, it was found that traffic circles have a better traffic flow in low densities, and the presence of large-sized and splitters islands enhances the fluidity and performance of the rotary. In the investigation of hybrid traffic flow at un-signalized intersections, a new model was proposed that takes into account the interactions between pedestrians and vehicles. The study found that the gridlock phase is reached when pedestrians have the right of way over vehicles, and their injection rate is larger than a critical value. The study also emphasized the importance of crosswalk location and vehicles changing direction in enhancing traffic flow conditions. Overall, the thesis highlights the importance of CA models in predicting and improving traffic flow situations in complex intersections.

Keyword: *Traffic flow, Cellular automata, Intersections, Pedestrians, Energy dissipation.*

Résumé

La thèse examine l'utilisation des modèles d'automates cellulaires pour prédire et améliorer la circulation routière, en se concentrant sur trois types d'intersections : le carrefour giratoire, le rond-point et l'intersection non signalée. Les modèles de CA sont efficaces pour les simulations informatiques en raison de leur précision relativement faible à l'échelle microscopique. Le taux de dissipation d'énergie a été étudié dans un système de carrefour giratoire et l'étude a montré que la phase d'écoulement libre est juste un écoulement quasi-libre où les véhicules décélèrent à chaque point d'entrée du giratoire. De plus, il a été constaté que les giratoires ont un meilleur écoulement du trafic dans les faibles densités, et que la présence d'îlots de grande taille et de séparateurs améliore la fluidité et la performance du rond-point. Dans l'étude du trafic hybride aux intersections non signalées, un nouveau modèle a été proposé prenant en compte les interactions entre les piétons et les véhicules. L'étude a montré que la phase de blocage est atteinte lorsque les piétons ont la priorité sur les véhicules et que leur taux d'injection est supérieur à une valeur critique. L'étude a également souligné l'importance de l'emplacement des passages piétons et des changements de direction des véhicules dans l'amélioration des conditions de circulation. En conclusion, cette thèse met en évidence l'importance des modèles de CA dans la prédiction et l'amélioration des situations de circulation dans des intersections complexes.

Mots-clé : *Trafic routier, Automates cellulaires, Intersection, Piétons, Dissipation énergie.*

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